River Basins and Change

Editors: Janos J. Bogardi, Jan Leentvaar, and Hans-Peter Nachtnebel

With contributions from Sina Marx and Eva Riedke

Global Water System Project

UNESCO-IHE Institute for Water Education

Imprint

River Basins and Change
Bogardi, Janos J.; Leentvaar, Jan; Nachtnebel, Hans-Peter (eds.)

International Project Office (IPO)
Walter-Flex-Str. 3
53113 Bonn, Germany
www.gwsp.org
gwsp.ipo@uni-bonn.de

UNESCO-IHE Institute for Water Education
Westvest 7
2611 AX Delft, The Netherlands
www.unesco-ihe.org

Layout by:
Bosse und Meinhard Wissenschaftskommunikation, Bonn

With input from:
Sina Marx
Eva Riedke

Introduction, summary and guide to the book

The present electronic book is aimed to bring together the major contributions to the international conference on The Global Dimensions of Change in River Basins – Threats, Linkages and Adaptation, organized within the Global Catchment Initiative of the Global Water System Project (GWSP) and held between 6 to 8 December 2010, in Bonn, Germany. This book contains papers which were presented during the conference, either as keynote lectures in plenary sessions or as submitted papers in one of the thematic sessions.

This book is based on selected papers. Neither all submitted papers, nor all presentations of the above cited conference are included in the book. Several key presentations which were held on the conference were not accompanied by written papers and thus could not be incorporated in this book. However, all presentations and abstracts and the corresponding power point presentations as well as video recordings of many keynote presentations are available at the website of the GWSP at www.gwsp.org/73html. The readers are encouraged to complete their review of the conference and its messages by regarding this interesting scientific online-material as accompanying literature.

The present publication follows two major objectives.

» to document major contributions to the conference by providing background reading for those interested to (re)visit the issues addressed and debates held in December 2010 at the GWSP-GCI conference, and

» to present those issues, debate and contributions of the conference for the present and future generation of graduate students.

By aiming to achieve these two objectives simultaneously, this e-book is an attempt to assist those who will soon enter the professional community of what may be called the "water world".

This introduction has been written to introduce the content and features of the book in the traditional sense. Furthermore it aims to guide the reader through the book.

While the conference was organized around three main thematic areas and subdivided into seven topical focal areas

» Impact of global change on river basins
  - Climate change impacts on river basins
  - Impacts of large-scale land use patterns and demographic changes

» Long-distance connectivities and linkages of river basins
  - Connectivities and linkages between river basins and the earth system
  - Connectivities and linkages within river basins
  - Virtual water flows between river basins

» The role of global governance in river basin management
  - Impacts of national and international actors on river basin processes
  - Influence of global and national governance on water resources in river basins

The present book is conceived with a much simplified structure. Contributions are grouped into three "thematic blocks" focusing on

Global change and river basins

This includes analyses of the drivers and impacts of global change, involving climate change but also that of population dynamics, socio-economic development, land use change and related processes. River and lake basins at different orders of magnitude from different parts of the world in quite different geographical, climatic, socio-economic and political settings and contexts are represented. Responses to global change drivers include changes in the hydrology of the basin, change of land use and water management.

Accounting for water and river basins

Under this part of the book methods of water balance at basin, national and global scales are highlighted. They account for the links between water management and global trade and economics but also water quality. Water availability, its changing spatial and temporal distribution and role in water security is a core subject with particular emphasis on the links between water and food security. 'Accounting for water' touches upon the question of valuation including the potential role of water charges and tariffs. While many examples are river basin related this part of the book is also an important presentation of how different methods can be applied.

Governance and river basins

This part deals with issues of how societal structures and values influence evaluation, development, selection and implementation of options regarding allocation, use and protection of water and related resources at basin, national and international scales. It includes examples of international stakeholder involvement, management of large transboundary basins as well as analyses of legal, administrative and other aspects of governance schemes at national and international levels. In addition, this part presents the summary of a panel discussion between basin managers, government representatives and scientists analyzing common challenges and outlining how science should be involved in practical water governance of large river basins.

Obviously there are several papers which would fit into more than one of the above defined three categories. The overwhelming majority of the contributions address water issues implicitly or explicitly within the conceptual framework of integrated water resources management (IWRM). This implies that irrespective of their assignment in any of the thematic blocks, most of them contribute at least to two of them. Placing a paper in a particular block, reflects the main emphasis of the paper but also its potential educational significance for the respective thematic area.

This publication aims to reach out to all graduate students whose curriculum includes water related topics, irrespective whether they are enrolled in and pursue academic programmes in hydrology, hydraulic engineering, water resources management, agriculture, climatology, geography, geology, ecology, environmental studies, economics, public administration, social or political sciences. Hence, this book constitutes neither classical conference proceedings nor a regular textbook.

As this book aims to assist young scientists and professionals from different (water related) academic disciplines, the editors felt the need to introduce definitions and give short explanations on issues, methods, and concepts being frequently used or referred to in the contributions to this book. The result is a selection of issues. Hence no claim of comprehensiveness is made either as far as issues or the detail of their discussion are concerned. These short explanations presented in the Annex of this book do not aim to substitute authoritative treatises on the respective issues. Rather they represent the views of the editors, highlighting debated, sometimes even contradictory aspects and views, thus drawing attention to potential pitfalls, misinterpretations and inherent uncertainties.

The editors take full responsibility for the selection and placing of the papers and the selected commented issues. They have defined their role as facilitators, especially for graduate students, to gain as much knowledge and insights from reading this book as possible. For the content of the published contributions the respective author(s) take full credit and responsibility. Thus this is definitely a multi-authored book, presenting a multitude of ideas, case studies, different settings and foci. This book presents the state-of-the-art, but also shows the limits of our present knowledge, inaccuracies and uncertainties in predicting what may lies ahead of us. The book highlights the frequent lack and inadequacy of data, but also that of conducive governance frameworks. Yet they set the constraints within which we have to deal with our present and future water challenges. No doubt that every graduate student, but even mature scientists and water professionals would find in this book intriguing research questions and practical problems still waiting to be answered and solved.

Bonn, January 2012

Janos J. Bogardi
Jan Leentvaar
Hans-Peter Nachtnebel

Content

Introduction, summary and guide to the book 3

Theme I: Global change and river basins

Impacts of climate change on rainfed agriculture in a semi arid zone - a case study from Sudan 8
Shamseddin M. Ahmed

HighNoon: adaptation to changing water resources availability in northern India 14
Hester Biemans & Eddy Moors

Impact of global change on hydrology and soil degradation - scenario analysis for the semi-arid Drâa catchment (South Morocco) 21
Bernd Diekkrüger, Henning Busche, Anna Klose, Stephan Klose, Christina Rademacher & Oliver Schulz

Impacts of climate variability and population pressure on water resources in the Lake Chad Basin 27
Roland Geerken, Sara Vassolo & Mohamed Bila

Impact of global change on water resources in the Ouémé catchment, Benin 34
Simone Giertz, Bernd Diekkrüger & Britta Höllermann

Drivers of land use changes in the Amudarya river basin 41
Darya Hirsch

Diverse impacts of climate change on streamflow in Alberta, Canada 50
Stefan W. Kienzle, Michael Nemeth, Katherine Forbes & James M. Byrne

Physical heterogeneity and socio-economic differences as determinants of change in the Danube basin 57
Hans-Peter Nachtnebel

» Global change is more than climate change 70

» Global sustainability 72

» Downscaling in climate change studies 74

» Interbasin transfer of water between river basins or to demand centers outside of the basin 76

Theme II: Accounting for water and river basins

Estimating green-blue water availability and needs for global food production 80
Dieter Gerten, Jens Heinke & Holger Hoff

The impact of water pricing in an arid river basin in Morocco considering the conjunctive use of ground- and surface water, water quality aspects and climate change 85
Claudia Heidecke & Thomas Heckelei

Assessing the use of hydrologic drought indicators in characterizing the extent and severity of the 1999-2005 drought on the Canadian prairies 91
Richard Lawford & Phillip Harder

Lake Winnipeg basin – confronting cultural eutrophication with bioeconomy opportunities 104
Richard Lawford, Dean Medeiros, Henry David Venema, Greg McCullough & Matt McCandless

Effect of changing anthropogenic and climate conditions on BOD loading and in-stream water quality in Europe 116
Anja Voß, Ilona Bärlund, Manuel Punzet, Richard Williams, Ellen Kynast, Olli Malve & Frank Voß

Virtual water flows - Methods of water accounting and examples 122
Hong Yang & Zhouying Zhang

» Water pricing and tariffs 128

» Accounting for both „blue water" and „green water" in water resources management 130

» Indicators and their limitations 132

Theme III: Governance and river basins

Dialogue between scientists and river basin managers: Documentation of a panel discussion at the GWSP GCI Conference in Bonn 137

Sustainability of basin organizations – The Mekong as case study 144
Bastien Affeltranger

Connectivities and linkages within the Volta Basin 152
Charles A. Biney

Impacts of national and international actors on river basin management – case of River Rhine 168
Esra D. Bozkir, Jan Leentvaar, Ine D. Frijters & Maarten A. Hofstra

Impacts of the governmental water policy on land use and streamflow in the arid Heihe River watershed, Northwest China 177
Changsheng He, LiFu, Yi Luo, Lanhai Li, Carlo Demarchi & Ninglian Wang

The influence of international water governance on water management in Zambia. 183
Jonathan M. Kampata

Multilateral environmental agreements – a catalyst for interlinkages in river basin management? A case study of Pahang river basin, Malaysia 188
Jing Lee

Asymmetry and accountability deficits in water governance as inhibitors of effective water resource management 194
Mike Muller

» Legitimate stakeholders? 199

» Integrated river basin management and its limitations 200

» Water security 201

Glossary and list of acronyms 203

Photo: Wadi Drâa, Michel Queyraud (wikipedia)

Impacts of climate change on rainfed agriculture in a semi arid zone - a case study from Sudan

Shamseddin M. Ahmed

Water Management and Irrigation Institute, University of Gezira, Gezira University Street., P. O. Box 20, Wadmedani, Sudan.
E-mail: Shams_id@yahoo.com.

Abstract

Sudan is one of the Nile basin countries. The Nile Agreement in 1959 has stipulated a limited share for Sudan. Thus, Rainfed agriculture has governed Sudan's agricultural expansion and food security. Negative climate changes will cause disruption in livelihood generation and environment, especially in rural areas where people depend on rainfed agriculture. This study aimed at answering questions of whether there is an indication of a climate change in the semi arid zone of Sudan or not? If it does, what its impact on rainfed agriculture and what would be the sustainable mitigation and adaptation actions that should be taken? The descriptive statistics showed that the semi arid zone experienced decreases of 16% (92 mm) and 15% (13 days) in the annual rainfall and the length of cropping season, compared to a baseline (1960s), respectively. The sowing and harvesting dates of cropping season were also disrupted. Using AQUACROP simulation program, a reduction of 37% is predicted in sorghum yield when annual rainfall was decreased to 250 mm. This was followed by a decrease of 10% in transpiration. Accordingly, rainwater productivity will drop from 0.49 to 0.13 kg/m^3. The two consecutive on-farm experiments indicated that in situ rainwater harvesting techniques (chisel and furrow) in average could increase yield by 412%.

Keywords:
climate change; simulation; rainfed agriculture; adaptation

Introduction

Agriculture as the main source of food would likely be affected by reduction in water availability due to climate change, especially in arid and semi arid zones of Africa (de Fraiture et al., 2010). Also, the increased frequency of drought will pose the greatest risk to agriculture, especially in arid and semi arid tropics which are likely to be most vulnerable to climate change (Sivakumar et al., 2005). A 2007 report of IPCC concluded that in Africa a decrease of 50% in yield of rainfed agriculture is expected by 2020. Moreover, by the year 2080, an increase of 5 to 8% of arid and semi arid land is projected. This is coupled with an accelerated growth rate of population. In sub-Saharan Africa by the year 2030, an annual rate of increase of 2.5% in food production is required (Rockström, 2003). Generally, since 1970s the Sahelian total annual rainfall fluctuated around the value of 400 mm, compared to 520 mm during the period of 1931-1960 (Hulme, 2001). However, future changes in seasonal rainfall in Africa haven't well defined, yet (Sivakumar et al., 2005).

Whatever was the direction taken by the climate change mitigation and adaptation actions should be taken. Sivakumar wrote that "*Whether or not there will be a significant climatic change, the inherent climatic variability in the arid and semi-arid regions of Africa makes adaptation unavoidable*". Rainfed agriculture is the dominant land use activity as it represents 80% of the world cultivated area, especially in Sub Saharan Africa. Accordingly, adaptation to climate change in this arena is highly required to sustain ecosystem services and livelihood generation. Rainwater harvesting techniques (RWHT) proved their suitability for bridging large dry spells the large yield's impairing factor. RWHT will increase soil water content in the unsaturated zone. Salas et al. (2009) gave many successful cases where rainwater harvesting provided adaptation opportunities to climate change. For instance, rainwater harvesting can reduce degradation of ecosystems; increase water supply; reduce energy used; reduce greenhouse gas emission; increase water productivity; release capital needed in times of disaster and help in realizing the Millennium Development Goals.

Any adaptation strategy for climate changes should pay attention towards anticipation and information (Sivakumar et al., 2005). Crop yield simulation models give anticipation, information and insights. Various crop yield simulation models were used worldwide (Ko, et al., 2009; de Wit and van Diepen, 2008; Richter and Semenov, 2005). The precision of these models depends on the ability to quantify outputs from different interconnected factors such as weather, soil and management (de Wit and van Diepen, 2008). In addition to the highly expert needed, most of the simulation models requires large amount of data (Bastiaanssen et al., 2007). Availability of the data therefore constraints using of such highly data demanding models, especially in developing countries. FAO AQUACROP may represent the less data demanding model and the simplest form of simulation environment.

Availability of irrigation water acts as a severe constraint to irrigation development in Sudan (Knott and Hewitt, 1996). Therefore, rainfed agriculture governs Sudan's agricultural expansion. Rainfed agriculture produces around 80% of cereals, 100% of sesame and 90% of groundnuts. Because it is the main food crop, sorghum is dominant in rainfed agriculture and characterized by its yield fluctuations (Ayoub, 1999). There are two objectives in this study. The first is to answer the question of whether there is climate change in the semi arid zone of Sudan or not; if it does, what is the impact of this change on rainfed agriculture and what would be the sustainable mitigation and adaptation actions that should be taken? The second objective is to simulate future crop yield under pessimistic conditions.

Materials and methods

The study area situated between 11.83 and 14.03° N in latitude and between 33.62 and 35.4° E in longitude. The climate is semi arid. The temperature ranges between 16.6 and 36.7 °C. The annual average evapotranspiration is 2100 mm. The rainy season is short and extended for 4 - 6 months. The soil is heavy clay soil ((Blokhuis, 1993) where cracks develop due to change of soil water. Rainfed agricultural system is the predominant economical activity.

Rainfall data (1960-2006) were collected from five representative stations; which are Gedarif, Sennar, Damazin, Abu Naama and Kosti. The descriptive statistic (mean, standard deviation, etc) was used to detect climate change. The mean rainfall of 1960s was the baseline. AQUACROP V 31 was used to simulate and quantify the effect of current climate change on yield of sorghum (*Sorghum bicolor* (L.), Moench). Reliability and accuracy of the program were checked through setting the current actual parameters influencing sorghum yield. These were climate, crop, field conservation practices and soil. Then, the simulated yield was compared to actual yield obtained from two on-farm consecutive experimental seasons. The prediction was based on the current shift in the length of cropping season coupled with an assumption that the semi arid zone has been transformed into arid zone conditions where the normal rainfall (1970-2000) is 250 mm. Some predicted soil water balance parameters were obtained and evaluated against the currently existed ones.

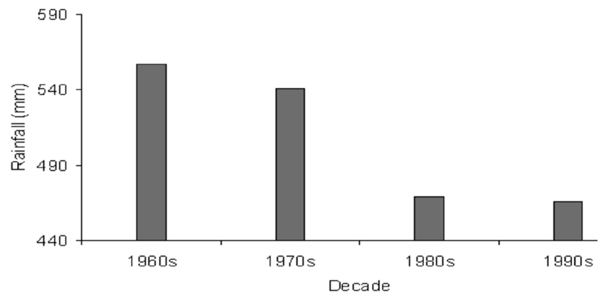
Two consecutive on-farm experiments were conducted in the Agricultural Farm of the University of Gezira. The tested rainwater harvesting techniques were chisel and furrow. Optimum sowing dates were determined on basis of Coche and Franquin approach (1967). ETo values were obtained using CROPWAT program.

Results

Rainfall analysis

Figure 1 shows the trend of the decadal (10 years) means since 1960s. Rainfall shows a decrease trend. Relatively to the mean of the baseline (557.3 mm), the decreases in rainfall were 16.5, 88.3 and 91.7 mm for the periods 1970s, 1980s and 1990s, respectively (Figure 2). The coefficient of variation ranges between 22 and 29%. The normal rainfall (1970-2000) was found to be 488 mm. The years 1979 and 1984 were the wettest and driest seasons, respectively. It seems that since 1982 deterioration in agricultural conditions has been experienced, probably due to the fact that the annual means of rainfall are below normal (Figure 3). The trend of monthly rainfall amount is shown in Figure 4. It is obvious that there are increasing trends in May and June; whereas, from July onwards a decreasing trend existed, suggesting a change in seasonality.

Figure 1. The decadal mean of rainfall



Changes of sowing date, end and length of cropping growing season

It seems that changes in annual rainfall resulted in altering the onsets, ends and season lengths (Figure 5). The current season length was reduced by 15% to be 74 days instead of 87 days of the baseline. Both the onset and end dates are shifted back, relative to the baseline. During the 1970s and 1980s the season length showed no change, however, onset and end of the cropping growing season have shown little disturbance. It is found that the current sowing dates lead to appreciated loss of early showers.

Impacts of climate change on yield and agricultural hydrological parameters

The average accuracy of the AQUACROP program on basis of the experimental seasons was 72%. Two regular dry spells were observed in the central Sudan (Hulme, 1986; Shamseddin, 1986); Which represent vegetation and flowering crop growth stages of sorghum (*Sorghum bicolor* (L.), Moench). Thus, the simulation with a time step of 10 days includes these two dry spells (<1.0 mm) (i.e. after 20 and 45 days of the sowing date). The simulation yielded 0.2 ton/ha. The current yield is 0.52 ton/ha. Some predicted hydrological parameters for rainfed agricultural system were shown in Table 1.

Mitigation and adaptation measures

The on-farm experiments resulted in increasing sorghum yield which ranged between 230 and 595% relative to the control as shown in Table 2. On basis of Wageningen's approach (Doorenboss, 1986), the potential yield is 4200 kg/ha. The furrow and chisel in-situ rainwater harvesting techniques increased soil water content by 89% and 94% over the control, respectively.

Figure 2. Annual standardized departure from 1970-2000 mean rainfall

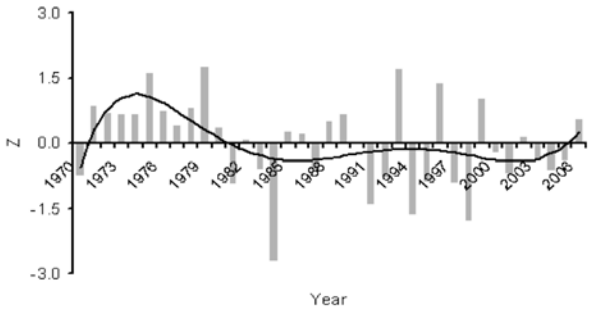


Figure 3. Decadal coefficients of variation (CV) and changes in rainfall (mm)

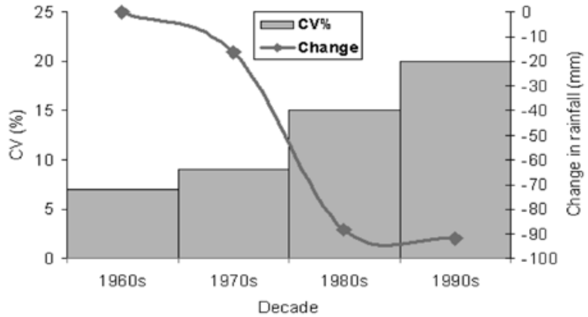


Table 1. Some current and predicted hydrological parameters

Parameter	Rain (mm)	E/Emax	T/Tmax	ET/ETmax
Current	302	0.64	0.50	0.50
Predicted	250	0.71	0.43	0.40

Figure 4. monthly rainfall pattern of change relative to the period of 1960s

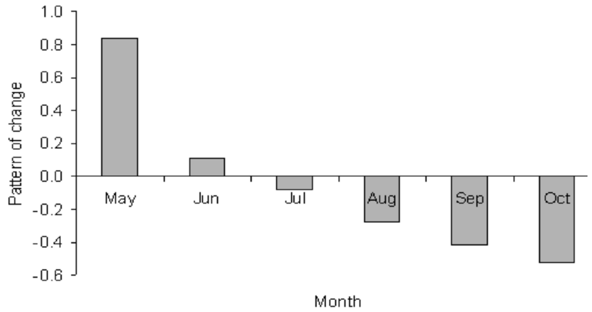


Figure 5. Onsets and Ends of agricultural season in the study area where first and second intersections of rainfall and reference evapotranspiration (ETo) represent the beginnings and end of season, respectively

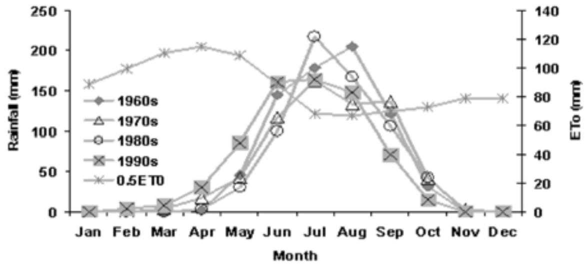


Table 2. In situ rainwater harvesting technique effects on sorghum yield

Season	Furrow	Chisel	Control	ET/ETmax
First season yield (kg ha^{-1})	1880	1623	493	0.50
Second season yield (kg ha^{-1})	396	625	90	0.40

Discussion

The resulted coefficients of variation reflected the high variability of annual rainfall in the semi arid zone of Sudan. This is not different from that found by Modarres et al. (2007) for the semi arid regions (30%), in Iran. Such variability makes the term normal rainfall questionable (Hulme, 2001). Hulme (2001) mentioned that "In African Sahel, the term normal rainfall is not important what is important is the spectrum of rainfall spatial and temporal variability". Abdallah (2009) stated that Sudan experiences a decrease in rainfall coupled with a shift back of rainfall isohyets and a complete disappearance of rainfall isohyets of 1200 mm from the

Sudanese climatic map. Some have suggested that changes in African rainfall amount are results of deterioration in land vegetation cover (Hulme, 2001; Sivakumar et al., 2005). Such deterioration has been observed in Sudan (Ayoub, 1999; ElFaroug, 1994; Nile Basin Initiative, 2003; Glover, 2005; UNEP, 2007). Rainfall variability will impose risk on water supply, sustainability of rainfed agriculture, livelihood generation and stability of societies. Hulme (1986) has stated deterioration in agricultural conditions in central Sudan.

The performance of rainfed agriculture depends on the onset and regular distribution of rainfall. Thus, a small shift in these two parameters will likely trigger great risks (Sivakumar et al., 2005). The decrease in monthly rainfall suggests shifts in the cropping season's onset, end and length. Such change in monthly rainfall is a regional pattern since August rainfall has showed a decreasing trend in the Sahelian zone (Sivakumar et al., 2005). Farmers used to start threshing of seeds upon traditional timings that acquired from ancients. Risk management in rainfed agriculture depends on management applications which divide into strategic, tactical and forecasting applications. Sowing date is very important element in the strategic applications, which take place prior to planting for the purpose of providing options through comparing alternative crop management scenarios evaluation, . The current climate change necessitates change in sowing dates to be in middle June. This is suggested a dissemination of weather data to farmers by the government responsible authorities/bodies. This should be started by owning the farmers the reasons of such change in advance.

Generally, Sudan experienced a decline in yield of rainfed crops, especially in the mechanized rainfed sector. A reduction of 50% of rainfed sorghum yield is observed in the period 1970-1990 (Ayoub, 1999). A 2005 study made by Glover revealed that most of the farmers attributed the reduction in yield to rainfall fluctuation. Impact of failure of agricultural season exceeds agriculture to natural ecosystems such as forestry. Local labors whose having limited livelihood generation options alternatively would practice charcoal production in unsustainable manner (Elfaki, 1994). Migration to far cities and markets is taken as alternative, too. Thus, climate change disturbs sustainability of agricultural farming systems, ecosystem service, societies etc.

The results of the simulation modeling based primary on a reduction in annual rainfall, show a reduction in crop yield. It should be noted that the results obtained by the crop simulation models often show differences with regional and national yield statistic. This is because of: (1) the inconsideration of socioeconomic status, (2) crop yield often shows an upward trend and (3) the difficulty of directly relating year-to-year variation in yield obtained by simulation to variability in regional statistics (de Wit and van Diepen, 2008). Hulme (1986) reported two distinctive dry spells in the central Sudan; the first one is after germination, which coincides with the period 10 to 20th of July, which necessitates re-sowing and it determines the success or failure of the season; the second occurs in the middle of the growing season during flowering stage and causes a serious reduction in yield. The expected increase in evaporation term (Table 2) suggests a room for hope. As adopting of rainwater harvesting may reduce this term, especially when coupled with good agronomic, engineering, management and institutional amendments or options.

Currently**,** some RWHTs were practiced in the region. However, they lack scientific pillars (Abdallah and Osman, 2003). The popular RWHT practice is bunds. Farmers construct field-ends dykes for preventing water runs out of fields. Generally, this technique is followed by soil tillage to a depth of 5 - 10 cm using Wide Disc Harrow. The successive plowing at this upper surface soil has created hard pans that lead to water-stagnant problems and increased runoff. This explains the low yields during the high rainfall seasons. Accordingly, in situ RWHT such as chisel and furrow would be good options. The results of the on farm experiments state this conclusion. This conclusion has been widely cited (Oloro et al., 2007; Mupangwa et al., 2006; Nuhu and Mahoo, 1999). Moreover, these techniques are simple and cost effective. But, the required machines are not easily available, in the region. Thus, affording such technique by government agencies or private enterprises will be a primary entry to adapt and to mitigate climate change, at rural areas. Also, it becomes rather imperative that introduction of early maturing cultivars of high yield potential and increasing the efficiency of water yield (total annual runoff) through appropriate treatments are seen as viable drivers that may push up the crop yield boundaries.

Introduction of newer technologies to adapt to climate change should be preceded by a socio-economic evaluation/study. Food and Agriculture Organization, FAO, (2005) attributed the failure of introduction of RWHT in western Sudan, during the eighties and nineties periods of the last century, to the lack of technical knowledge, and because of the use of inappropriate approaches.

Conclusion

In the semi arid zone of Sudan signs for climatic change, especially in water supply i.e. rainfall, were observed. This is jeopardized and deteriorated the rainfed farming system which is the backbone of Sudan's food security. This deterioration resulted in disturbing the local societies and ecosystems. In some places such disturbance exaggerated conflicts. AQUACROP program proved its suitability, simplicity and accuracy for simulating the environment for rainfed farming and predicting crop yields with minimum input data. In rural areas, climate change adaptation programs should be based on simple and cost effective techniques. Rainwater harvesting provides good option for easing climate change effects. Also, amendments in cultural practices i.e. sowing date and cultivars are crucial for traditional farmers. The government should pay more attention to climate change effects at rural areas.

Acknowledgements

Part of this work is PhD study which funds by DAAD. The author would like to thank Prof. Adeeb, Ali the dean of WMII, University of Gezira for his valuable suggestions. Thanks also extend to Ministry of Agriculture and Forestry, Sennar State, Sudan.

References

- Abdallah, K., 2009. Climate change indices in Sudan. A workshop paper presented in the climate change: Its impacts and involvement in scientific research in Sudan. Higher Council for Environment and Natural Resources. Wadmedani, Sudan
- Abdalla, A., Osman, M., 2003. Rainwater Harvesting: Concepts and Techniques. Conference on Water harvesting and the future of the development in Sudan. UNESCO Chair in Water Resource, Khartoum, Sudan.
- Ayoub, A., 1999. Land degradation, Rainfall variability and food production in the Sahelian zone of the Sudan. Land degradation and development, Vol. 10. John Wiley and Sons, Ltd.
- Bastiaanssen, W., Allen, R., Droogers, P., Urso, G., Steduto, P. 2007. Twenty-five years modeling irrigated and drained soils: State of the art. Agricultural Water Management, 92: 111-125.
- Blokhuis, W., 1993. Vertisols in the central clay plain of the Sudan. Doctoral Thesis, Wageningen, Netherlands.
- Coche, J., Franquin, 1967. A study of agro-climatology of the semi arid areas south of the Sahara in West Africa. WMO technical note No.86.
- De Fraiture, C., Molden, D., Wichelns, D. 2010. Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture. Agricultural Water Management. 97: 495–501
- De Wit, A., and van Diepen, C. 2008. Crop growth modeling and crop yield forecasting using satellite-derived meteorological inputs. International Journal of Applied Earth Observation and Geoinformation. 10: 414–425.
- Elfaroug, A. E. 1994. Population and environmental degradation in the Sudanese Agriculture and Forestry. In proceedings of the Khartoum Nile 2002 Conference. Comprehensive Water Resources Development of the Nile Basin: The vision a head. Khartoum, Sudan.
- Glover, E., 2005. Tropical dry land rehabilitation: Case study on participatory forest management in Gedarif, Sudan. A Ph. D. thesis, Faculty of Agriculture and Forest, Helsinki University, Finland.
- Hulme, M., 1986. Secular changes in wet season structure in central Sudan. Journal of Arid Environments. Academic Press Inc. (London) Limited.
- Hulme, M. 2001. Climatic perspectives on Sahelian desiccation: 1973-1998. Global Environmental Change 11: 19-29.
- Knott, D., Hewitt, R., 1996. Future water development planning in the Sudan. In: the Nile sharing a scarce resource. An historical and technical review of water management and of economical and legal issues (Howell, P. and Allan, J.), eds; Cambridge University press.
- Ko, J., Piccinni, G. Guo, W., Steglich, E. 2009. Parameterization of EPIC crop model for simulation of cotton growth in South Texas. Journal of Agricultural Science. 147, 169–178.
- IPCC, 2007. Climate Change, Synthesis Report. The 4th Assessment Report of the Intergovernmental Panel on Climate Change. Valencia, Spain.
- Modarres, R., Silva, V., 2007. Rainfall trends in arid and semi arid regions of Iran. Journal of Arid Environments. Vol.70.
- Mupangwa, W., Love, D., Twomlow, S., 2006 Soil–water conservation and rainwater harvesting strategies in the semi-arid Mzingwane Catchment, Limpopo Basin, Zimbabwe. Physics and Chemistry of the Earth, Parts A/B/C. Volume (31), Issues (5-16). Elsevier Ltd.
- Nile Basin Initiative, 2003. Nile River Basin: Transboundary Environmental Analysis report. Nile Basin Initiative, Global Environment Facility, UNDP and World Bank.
- Nuhu, H., Mahoo, H., 1999. Rainwater harvesting technologies for agricultural production: A case study for Dodoma, Tanzania. Conservation Tillage with Animal Traction (Kaumbutho, P. and Simalenga, T.), eds; A resource book of Animal Traction Network for Eastern and Southern Africa (ATNESA). Harare, Zimbabwe.
- Oloro, V., Tammo, S., Berihun, A., Erick, C., Fernandes, M. 2007. Performance of in situ rainwater conservation tillage techniqueson dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands. Soil and Tillage Research. Vol. 97.

» Richter, G. and Semenov., M. 2005. Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks. Agricultural Systems. 84: 77–97.

» Rockström, J., 2003. Managing rain for the future. Rethinking water management: Innovative Approaches to contemporary issues: In Figueres, C; Tortajada, C; Rockstroem, J. (eds); EARTHS-CAN, London, Sterling, UK.

» Salas, J., Klaus, K., Andrew, L., 2009. Rainwater Harvesting providing Adaptation Opportunities to Climate Change: In: Rainwater Harvesting: a Lifeline for Human Well- being. A report prepared for UNEP by Stockholm Environment Institute.

» Seckler, D., Amarasinghe, U., 2000. World Water supply and demand: 1995 to 2025. Chapter Three: Water scarcity and major issues. IWMI, Colombo, Sri lanka.

» UNEP, 2007. Sudan post-conflict environmental assessment. United Nations Environment Programme.

HighNoon: adaptation to changing water resources availability in northern India

Hester Biemans[1] & Eddy Moors[2]

[1] *E-mail: Hester.Biemans@wur.nl*

[1,2] *Wageningen University and Research Centre. Team Earth System Science and Climate Change. Wageningen, the Netherlands.*

Abstract

Climate change is expected to have a profound impact on the availability of water in the Ganga Basin. The combined changes in glacier melt and monsoon precipitation will affect the total amount of water available. In addition, the magnitude and timing of these changes are highly uncertain.

At the same time, rapid socio-economic changes also influence current and future water resources demand (and availability). The combined effect of water availability and demand will determine the stress on available water resources.

The main objective of the HighNoon project (www.eu-highnoon.org) is to develop possible adaptation measures in the Ganga basin, with the central component to provide the necessary methods and information for a truly stakeholder driven approach.

In order to be informative to stakeholders it is important to present water resources projections with high geographical detail to get a complete picture of the most vulnerable areas and to assign the best locations for (combinations) of adaptation measures.

On a global scale, climate and socio-economic scenarios are developed and updated in a consistent way, using integrated assessment models. However, the global models and results do not contain enough detail to relate directly to the needs and wishes of stakeholders involved in water resources management at the catchment scale, where adaptation takes place. On the other hand, scenarios developed on a more regional level capture regional adaptation measures, but often lack the consistency and context of larger scale trends.

This paper presents the development of an integrative framework that will be used to evaluate the effect of changes in the biophysical and socio economic system on water resources, as well as the potential impact of adaptation measures.

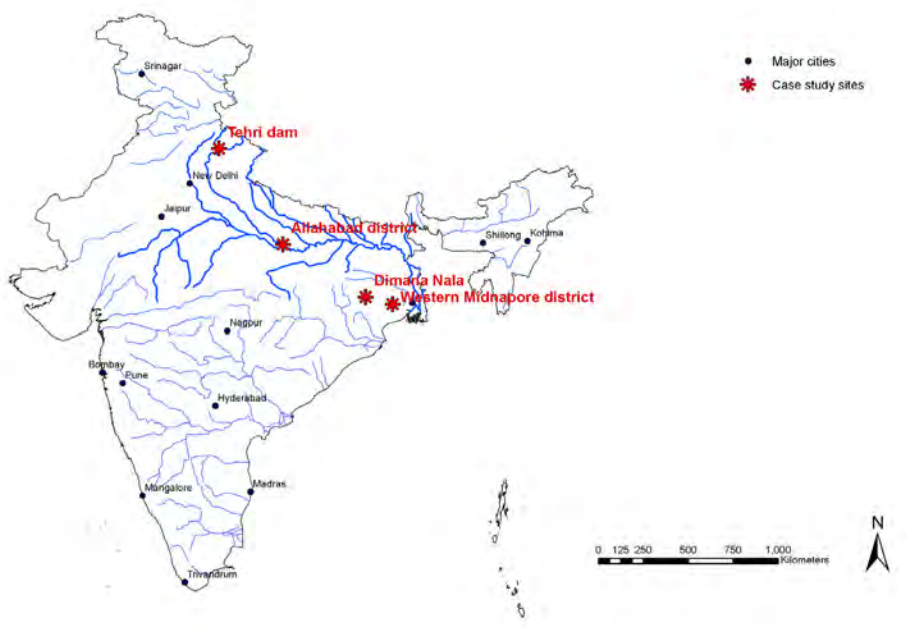
Introduction

Rivers draining from Himalayan headwater basins, in which precipitation is enhanced orographically, deliver large quantities of runoff to tributaries of the major rivers of the Indo-Gangetic plain (Figure 1). Strong regional climatic variation along the Himalayan arc leads to increasing impact on runoff of monsoonal precipitation from west to east. The magnitude and timing of these changes are highly uncertain. At the same time, rapid socio-economic changes also influence current and future water resources demand (and availability). Their combined effect will determine the stress on available water resources.

Started in May 2009, the EU funded project HighNoon brings together European and Indian climatologists, hydrologists and social scientists to work together towards an improved integrated assessment of water resources in Northern India. This integrated assessment supports the main objective of HighNoon: to develop possible adaptation measures in the Ganga basin, with one of the central components to provide the necessary methods and information for a truly stakeholder driven approach.

The HighNoon project is centered around the participative development of adaptation measures for the Ganga basin. The other activities in the project are feeding this process by providing the information and methods needed to make a well funded choice for preferred (sets of) measures. On the one hand the changes in the physical system will be explored. Improved simulation of changes in monsoon patterns will be made with Regional Climate Models REMO and PRECIS. Multiple hydrological models used in this project (LPJmL, VIC, JULES and SWAT) will be compared and eventually changed to give a better representation of the snow- and glacier melt processes. On the other hand, the changes in water demand are taken into account by the development of district scale socio economic scenarios. The combined impacts of climate- and socio economic changes on water resources will be evaluated using a set of indicators. Subsequently a method for prioritizing adaptation measures is developed

Figure 1. Location of the Ganga basin



to help stakeholders choose a set of adaptation options. Each new set of adaptation options will be evaluated..

In order to be informative to stakeholders it is important to present water resources projections with high geographical detail to get a complete picture of the most vulnerable areas and to assign the best locations for (combinations) of adaptation measures.

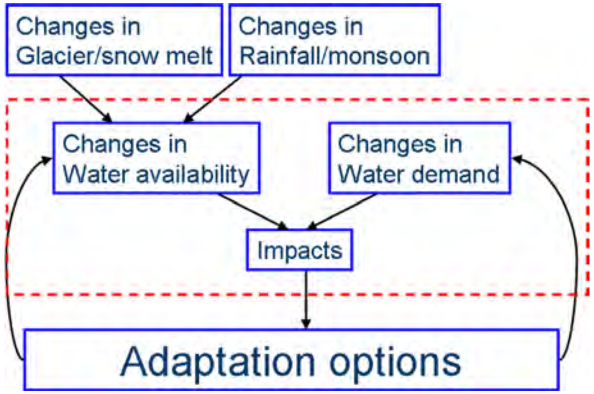
On a global scale, climate and socio-economic scenarios are developed and updated in a consistent way, using global integrated assessment models. However, the global models and results do not contain enough detail to relate directly to the needs and wishes of stakeholders involved in water resources management at the catchment scale, where adaptation takes place. However, scenarios developed on a more regional level capture regional developments, but often lack the consistency and context of larger scale trends. HighNoon tries to bridge this gap by comparing and merging models and scenarios at different scales, in this way combining available knowledge from local to global scale.

This paper presents the process of developing an integrative framework to evaluate the effect of changes in the physical and socio economic system on water resources, as well as being a useful tool for showing and evaluating the effects of adaptation measures.

Framework for integrated water resources assessment

A framework for integrated assessments of water resources has to be able to take into account all components illustrated in Figure 2. To address changes in water availability, the regional climate models REMO and PRECIS are ran at high resolution (0.25 degree lat lon), for the A1B emission scenario. Changes in glacier melt are addressed by first comparing four hydrological models with observation data and eventually adjusting the snow and ice melt algorithms.

Figure 2. Schematic representation of the framework for integrated assessment of water resources.



HighNooN uses the hydrology and vegetation model LPJmL [*Bondeau, et al.*, 2007; *Sitch, et al.*, 2003] which integrates the effect of changes in water availability and demand and explicitly accounts for water extractions for irrigation and other uses. LPJmL integrates a hydrology and crop model, which makes it a very suitable tool to study impacts of water shortage on crop yields. LPJmL is validated and tested for its simulation of many components of the water and carbon cycle: eg. river discharge [*Biemans, et al.*, 2009], irrigation water use [*Rost, et al.*, 2008], crop yields [*Fader, et al.*, 2010], and sowing dates [*Waha, et al.*, submitted]. Recently, LPJmL has been extended with a reservoir module, simulating the operation of large dams, including the water supply from irrigation reservoirs to the irrigated fields [*Biemans, et al.*, in press]. It has been applied to study the effect of climate change on water availability and requirements for food production have been made [*Gerten, et al.*, in review].

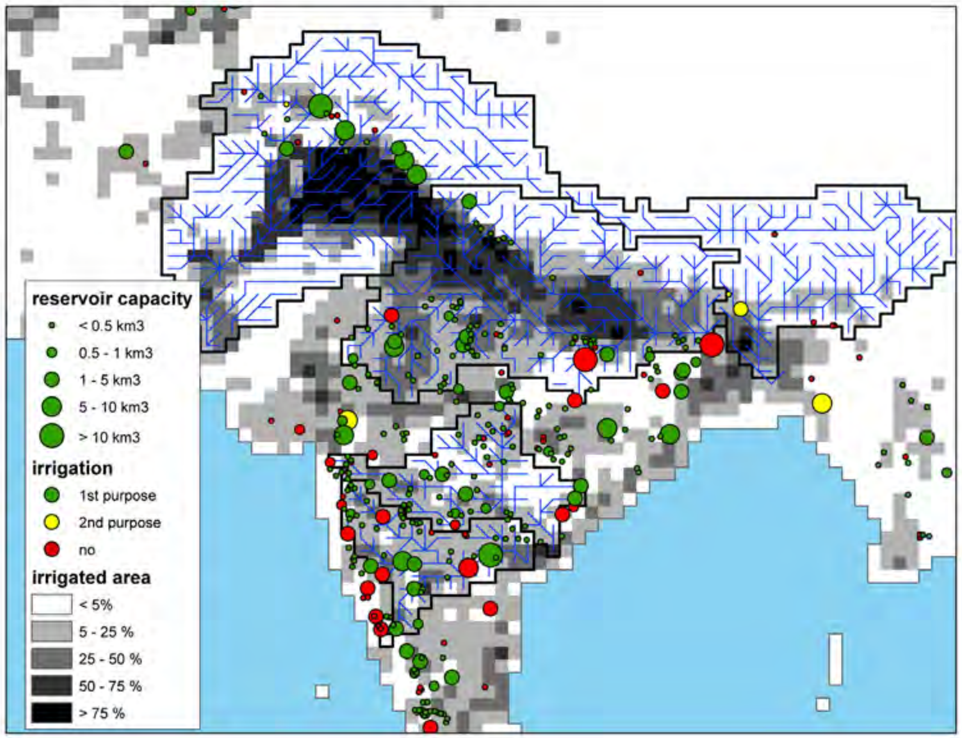
Although proven capabilities to simulate the carbon and hydrological cycles at global scale, the model has not often been applied on specific basins. An intercomparison of discharge simulations made by four hydrological models operating at different spatial scales will eventually lead to adjustments and improved simulations of water availability of LPJmL in this region [*Siderius, et al.*, in preparation].

Figure 3 shows a characterization of the model for the considered region. It shows the representation of the Northern Indian basins by a simplified river network at 0.5 degree resolution [*Vörösmarty, et al.*, 2000], the percentages of the gridcells that are covered with irrigated crops and the locations of large dams that are included in the model [*Lehner, et al.*, submitted].

Climate change impacts on water availability

Daily bias corrected climate data of three GCMs [*Hagemann, et al.*, in review] and one emission scenario (A2) have been used to force the LPJmL model. For reference, the model has also been forced using the WATCH forcing data [*Weedon, et al.*, in review] (all datasets were developed for the EU WATCH project). Figure 4 shows that the total precipitation simulated by the GCMs over the basin already differ during the control period (1960-2000) for which the bias correction was applied, but are further diverging during the simulation period (2000-2050). As already stated by the IPCC [*IPCC*, 2007] these results confirm that the uncertainty in climate change induced changes in precipitation are still uncertain in this region. The right panel of

Figure 3. Locations of dams relative to irrigated areas. Points: all dams that are implemented in the model; colors show whether the reservoir is used for irrigation, the size refers to the capacity of the reservoir. Grey shades: the percentage of the cell that is irrigated according to the land use input (see Fader et al, submitted). Green shade: the area that is (partly) supplied from an irrigation reservoir, according to the models' allocation rules. Blue lines: STN30 river network at 0.5 degree.



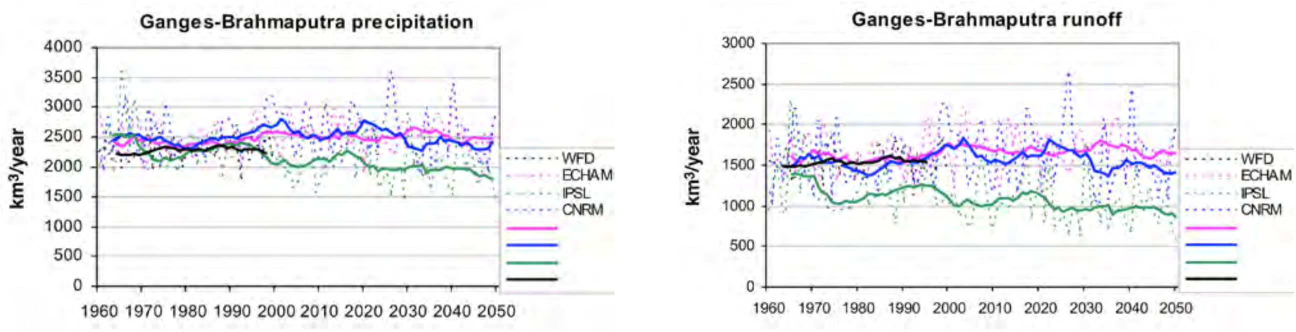


Figure 4. Left: annual precipitation (1960-2050) over the Ganges-Brahmaputra basin as simulated by 3 gcm's (A2 scenario) and the WATCH forcing data (dashed lines, solid lines represent 10-year averages) and right: associated simulated runoff

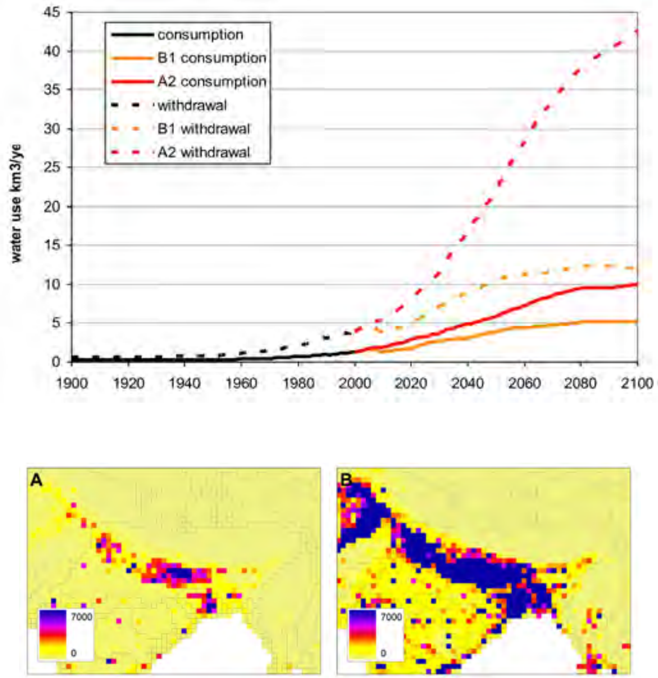


Figure 5. Top: Annual withdrawal and consumption of water for industry, households and livestock in the Ganga-Brahmaputra basin as calculated by the WaterGAP model for the EU WATCH project (in km3 year-1). Bottom: Spatial distribution of this water consumption in 1971-2000 (A) and 2036-2065 for the A2 scenario (B) in million cubic meters per year.

Figure 4 shows the effect of using different climate input data on the simulated runoff for the basin. As expected, the uncertainty in precipitation input leads to even larger uncertainties in the simulated runoff [*Biemans, et al.*, 2009].

Reasons that GCMs show a large uncertainty in North India, are amongst others the complex topography of the region and the poor representation of the Monsoon. Within HighNoon, regional climate models will be run at high resolution to improve the climate simulation for this region. In a next step, water availability will be calculated based on these high resolution climate input.

Socio economic changes and impacts on water and food demand

From a human point of view, a pressure on the available water resources only exist if the demand for water at a specific location and at a specific time cannot be met. India is a rapidly changing country where the demand for food and water will change as a result of socio economic changes. Therefore, it is not only important to estimate changes in water availability, but also in water demand. Their combined effect will determine the stress on available water resources. With expected development changes in demography, industrialization, and intensification in agriculture the estimate of future socio-economic conditions is a critical factor in water resources assessments. It is important to evaluate these socio economic changes and associated water use projections to be able to get a complete picture of the most vulnerable areas and to assign the best locations for (combinations of) adaptation measures.

On a global scale climate and socio-economic scenarios are developed and updated in an consistent way, using integrated assessment models like IMAGE [*Bouwman, et al.*, 2006]. Estimates of associated water demand for households, industry and livestock are calculated with the WaterGAP model [*Alcamo, et al.*, 2003] (Figure 5)

Water demand for irrigation is calculated with LPJmL (Figure 6). Because the global scenario does not yet include an expansion of irrigated areas, this figure presents only the climate driven changes in water demand on current irrigated areas. For all climate models, the demand shows a slightly decreasing trend.

Figure 6. Climate change driven annual water demand on current irrigated areas.

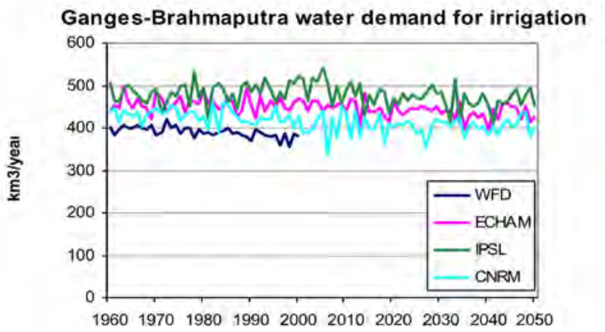


Figure 7. Spatial distribution of current surface water stress as calculated by LPJmL

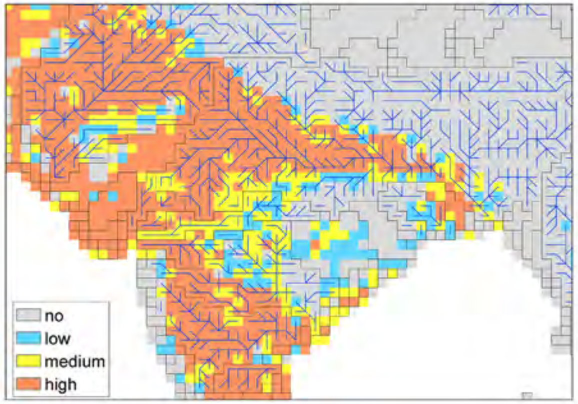
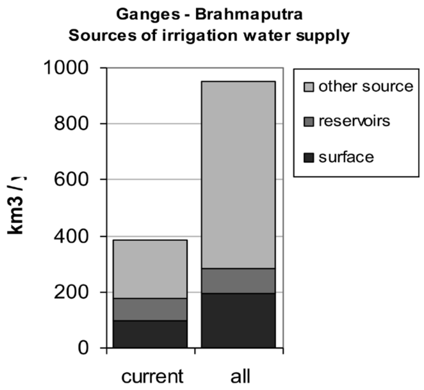
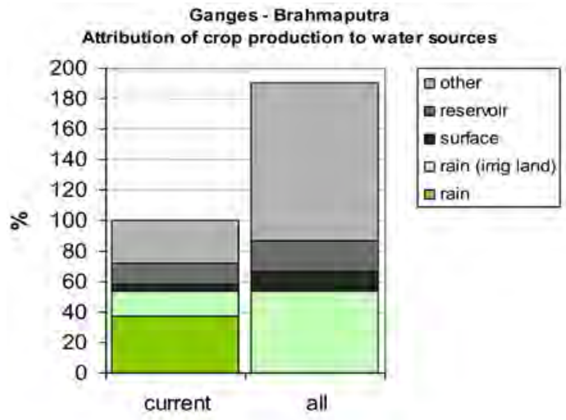


Figure 8.

Top: Sources of irrigation water for current irrigated areas, and if all current crop land would be irrigated.

Bottom: attribution of crop production to the different sources of water on current cropland (rain fed and irrigated) and if all current cropland would be irrigated.





The water demand scenarios presented here are developed for global scale applications, and do not incorporate heterogeneities within countries. Further, assuming all the additional food projected by the scenarios to be produced on rain fed agriculture is not realistic. India expects to be able to increase their production mainly by intensification of current agriculture and conversion of rain fed to irrigated agriculture (S. Bhadwal, personal communication). District scale scenarios for population development, water demand and land use are being developed within the HighNoon project and will be used to increase the spatial distribution of water demand in LPJmL.

Baseline and first assessment

Using the framework of Figure 2, a first analysis of the current surface water stress (demand to availability ratio) has been made (Figure 7). This figure shows that, according to our calculations the Brahmaputra basin does not experience stress at all, and the water scarcity is highest in the low lying parts of the Ganga basin, where most people live. It is important to notice that this figure shows surface water stress. This means that the availability of groundwater is not taken into account, because the size of groundwater reservoirs is unknown.

Amongst the list of possible adaptation options to be evaluated are creating extra storage (in reservoirs), changing cropping patterns, increasing irrigation efficiency, and increasing crop production by expanding irrigated area. The effect of expanding irrigated area on water demand, sources to extract this water as well as effects on crop yields have been evaluated by using the integrated framework LPJmL. Climate change effects have not been taken into account yet. In this land use strategy, all current rain fed crop areas are changed to irrigated, which is a plausible strategy to meet the growing food demand (S. Bhadwal, personal communication). Figure 8 shows the results of this analysis. According to our calculations, the water demand for irrigation would increase from 383 to 953 km^3 per year (which is 2.5 fold higher). The potential contribution of surface water and reservoirs cannot meet this demand. Most of the additional supply should come from "other sources", which can partly be groundwater. The total crop production can grow with 90%, if all crops will be irrigated. However, the analysis clearly shows that the major part of this extra production can not be met by using surface water only, and requires water supply from other sources.

Future work

To be informative to stakeholders, scenarios for the Ganges-Brahmaputra region need spatial detail, and scenarios should be used that take into account the heterogeneity of developments in the region. Further, it is necessary to work on the presentation of results. To show the effect of adaptation strategies, the best indicators should be chosen in consultation with stakeholders. To answer these questions, HighNoon is taking the following steps:

- » Refine water availability and demand projections by forcing with regional climate models that are currently being developed.
- » Improve discharge based on recommendation of comparison study, and take into account the effect of melting glaciers and snow on future water availability.
- » Improve water demand scenarios by implementing district scale scenarios, that are currently being developed.
- » Test the suitability of the here presented framework to evaluate large scale adaptation measures.
- » Make a choice for (combinations) of adaptation measures to be taken and evaluate these measures with the here presented framework.

References

- » Alcamo, J., P. Doll, T. Henrichs, F. Kaspar, B. Lehner, T. Rosch, and S. Siebert, 2003. Development and testing of the WaterGAP 2 global model of water use and availability, Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 48, 317-337.
- » Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R. W. A. Hutjes, J. Heinke, and D. Gerten, in press. Impact of reservoirs on river discharge and irrigation water supply during the 20th century, Water Resources Research.
- » Biemans, H., R. W. A. Hutjes, P. Kabat, B. J. Strengers, D. Gerten, and S. Rost, 2009. Effects of precipitation uncertainty on discharge calculations for main river basins, Journal of Hydrometeorology, 10, 1011–1025.
- » Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, and D. Gerten, 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Global Change Biology, 13, 679-706.
- » Bouwman, A. F., T. Kram, and K. Klein Goldewijk (Eds.), 2006. Integrated modelling of global environmental change. An overview of IMAGE 2.4, Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.
- » Fader, M., S. Rost, C. Müller, A. Bondeau, and D. Gerten, 2010. Virtual water content of temperate cereals and maize: Present and potential future patterns, Journal of Hydrology, 384, 218-231.
- » Gerten, D., J. Heinke, H. Hoff, H. Biemans, F. Fader, and K. Waha, in review. Global water availability and requirements for future food production, Journal of Hydrometeorology.
- » Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch, 2004. Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model, Journal of Hydrology, 286, 249-270.
- » Hagemann, S., C. Chen, J. O. Haerter, J. Heinke, D. Gerten, and C. Piani, in review. Impact of statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrological models, Journal of Hydrometeorology.
- » IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 996 pp., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- » Lehner, B., C. A. Reidy Liermann, C. Revenga, B. Fekete, C. Vörösmarty, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J. Robertson, R. Rödel, N. Sindorf, and D. Wisser, submitted. High resolution mapping of global reservoirs and dams and their impact on downstream rivers, edited.
- » Rost, S., D. Gerten, A. Bondeau, W. Lucht, J. Rohwer, and S. Schaphoff, 2008. Agricultural green and blue water consumption and its influence on the global water system, Water Resources Research, 44, W09405.
- » Siderius, C., H. Biemans, W. Franssen, A. K. Gosain, S. Rao, P. Singh, and A. Whiltshire, in preparation. Rainfall and Snowmelt Contributions to Discharge of the Ganges - A Multi-Model Approach.
- » Sitch, S., B. Smith, I. C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. O. Kaplan, S. Levis, W. Lucht, M. T. Sykes, K. Thonicke, and S. Venevsky, 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Global Change Biology, 9, 161-185.

» Vörösmarty, C. J., B. M. Fekete, M. Meybeck, and R. B. Lammers, 2000. Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution, Journal of Hydrology, 237, 17-39.

» Waha, K., L. G. J. v. Bussel, C. Müller, and A. Bondeau (submitted), Climate Driven Simulation of Global Crop Sowing Dates.

» Weedon, G. P., S. Gomes, P. Viterbo, W. J. Shuttleworth, E. M. Blyth, H. Österle, J. C. Adam, N. Bellouin, O. Boucher, and M. Best, in review. Assessing global potential evapotranspiration over land in the twentieth century using the WATCH Forcing Data, Journal of Hydrometeorology.

Impact of global change on hydrology and soil degradation - scenario analysis for the semi-arid Drâa catchment (South Morocco)

Bernd Diekkrüger[1,4], Henning Busche[1], Anna Klose[1], Stephan Klose[2], Christina Rademacher[3] & Oliver Schulz[1]

[1] *Department of Geography, University of Bonn, Meckenheimer Allee 166, 53115 Bonn, Germany*

[2] *Steinmann Institute, University of Bonn, Nussallee 8, 53115 Bonn, Germany*

[3] *Institute of Social and Cultural Anthropology, University of Cologne, Albertus Magnus Platz, 50968 Köln, Germany*

[4] *E-mail: b.diekkrueger@uni-bonn.de*

Abstract

The Drâa catchment in Morocco reaching from the southern declivity of the High Atlas to the Saharan foreland is highly vulnerable towards Global Change concerning hydrology and soil degradation. Relief energy is high in the mountainous areas of the High Atlas and Antiatlas, soils are generally shallow, and vegetation is sparse. Precipitation events are extremely variable in time and space. Snow storage in the High Atlas Mountains is important for reservoir filling but extremely sensitive to Climate Change. Hydrological processes are controlled by shallow soils and sparse vegetation. Soil erosion in the valley affects soil quality and fertility at the local scale, but also causes siltation of the reservoir. Scenarios of climate change based on the downscaled results of the regional climate model REMO as well as scenarios of socio-economic development are used to quantify the impact of Global Change on water resources and soil degradation. Socio-economic development does not only depend on internal but mainly on external drivers. Political decision whether the Drâa valley will receive support from the government influences socio-economic development, water demand, and use of other natural resources. Approaches and results from GLOWA-IMPETUS are presented and discussed with a focus on the Drâa valley. Scenarios are developed and quantified using dynamic simulation models. Options for action show scales ranging from local scale erosion protection measures to basin wide water management options.

Keywords

soil degradation, Global Change, scenario development, scenario quantification

Introduction

African's water and land resources are under severe pressure. This is caused by Global Change which consists not only on Climate Change but also on land use change driven mainly by population growth. In many parts of this continent, water resources are overexploited and land is degraded. Future development may significantly threaten the current situation as increasing water demand, mainly due to high population growth, will reduce water availability per capita dramatically.

Global Change will threaten African countries in different ways. While West Africa suffers from high population growth, Northwest Africa has a moderate growth rate (UNDP, 2006). Overgrazing, severe soil erosion, soil salinization, and overuse of groundwater resources are the main problems in the Maghrebian countries. Currently, Morocco has a water availability per capita of about 934 m^3/a which is below the critical threshold of 1000 m^3/capita/a. But even within Morocco, environmental conditions vary significantly. The climate of the study area is arid to semi-arid and shows a high interannual variability.

To solve present and possible future problems with regard to water related aspects, a clearly interdisciplinary and holistic approach is necessary. This is done for West and Northwest Africa in an initiative named IMPETUS ('An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa'), a joint venture of the Universities of Cologne and Bonn, Germany. The work done within IMPETUS is part of a research programme concerning the global water cycle (GLOWA), which is financed by the German Federal Ministry of Education and Research (BMBF). The aim of GLOWA is the development of strategies for sustainable future water management at a regional level while taking into account global environmental changes and socio-economic framework conditions. Details concerning the IMPETUS project are given by Speth et al. (2010) and Christoph et al. (2008).

Water and land management requires a thorough understanding of the underlying processes, structures, pools, and fluxes. While some pools like surface water reservoirs and groundwater may be quantified by measurements, the description of their dynamic requires appropriate simulations models. After successful model calibration and validation environmental models can be applied for analyzing the status (to assess current environmental conditions), for determining trends (to evaluate historical change), for predictions (to evaluate future impact as a result of change), and for decision making (to evaluate alternative management plans). Integrated water and land management is concerned with all of these topics. The assessment of the current condition is a prerequisite for balancing options for action. To be able to differentiate between short term and long term effects, trends have to be identified. Because management means interventions, it is important to quantify the effects of those interventions on water related issues. Robust decisions can only be taken if alternative solutions are balanced. Because this can usually not be done by experiments, evidence-based decision making requires adapted modelling systems.

The aim of this study is to analyse the impact of future Global Change on hydrology and soil degradation by quantifying climate and socio-economic scenario for the semi-arid Drâa catchment (South Morocco) using distributed simulation models.

Study area

The regional focus of this work is on the upper and middle catchment of the Wadi Drâa in South Morocco. The study area reaches from the High Atlas Mountains to the former endlake Lac Iriki in the Saharan Foreland (Figure 1). It covers an area of approximately 28,400 km^2, and the elevation ranges from 450 to 4071 m above sea level. The population is generally concentrated along the rivers, where water is readily available both for drinking and irrigation.

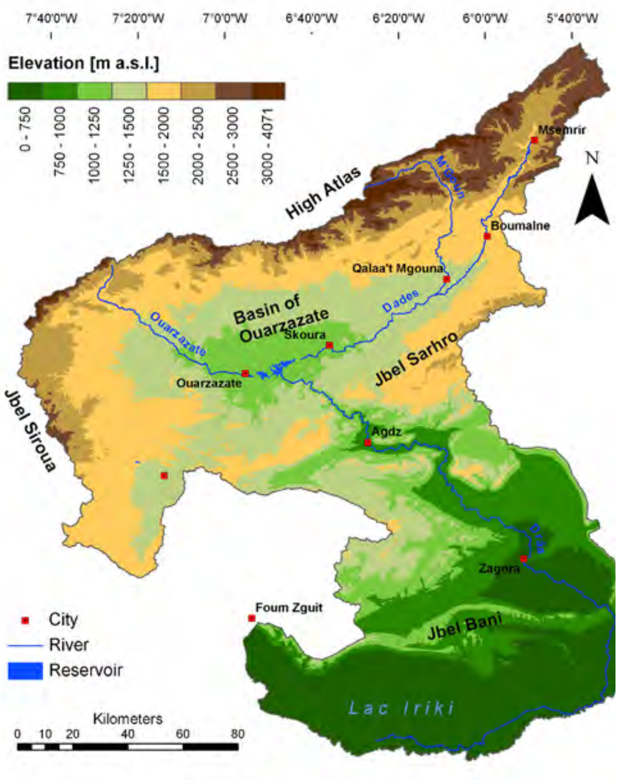
The only industry within the catchment is mining in the Anti-Atlas and Western High Atlas Mountains. Income mainly comes from agricultural activities. In the oases along the wadis, few cashcrops are grown in irrigation agriculture; subsistence agriculture is widespread. Outside the oasis, pastoralism is the only agricultural activity. Transhumance dominates in the mountainous areas, whereas nomadism is widespread in the Saharan Foreland close to the Algerian border. However, since in most cases in the Drâa area, the income produced from agriculture and/or informal activities is not sufficient, labour migration is a common strategy to guarantee a certain income.

Morocco is characterised as a nation of medium human development (Human Development Index, HDI, of 0.65), as stated by UNDP (2006). In the urban areas of the Drâa catchment the national HDI average is reached, but, especially in the rural areas of the High Atlas and the Saharan Foreland, the HDI does not exceed 0.52 (Belfkih et al., 2006). As 75% of the population lives in rural areas, the Drâa catchment can be characterised as a marginal zone regarding the HDI.

The climate of the Drâa catchment is dominated by its orographic location south of the High Atlas Mountains and the pronounced gradient of altitude and aridity in north-south direction. While the climate varies from semi-arid in the northern part of the region to hyper-arid in the Saharan Foreland, some peaks in the High Atlas Mountains are characterised as sub-humid. The climate of the cities of Ouarzazate and Zagora is classified as ***Saharan with cool winters*** and ***Saharan temperate*** respectively.

The hydrological regime is dominated by the region's climatic situation. Furthermore, there exists an important anthropogenically induced difference between the upper and middle Drâa basin. The upper catchment experiences an undisturbed hydrological regime

Figure 1. Drâa catchment in Morocco



of the semi-arid subtropics, whereas the hydrology of the middle Drâa valley is controlled by releases of the Mansour Eddahbi reservoir. The effective refilling of the reservoir depends on extreme precipitation events leading to the generation of discharge in the ephemeral and episodic rivers. The Mansour Eddahbi reservoir was constructed in 1972 and had an initial capacity of 583 million m^3. By the time of the last bathymetric survey in 1998, the capacity was reduced by approximately 25% to 438 million m^3 due to siltation. This corresponds to a mean erosion rate of 5.6 t/ha/year. The hydrology of the middle Drâa valley is completely controlled by the releases from the reservoir. Almost no natural flow systems exist, and the river bed remains dry for most of the year. As the releases from the reservoir are not always sufficient for irrigation agriculture, farmers more commonly use groundwater for irrigation. Since the introduction of motor pumps in the 1980s, this tendency has led to decreasing groundwater levels.

Vegetation distribution depends primarily on the climatic gradient in the catchment. The Drâa catchment is part of the arid steppeland north of the Sahara. Vegetation density is generally low in the Drâa region which is due to climatic conditions as well as the extensive extraction of firewood and severe overgrazing.

Scenario development

Nowadays, scenario development is a common tool for studying the effect of Global Change on environmental processes. Scenarios are not predictions as no one can forecast future. Therefore, scenarios can not be qualified by probability. Nevertheless, scenarios should be consistent and plausible images of alternative futures that are detailed enough to support the decision making process (Reichert & Jaeger, 2010). It is required that the most important driving forces are considered. In the case of water resources and soil erosion, the main driving forces are climate and land use change.

The storylines of the socio-economic scenarios developed by IMPETUS consider the main economic development, the development in the agricultural sector, the development of political framework conditions, the demographic development / quality of life, and the environment / natural resources. Basically, three different scenarios are developed that follow different basic logics. Two scenarios reflect more extreme, yet realistic development paths. In contrast the third scenario was constructed as a business-as-usual scenario. Climate is not an explicit thematic issue described in the above mentioned storylines. Instead we defined three climate reference scenarios which serve as external drivers of the more general scenarios. This procedure allows for a more flexible combination of the two types of scenarios. In this study three ensemble runs with the regional climate model REMO for the period 1960-2000 and for the IPCC SRES scenarios A1B and B1 for the period 2001-2050 were used (Christoph et al., 2010). While scenario A1B describes a more globalized world with strong economic growth, scenario B1 is characterized by a more sustainable economic growth.

For Morocco the three socio-economic scenarios are developed under the following frame assumptions (see Reichert & Jaeger, 2010) for more details:

- Scenario M1 "Marginalisation – non-support of the Drâa-Region" governmental and international institutions withdraw their support. As a result, the marginalisation of the region and the impoverishment of the local population accelerate.
- Scenario M2 "Rural development in the Drâa-Region through regional funds" is a constant economic growth scenario. Against the background of overall political stability and supported by governmental aid programs, under-developed regions like the Drâa-Region experience an improvement of overall living conditions and economic development, too. As a result, migration declines and the population increases.
- Scenario M3 "Business as usual" extrapolates the dominant trends of past decades. The status as a marginalised region remains unchanged and only incremental improvements in the overall living conditions and economic development occur.

In the research area we distinguish the following three scenario regions:

- High Atlas: This sub-region is a marginalised mountain region with a poorly developed infrastructure. Water availability is, however, relatively good and is thus only a weak limiting factor for agricultural production.
- Basin of Ouarzazate: The good water availability is a specific feature of this sub-region that is also characterised by a well-developed infrastructure and a number of strong urban centres like Ouarzazate and Boumalne Dadès.
- Oases southern of Mansour Eddahbi Dam: Low water availability is a main impediment for economic development is this sub-region. Agriculture is dependent on the management of the Mansour Eddahbi dam.

The temporal resolution is 5 years. The target year is 2020 for Morocco which is motivated by pre-existing long-term strategy papers of local governments.

Simulation model PESERA

The PESERA (Pan-European Soil Erosion Risk Assessment) was developed as part of the project of the same name funded by the European Commission. PESERA is a physically-based, spatially distributed soil erosion model designed to carry out an erosion risk assessment for all of Europe at a spatial resolution of 1 km^2 (KIRKBY et al., 2008). The model combines the effects of topography, soil, vegetation and climate to produce an estimation of runoff, vegetation cover and erosion under long-term conditions. In this model, hillslope erosion and the delivery of the eroded material to the hillslope base are predicted, but channel delivery processes and channel routing are not considered. It has the capacity to simulate scenarios of land use and climate change, as it implies a vegetation growth routine adjusting vegetation cover to given climatic conditions. This model also calculates mean long-term erosion rates on a monthly time step for a single year. Precipitation is partitioned into infiltration excess runoff, saturation excess runoff, snowmelt, evapotranspiration and changes in soil moisture storage. To reproduce long-term conditions, mean monthly climate data are used and daily rainfall is integrated using a gamma function to display the monthly frequency distribution of rainfall. The principle model concept is to first establish stable hydrological and vegetation conditions under the given climate and to subsequently use these conditions to calculate mean monthly erosion rates. This is reached by iteratively solving the equations to calculate hydrological and vegetation-related parameters in an annual cycle until stable conditions are reached. PESERA was chosen in this work as it requires a manageable amount of input data at a coarse spatial and temporal resolution. The data availability in the Drâa catchment is limited and regionalising climate and soil data is especially difficult due to the highly heterogeneous terrain. More details are given by Klose (2009).

Results and discussion

PESERA was applied to simulate current conditions in the Drâa valley. Actual evapotranspiration (ETact) accounts for more than 90% of the water losses (Figure 2). In the High Atlas Mountains, ETact is lowered due to lower temperature and higher relative humidity. The pattern of surface runoff is opposite to ETact and erosion risk is high (mean rate 19.2 t/ha/a from which 5.6 t/ha/a will reach the reservoir causing severe siltation). In the oases, erosion risk is low although bank erosion may cause losses in agricultural land.

According to the climate scenarios, the Drâa-valley will face a decrease in rainfall of 30 ± 11mm and an increase in temperature up to 1.4 ± 0.7 °C up to 2050. Rainfall variability and ETact will increase which results in a reduced vegetation coverage amplifying rainfall effects. This results in an increase of the erosion rate up to 21 ± 17%. Due to increase in temperature, ETact will increase and results in a reduced vegetation coverage which amplifies rainfall effects.

In the socio-economic scenario M1 "marginalization - low income, high energy costs" soil erosion rate will increase up to 27% while in the scenario M2 "rural development - loss of importance of nomadic lifestyle" it will decrease up to 50% due to reduced pressure on vegetation coverage. The combination of climate change and socio-economic scenarios leads to complex responses which dif-

Figure 2. Results of the PESARA models for surface runoff, actual evapotranspiration, groundwarer recharge, and erosion for the period 1980 to 2000.

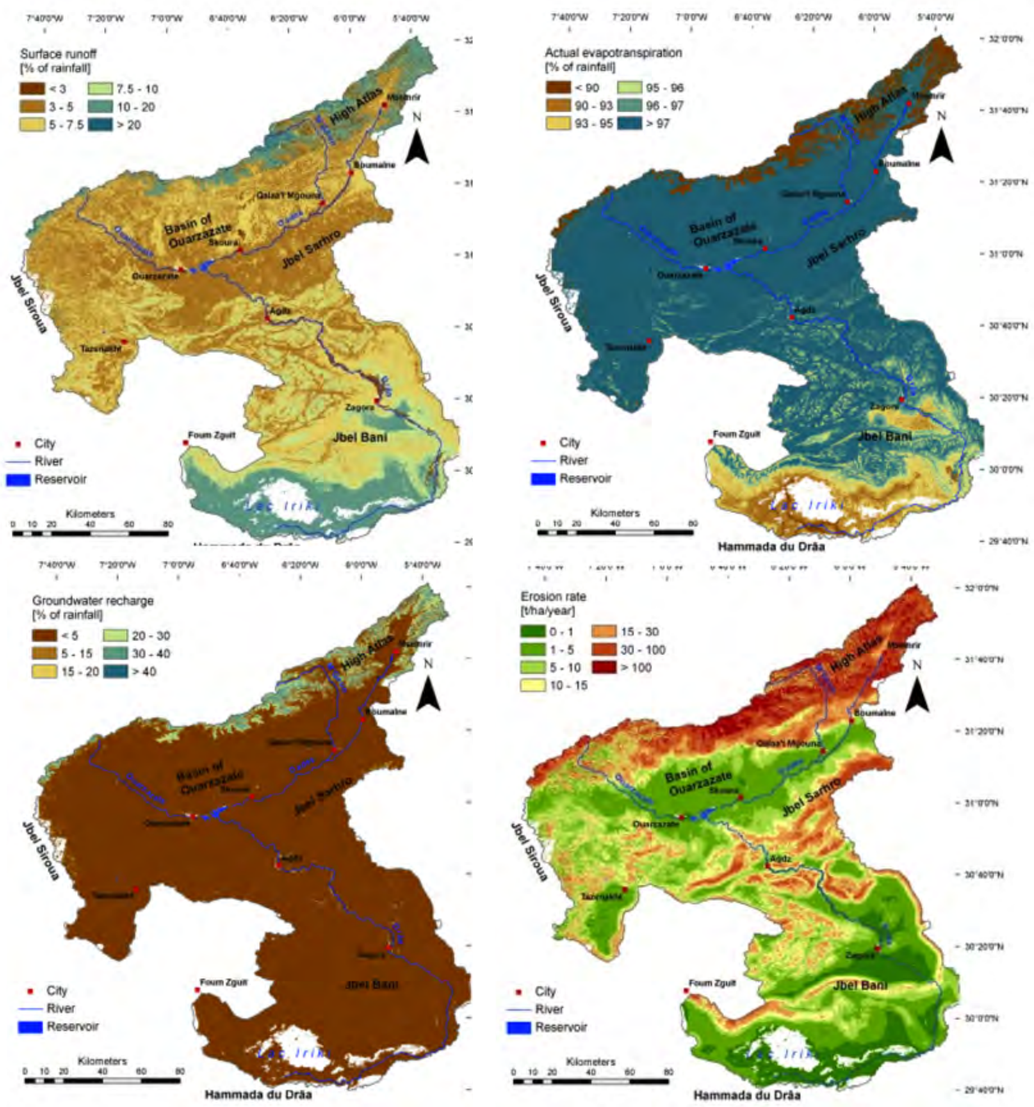
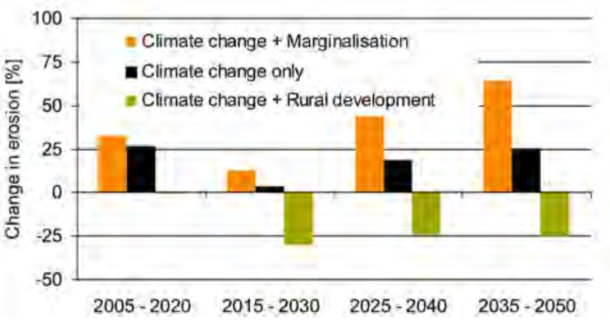


Figure 3. Simulated development of the erosion rates in the Drâa valley under socio-economic scenario M1 "marginalization" and M2 "rural development" in the climate change scenario. 250 Mio m³ is required for satisfying water demand of the middle Drâa-valley



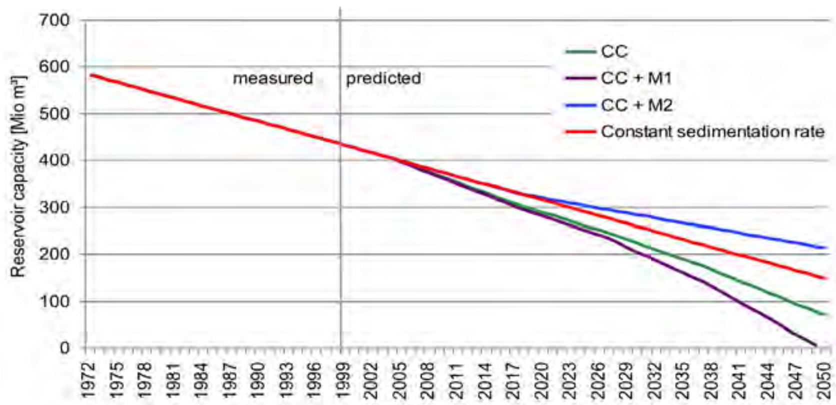
fer in the three scenario regions (Figure 3). In the marginalization scenario climate change impact will be aggravated while in the rural development scenarios climate change impacts will partly be compensated by reduced land use. Nevertheless, according to the scenario calculations the remaining reservoir is between nearly 0 and 200 Mio m³ in 2050 which severely threatens water management for the middle Drâa valley (Figure 4).

The options for direct human intervention to attenuate soil erosion risk are limited. The key is to increase vegetation coverage which can not be realized on a short-term. Klose (2009) exemplary analysed two intervention scenarios: first, an afforestation of 6300 ha and second, the exclusion of grazing on 75 000 ha. Both measures take place in the Skoura Mole, which is identified as an erosion hotspot. The efficiency of the measures clearly depends on the spatial scale that is under consideration. At the local scale where the intervention actually takes place, the erosion is reduced by 35.7 to 99.8% up to the year 2050. Thus, afforestation is clearly more efficient than pasture exclusion. At the scale of the High Atlas, the effect of both measures is limited; the soil loss is reduced between 0.6 and 13%. At this scale, the effect of pasture exclusion exceeds that of afforestation, which is simply due to the larger area. Concerning the sedimentation of the reservoir, the remaining capacity of the reservoir in the year 2050 is 0.7 to 16.8% higher than without intervention. Afforestation raises the reservoir capacity by 2.4 and 0.7% for scenarios M1 and M2, respectively. Pasture exclusion has a more pronounced impact in dampening the reservoir siltation by 16.8 and 4.8% for the M1 and M2 scenarios, respectively. The effect in the M2 scenario is lower due to the already reduced grazing pressure.

The influence of direct human intervention is either limited to the local scale or has to incorporate large areas to mitigate reservoir siltation. The PESERA model is explicitly applicable to the global change impact assessment due to the internal plant growth routine. The routine allows the protecting vegetation cover to adapt to the changed climate conditions and thus allows the feedback mechanisms between climate/vegetation/soil erosion to be identified. In the case of the Drâa catchment, reduction in vegetation cover that is induced by climate change leads to an increase in soil erosion, although precipitation decreases. This relationship would not have been identified with a model that uses static vegetation information such as the USLE.

In conclusion, climate change leads to increased soil loss rates whereas socio-economic development can either aggravate or mitigate the consequences of climate change. The drivers for Global Change are outside of the catchment and can therefore not be influenced by the local population. The contribution of the Drâa-valley to Climate Change is negligible and the fate of the economic development depends on political decision taken at the government and by money transfer from migrants. The adaptation potential of the local population is limited as they do not have resources for sustainable use of the environment. Overgrazing, overexploitation of water resources and other degrading activities are a result of poverty. Land degradation and especially soil degradation by water erosion is a severe problem causing on-site and even more important off-site damages. As often observed in those climate zones, reservoir capacity is reduced dramatically resulting in reduced buffer capacity for coping with climate variability which is likely to increase in future. Local solutions like afforestation and management of range land requires additional financial support which may be a good investigation if the lifetime of the reservoir is extended by those measures.

Figure 4. Simulated development of the capacity of the reservoir "Mansour Eddahbi" under socioeconomic scenario M1 "marginalization" and M2 "rural development" and climate change scenario. 250 Mio m³ is required for satisfying water demand of the middle Drâa-valley



Acknowledgement

The authors would like to thank the Federal German Ministry of Education and Research (BMBF, Grant No. 01 LW 06001A/B) as well as the Ministry of Innovation, Science, Research and Technology (MIWFT) of the federal state of Northrhine-Westfalia (Grant No. 313-21200200) for the funding of the IMPETUS project in the framework of the GLOWA program. Many thanks to our partners in Benin and all colleagues of the IMPETUS project, who provided data and assistance.

References

» Belfkih, A.M., Azzimane, O., Barkaoui, M., Benhima, D., Benabdellah, B.R., Bourqia, R., Boutaleb, H., Chkili, T., Chraibi, S., de Casterle, E.D., Guessous, M., Hajoui, M., Lahjomri, A., Alami, A.L., M'Jid, M., Toufiq, A., 2006. 50 ans de développement humain et perspectives 2025. http://www.rdh50.ma. Accessed 20 October 2010.

» Christoph, M., Fink, A., Diekkrüger, B., Giertz, S., Reichert, B., Speth, P., 2008. IMPETUS: Implementing HELP in the Upper Ouémé Basin. Water SA (online). 34 (4), Special HELP edition, 481-490.

» Christoph, M., Fink, A., Paeth, h., Born, K., Kerschgens, M., Piecha, A., 2010. Climate scenarios. In: Speth, P., Christoph, M., Diekkrüger, B. (Eds.) Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Germany. 402-435.

» Reichert, B., Jaeger, A., 2009. Socio-economic scenarios. In: Speth, P., Christoph, M., Diekkrüger, B. (Eds.) Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Germany. 426-441.

» Kirkby, M.J., Irvine, B.J., Jones, R.J.A., Govers, G., Team, P., 2008. The PESERA coarse scale erosion model for Europe. I. - Model rationale and implementation. European Journal of Soil Science 59(6): 1293-1306.

» Klose, A., 2009. Soil characteristics and soil erosion by water in a semi-arid catchment (Wadi Drâa, South Morocco) under the pressure of global change. PhD Thesis, Faculty of Mathematics and Sciences, University of Bonn http://hss.ulb.uni-bonn.de/2009/1959/1959.htm Accessed 25 November 2009

» Speth, P., Christoph, M., Diekkrüger, B. (Eds.), 2010. Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Germany, 675.

» UNDP – United Nations Development Programme, 2006. Data – Algeria, Morocco, Tunisia. http://hdrstats.undp.org/countries. Accessed 18 November 2009.

Impacts of climate variability and population pressure on water resources in the Lake Chad Basin

Roland Geerken[1], Sara Vassolo[2] & Mohamed Bila[3]

[1] Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, 65760 Eschborn, Dag-Hammarskjöld-Weg 1-5, Germany
E-mail: roland.geerken@gtz.de

[2] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, 30655 Hannover, Germany
E-mail: saraines.vassolo@bgr.de

[3] Mohamed Bila, Lake Chad Basin Commission (LCBC), Rond Point de l'Etoile, N'Djaména, Chad
E-mail: mdbila@yahoo.com

Abstract

The Lake Chad Basin is located in the central part of northern Africa and expands over Niger, Nigeria, Cameroon, Central African Republic, Chad, Sudan, Libya, and Algeria. It is an endorheic basin of about 2,300,000 km^2 with hyper-arid to arid climate in the north, semi-arid or sahelian in the centre, and subtropical in the south. Mean annual precipitation varies from less than 50 mm in the north to over 1,000 mm in the south. High temperatures throughout the whole year lead to levels of annual evapotranspiration of around 2,200 mm.

From the hydrological point of view, the basin is subdivided by the 14° north parallel into an inactive basin in the north and an active in the south. Two main river sub-basins feed the Lake Chad, the Chari-Logone that brings water from the South and the Komadugu-Yobe that flows mostly in a west-east direction along the Sahel zone. Both hydrological sub-basins are very sensitive to climatic variability and sort of over-react to droughts, which are well-known as devastating in the region. For example, the last long-term drought period from 1973 to 1984 led to the reduction of the lake open water surface from 17,620 km^2 to 1,920 km^2.

This work will show the effect of climate variability on water availability for the last 60 years based on field data. Precipitation has increased since the mid-80's to reach almost the levels of pre-drought. However, due probably to ground water level decline and population pressure, discharges do not increase as expected and the lake does not recover.

Keywords
Lake Chad Basin, Sahel region, climate variability, river discharge

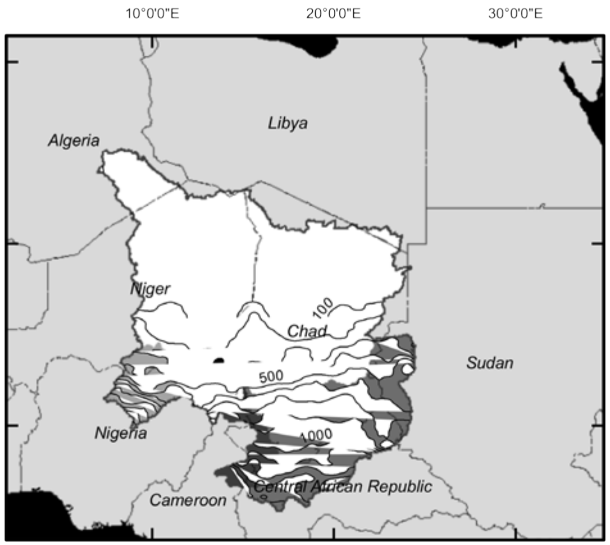
Introduction

Following a period of reduced rainfall (70ies and 80ies) with severe droughts during 1973 and 1984 Lake Chad, a terminal fresh water lake at the fringes of the Sahara Desert, did not recover from a substantial drop of its lake level that reduced its open water area from about 17,620km^2 to 1,920km^2. The open water area is currently limited to a southern pond separated from a deeper, northern pond by a morphological barrier. The low rainfall period and the following years after 1984 were not only marked by high precipitation variation and a temperature increase of approximately 1°C, but also saw a significant population increase, leading to extensive dam constructions, ground water pumping, and land cover / land use changes.

Main tributaries to Lake Chad are the Chari and Logone River (Figure 1). Minor contribution used to come from the Komadugu-Yobe River whose discharge, however, has become insignificant during recent years because of flow retention and diversions. All river systems are linked to extensive wetland systems that are believed to play a crucial role in ground water recharge.

Several authors claim Lake Chad to be predominantly precipitation driven (Chouret and Mathieu, 1976; Lemoalle et al., 2005; Olivry et al., 1996) concluding, it will recover as precipitation amounts increase. We argue that ground water, and its lowering in particular, has become a critical factor in the water balance of Lake Chad. At this stage we are collecting evidence from different data sources with the aim to identify relevant parameters and understand the mechanisms and feed backs that control the lake level of Lake Chad. With only limited ground water data available, evidence comes from the analyses of satellite data, lake level measurements, climate- and river discharge

Figure 1. Location Map Lake Chad Basin.



data, isotope and chemical analyses, comparative studies, and results from hydrologic modelling. From our findings we intend to construct a model that includes a surface – ground water exchange component that will explain water level variations.

Impacts of post-drought precipitation increases

Biomass

The most visible change since the droughts of the 70ies and 80ies is the strong rebound of green biomass in the northern Sahel (Anyamba and Tucker, 2005; Hermann et al., 2005). A trend analyses (1982 – 2006) of the annual maximum NDVI (Normalized Difference Vegetation Index, used as a surrogate for green biomass) taken from AVHRR satellite data[1] shows biomass increases of up to 70% (Figure 2). The pattern of strong biomass increases north of the 600mm isohyete and more or less unchanged biomass values south of it expands from the West coast of the African continent to Ethiopia. As shown in Figure 3 for an area in the Lake Chad Basin, biomass increases are strongly linked to increases in precipitation (use of fertilization in the region is very low and can thus can be discarded).

Using an approach described in Evans and Geerken (2004), we can show that many areas even respond increasingly better to rainfall, indicating improving growing conditions for vegetation.

As already indicated this development is most apparent in the northern Sahel. Though these areas do not form a substantial surface water contribution to Lake Chad, they most strikingly emphasize the positive changes the region experienced during the past two decades.

Different to the overall biomass improvement in the northern Sahel, we see several anomalies indicating deteriorating vegetation covers that do not fit into the general trend of precipitation increase. The largest such area, showing the strongest, negative trends are the Manga Grasslands, west of Lake Chad. Figure 3 displays graphs of biomass (annual NDVI maximum) and precipitation averaged over the deteriorating area. Biomass and precipitation are strongly correlated until 89 but the relationship becomes rather erratic from 89 onwards. While precipitation continuously increases, biomass decreases. For the sudden decoupling between precipitation and biomass we have only one explanation that is a drop of the ground water level, disconnecting vegetation from its water supply. Overgrazing and population pressure could also be driving forces, but they are homogenous and strong everywhere and not only in the Manga Grasslands.

[1] The normalized difference vegetation index (NDVI) is a product derived from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17.

Edmunds et al. (1999) describe the elevated area of the Manga Grasslands as a net recharge area for Lake Chad, indicating that there is a connection between ground water and Lake Chad. However, this information does not provide an explanation what is the cause of the ground water drop (ground water pumping, reduced ground water renewal, dropping lake levels) or what may be cause and what may be consequence inside the system of ground water and lake levels.

Climate, river discharge

The comparison of precipitation anomalies with river discharge anomalies shows how minor changes in precipitation cause significantly larger river discharge variations (Figure 4). This is probably an intrinsic characteristic of the sub-watersheds, defined by the water holding capacity of their soils, their infiltration-, and run-off characteristics. Since the mid 80ies we see a continuous recovery of annual precipitation, a trend even more strongly reflected in river discharge amounts. In all sub-watersheds shown, except Bahr Azoum which has a larger share of areas with a semi-arid climate, vegetation remains unaffected from this trend, due to generally high precipitation amounts in the southern sub-watersheds and/or a deeper rooting vegetation covers.

The open water area in the southern pond of Lake Chad remained more or less unaffected by these trends as water levels cannot increase beyond the spill point that transfers water into the northern pond once water level reaches a height of about 281m above mean sea level (m amsl). Water spilling over into the northern, deeper pond rarely forms open water bodies but rather densely vegetated, seasonal or perennial wetlands. Similar areas that are densely grown by typha are found in the southern pond. Their variable spatial distribution and temporal occurrence, as well as uncertainties in the amount of water transpired from the wetland vegetation form a particular challenge in calculating sound water budgets.

To understand the seasonal, spatio-temporal variability of wetland areas, we classified vegetation cycles using an approach described

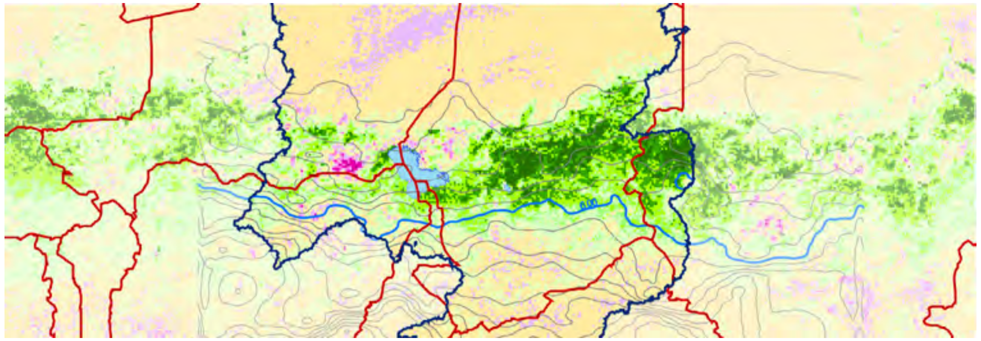


Figure 2. Annual NDVImax trends between 1982 and 2006.

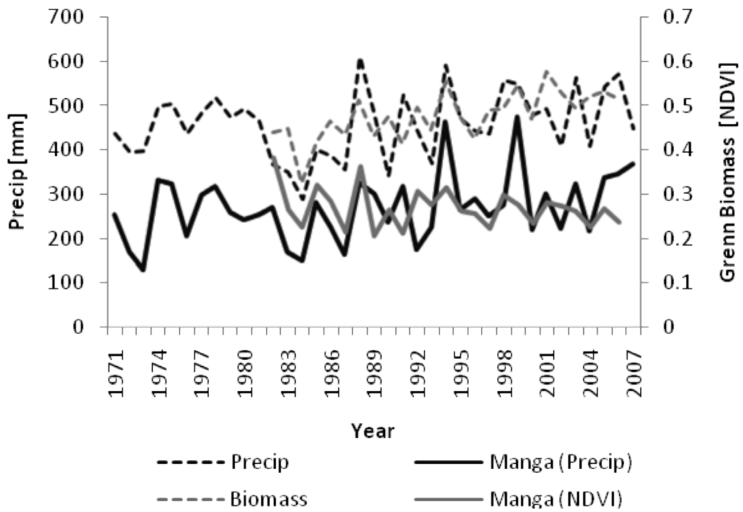


Figure 3. Averaged rainfall and biomass trends for the degrading area of the Manga Grasslands and the improving area east of Lake Chad.

in Geerken (2009). Assuming that vegetation in an arid environment should follow the seasonality of rainfall, any vegetation cover maintaining high biomass amounts beyond the wet season must receive water from some other source. This allows us to track water flow within the shorelines of Lake Chad offering a possibility to approximate water losses due to evapotranspiration and infiltration. Each class in Figure 4 represents distinct phenology (NDVI shape) providing information about spatio-temporal vegetation conditions.

Progression of water flow from the southern to the northern pond becomes visible in a second green up of vegetation cover that occurs after the end of rainy season (graphs with blue arrows in Figure 5) and marks the arrival of the flood wave from the spill over. The induced green up is temporally shifted to later times as we move north. The drop in green biomass after the rainy season may indicate senescence (biological aging of vegetation) or the formation of small, open water bodies from the spill over, creating mixed signatures (vegetation and water) which result in lower NDVI values. The latter is certainly true for the most northern phenology in Figure 4 where NDVI values drop below zero. This area coincides with the deepest part of the 'Lake'.

The timing and the temporal shift in flood arrival also recommends that this water does not originate from the Komadugu-Yobe River but from waters spilling over from the southern pond.

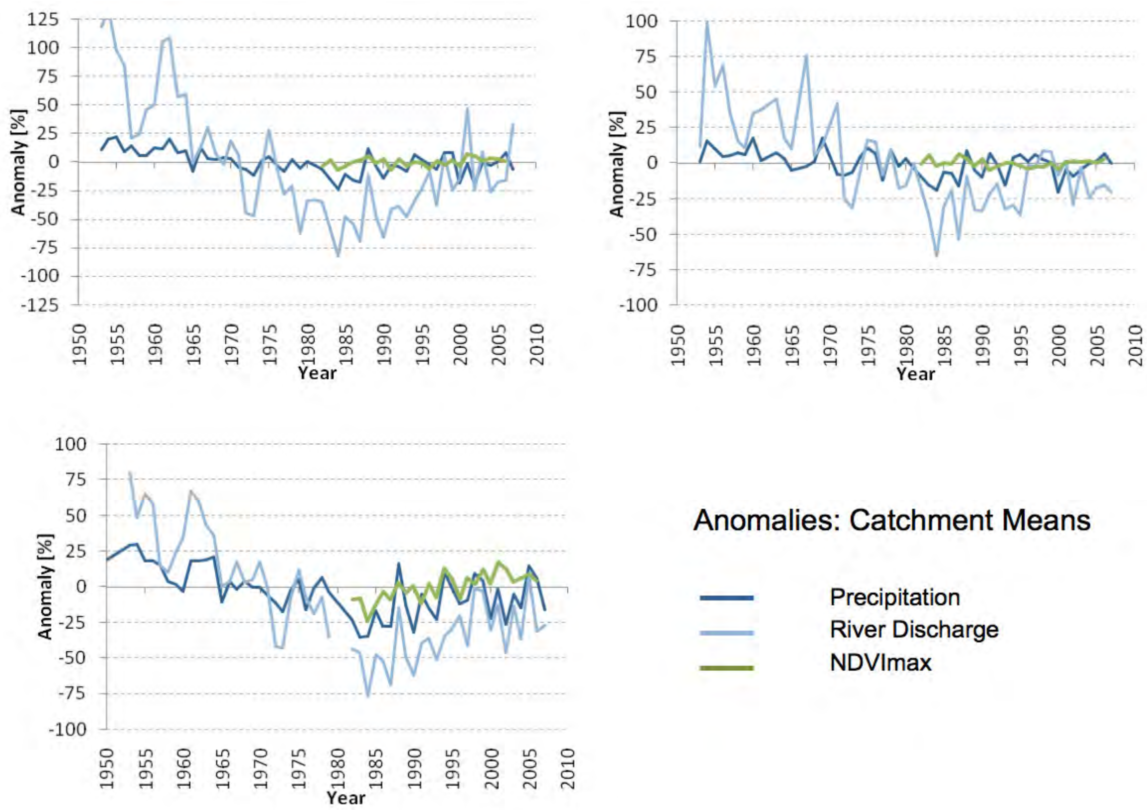
The spill over and spatio-temporal characteristics in wetland distribution will form an essential part in water budget calculations.

Lake level variations

Pre-drought seasonal lake level variations were limited to 0.5 to 1 meter. Today we see seasonal variations of up to 2 meters and more2

[2] *Because the gauging station 'Bol' is located at the dead-end of a channel in the archipelago region (to the north of the southern pond), it is disconnected from the main water body during times of low water levels. For studying recent lake level variations we rather relied on satellite altimetry measurements made available by LEGOS (data starts from 1992).*

Figure 4. Anomalies calculated from annual means for selected watershed areas: Chari watershed at Mailao (UL), Logone watershed at Logone-gana (UR), and Bahr Azoum watershed at Tarangara (LL).



(Figure 6). Average annual evaporation over the southern pond is around 2480 mm per year. This is too little to explain post-drought water losses leading to lake level drops of up to 2 meters just over a period of seven months. The additional water losses can only be explained by infiltration into ground water, especially considering that the lake lies on a very flat plane of quaternary sands.

In contrast, pre-drought lake level drops are far less than the potential evapotranspiration, with incoming river discharge being too little to explain water level variations. Accordingly, ground water must have recharged the Lake during the dry season. Also, during times of rising lake levels (pre-drought situation), substantial amounts of water from the lake must have recharged the aquifer, as more water was discharged into the lake than could be evaporated from its surface area.

Like during pre-drought times we expect the post-drought lake to loose water to the aquifer when lake levels rise, but we did not calculate this scenario because of likely errors introduced through water losses due to the spill over into the northern pond that we cannot yet quantify. The extraordinary seasonal rise in lake level of up to 2 meters is because river discharge is only discharged into the southern pond until it spills over.

To summarize these finding: the interaction between lake and ground water switched into a different mode, with the lake today permanently loosing water to the underground where there once existed a seasonal exchange of waters between lake and aquifer. While seasonal rainfall controls seasonal lake level variations, ground water level acts on a longer time scale. At lower ground water levels, its stabilizing influence is lost, also increasing water losses from the lake. This we see as a major reason for the slow recovery of Lake Chad which barely responds to the positive trends in rainfall and river discharge since 1984.

Figure 5. Fourier Component Classification of a MODIS NDVI time series (MOD13Q1) from 2007. NDVI graphs (green line) indicate well watered soil conditions after the end of the rainy season (blue line) and the progression of the flood wave into the northern pond as water spills over from the southern pond once water levels exceed the spill point (~ 281 to 281.5 meters) formed by a natural barrier separating the two ponds. Areas in white colors represent open water (Southern Pond) or unclassified pixels (north of former Lake Chad shore line, blue line).

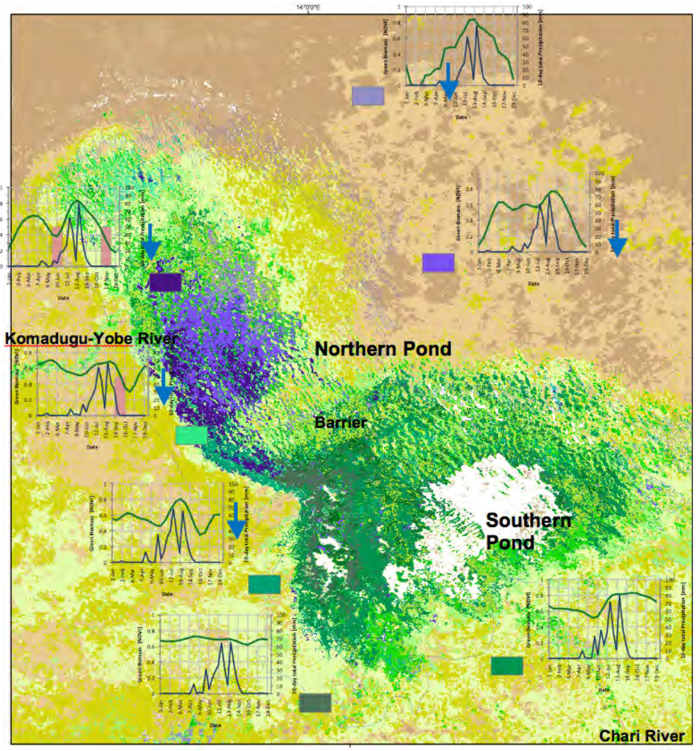
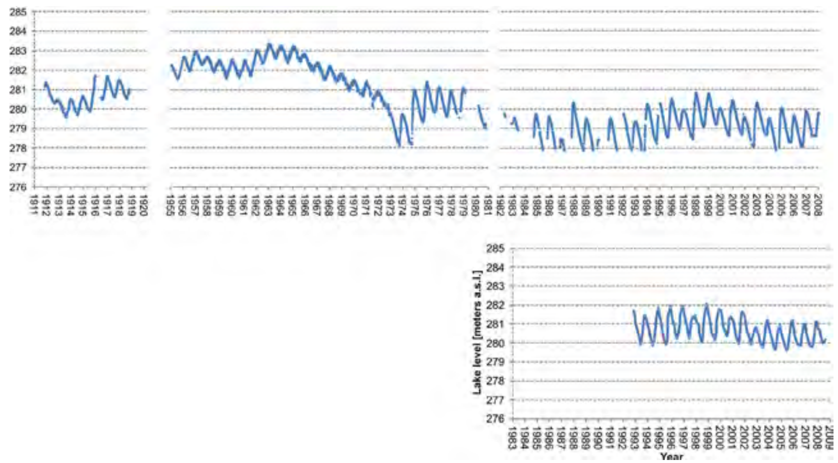


Figure 6. Lake level variations of Lake Chad measured at Bol station (top) and from satellite altimetry measurements (bottom), published by LEGOS.



Isotope/chemical analyses

The connection of Lake Chad to the underlying aquifer has been subject of investigation for many years. However, it is not yet completely understood how ground water and especially regional ground water level fluctuations affect the lake.

Chouret and Mathieu (1996) and Olivry (1996) indicate the presence of a leakage from Lake Chad towards a hydrological depression in the Bol region (NE of the southern basin), which is located some 10 km from the former lake shoreline.

Roche (1970), considering an homogeneous salt content along the lake shoreline, estimates the water losses by percolation along the shoreline at 7.7% to 9.5% of the water input by river discharge and precipitation. Carmouze (1973), using the ion sodium as a stable tracer, calculates water losses through infiltration equivalent to 4% to 7% of the hydrological inputs.

Isiorho and Matisoff (1990) and Isiorho (1996) have shown leakage of Lake Chad towards the SW in the Nigerian territory using sodium as a tracer. They estimated seepage velocities within a range of 0.002 mm/d to 11.7 mm/d (mean value of 1.15 mm/d).

We have performed an intensive environmental isotope campaign (^{2}H and ^{18}O) in the Chadian part of the basin. The results show leakage of Lake Chad towards the SE and the plume is still perceived at distances as far as 80 km from the shoreline (Figure 7).

Lemoalle et al. (2005) report a sulphate concentration of 210 mg/l in lake water measured in February 2004 in the northern pool. Due to the fact that high sulphate concentrations are unusual for rainfall and river water, they propose seepage of ground water as a possible source. However, other than ground water seepage, this may also be caused by dissolving the sulphate that had formed on the surface when water evaporated (surface- or capillary water).

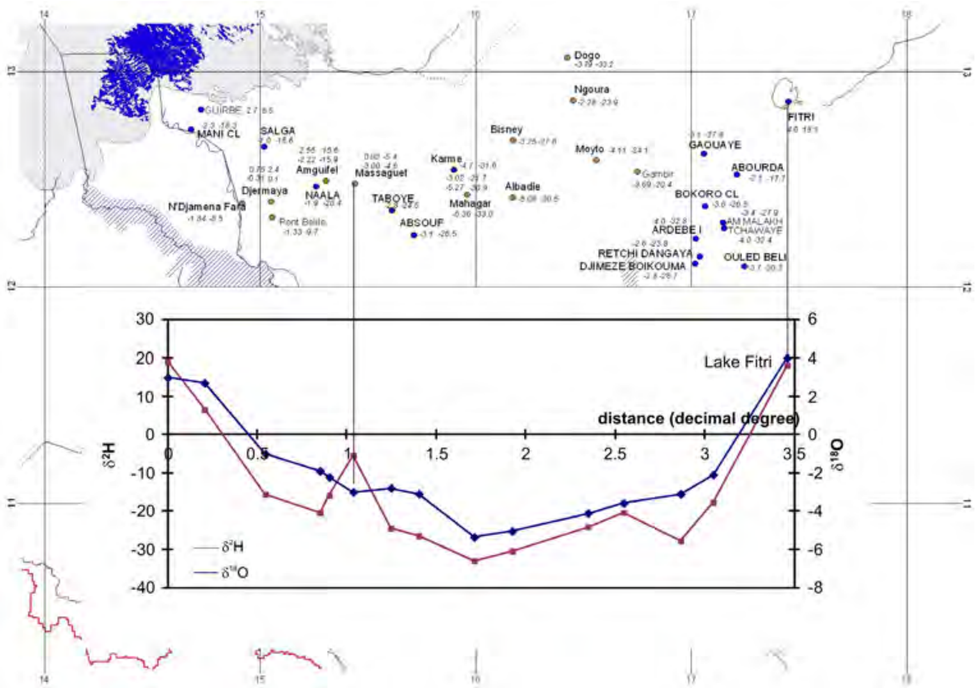


Figure 7. Regional ground water flow direction is indicated by the blue arrows, which is confirmed by the fact that the isotopes δ18O and δ2H decline with increasing distance to the lakes Chad and Fitri. The sudden increase of the isotope values at Massaguet is an indication of recharge by surface water, probably a palaeo-channel from the River Chari (Djoret 2000).

Conclusions

Studies from various authors and our own research clearly show there is an exchange of waters between Lake Chad and ground water. However, because of missing continuous measurements, the seasonally changing mechanisms (discharge and recharge) are not fully understood. Existing data suggest that the lake used to be re-charged by ground water during the dry season but lost water to the aquifer during the rainy season. This system showed a stable equilibrium until beginning of the 70ies even during short periods of dryness. Due to the slow responsiveness of ground water to droughts, evaporative losses could be compensated by the aquifer thus ensuring higher lake levels. This system was then disturbed by a long period of reduced rainfall (70ies and 80ies), but also by human interventions that together resulted in lower river discharge rates and lower ground water renewal rates. The construction of dams during the 70ies and 80ies further reduced the discharge of rivers which in turn could not supply downstream wetlands with the water flow that is needed to recharge the aquifers. The situation grew worse through excessive ground water pumping. With the stabilizing effect of ground water gone, the lake is now trying to level the imbalance between lake level and ground water level. Today lake levels are controlled by surface water input, evaporation and infiltration. Our studies and personal communications point to a considerable drop in ground water levels particularly in the Komadugu-Yobe Basin. The Komadugu-Yobe basin is the most densely populated watershed in the Lake Chad Basin. Though, river discharge of the Komadugu-Yobe River was never considered substantial (about 12% of total river inputs) its ground water is likely to have a more crucial influence on the water budget of the lake.

Initial hydrologic model runs where we simulated a temperature increase of 1 to 1.5°C show only minor changes in surface water availability and are far too little to explain the water losses in the lake. This is further supported by the situation of Lake Fitri situated 200km east of Lake Chad. After it almost disappeared in 1984, Lake Fitri fully recovered to its pre-drought extent, more or less excluding a purely climate driven cause. Modelling results also showed that the effective surface catchment area of Lake Chad may actually be too small to support a lake equivalent to its pre-drought size. With a mostly flat topography, run-off is only produced along the basins southern periphery, making ground water a vital component in the preservation of Lake Chad.

References

» Anyamba, A. and Tucker, C. J., 2005. Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981-2003. Journal of Arid Environments, 63(3): 596-614.

» Carmouze, J.P., 1973. Hydric and Saline Regulation of Lake Chad. Cahiers Orstom Hydrobiologie, 7(1): 17-23.

» Chouret, A. and Mathieu, P., 1976. La nappe phreatique a la peripherie du Lac Tchad: Resultats preliminaire des traveaux recents de l'ORSTOM, 3ième Conférence de Géologie Africaine, Khartoum, Sudan.

» Djoret, D., 2000. Etude de la recharge de la nappe du Chari-Baguirmi (Tchad) par les methodes chimiques et isotopiques. PhD Thesis. Universite d'Avignon et des Pays de Vaucluse, Avignon.

» Edmunds, W.M., Fellman, E. and Goni, I. B., 1999. Lakes, groundwater and palaeohydrology in the Sahel of NE Nigeria: evidence from hydrogeochemistry. Journal of the Geological Society, 156: 345-355.

» Evans, J. and Geerken, R., 2004. Discrimination between climate and human-induced dryland degradation. Journal of Arid Environments, 57(4): 535-554.

» Geerken, R., 2009. An algorithm to classify seasonal variations in vegetation phenologies and their coverage and monitor their inter-annual change. Journal of Photogrammetry and Remote Sensing.

» Hermann, S. M., Anyamba, A. and Tucker, C. J., 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. Global Environmental Change, 15: 394-404.

» Isiorho, S. A. and Matisoff, G., 1990. Groundwater Recharge from Lake Chad. Limnology and Oceanography, 35(4): 931-938.

» Isiorho, S.A., Matisoff, G. and Wehn, K.S., 1996. Seepage relationships between Lake Chad and the Chad aquifers. Ground Water, 34(5): 819-826.

» Lemoalle, J., Favreau, G., Seidel, J.-L. and Zairi, R., 2005. Changes in Lake Chad water chemistry during a drought period. Geophysical Research Abstracts, 7: 2.

» Olivry, J.-C., Chouret, A., Vuillaume, G., Lemaolle, J. and Bricquet, J.-P., 1996. Hydrologie du lac Tchad, Paris.

» Roche, M.A., 1970. Evaluation des pertes du Lac Tchad par abandon superficiel et infiltrations marginales. Cahiers Orstom Geologie, 2(1): 67-80.

Impact of global change on water resources in the Ouémé catchment, Benin

Simone Giertz[1,2], Bernd Diekkrüger[1] & Britta Höllermann[1]

[1] Department of Geography, Meckenheimer Allee 166, 53115 Bonn, Germany

[2] E-mail: sgiertz@uni-bonn.de

Abstract

Today, fresh water has already become a critically scarce resource in many regions of the world. In many developing countries insufficient water supply infrastructure aggravates this problem. With the ongoing global change and population growth water security will become one of the major problems in the 21st century.

Regarding the annual water balance the West African Country Benin is not suffering from physical water scarcity. Nevertheless, investigations show that water scarcity occurs at the local scale, especially at the end of the dry season, which is caused by reduced water availability in this period and particularly by the inadequate water supply infrastructure. For an efficient long-term planning of water management the future development of the water resources and the water demand has to be analysed on different temporal and spatial scales, particularly regarding the impact of global change on the water resources.

In the presented study, which is part of the GLOWA-IMPETUS project, the effects of land use/land cover change, climate change, and demographic development on water availability and water demand in the Ouémé catchment (49,285 km^2) in Benin are quantified based on an interdisciplinary scenario analysis. To calculate water availability, the output of a regional climate model was linked to a hydrological model that also considered land use change calculated by a cellular automata model. Future water requirements were computed by linking population growth and per capita water demand, which was derived from a regional survey as well as the developments in industry and irrigation agriculture. The results reveal a significant decrease in future water availability (surface water and groundwater) for the IPCC climate scenarios A1B and B1 due to a decrease in rainfall and an increase in evapotranspiration. Using the water management model WEAP it can be shown that water shortages during the dry season will increase in future scenarios.

Keywords

hydrological modelling, climate change, land use change, water resources, water demand

Introduction

Benin is not a water-scarce country based on its annual precipitation, but due to its location in the wet savanna, seasonal shortages are common (Falkenmark and Rockström 2004). Moreover, studies (Schopp 2004; Behle 2005) have revealed that the water supply during the dry season does not meet the actual demand due to physical, economic and institutional reasons. Facing the impacts of climate change and the further stress on this resource due to population growth, Benin's water supply is at risk (GWP 2007).

Scenarios of land use change and climate change: Impact on hydrology and water availability

For future water resources management, it is important to assess the possible impacts of these changes on water resources for a longer time horizon of 20-50 years. As it is impossible to predict the exact developments of climate, land use and socio-economic aspects and their impact on the water resources for such a long time span, scenarios regarding the trends of important drivers are often used in interdisciplinary modelling approaches. In these approaches, models from different disciplines, such as climate models and hydrological models, are linked via data exchange or dynamic coupling. As a prerequisite, the models used should be validated for the region and tested for the modelling purpose (e.g., land use change, Climate Change). For the Ouémé catchment, the hydrological model UHP-HRU was used in an interdisciplinary modelling approach (Giertz et al. 2006). The new model version (UHP-HRU 2.5) was validated for different sub-catchments under different land use scenarios for both dry and wet years. The spatially distributed results have shown that the model results, particularly surface runoff, are highly sensitive to changes in land use (Giertz et al. 2010a). In the following section the impact of Climate Change on future water availability is described. This was simulated for the two IPCC SRES scenarios A1B and B1 for the whole Ouémé catchment for the period 2001-2049 using downscaled results of REMO (REgional MOdel). The impact of land use was only simulated for the Upper Ouémé catchment as no land use scenarios were available for the Ouémé-Bonou catchment. The impact of land use change on the hydrology of the Upper Ouémé catchment is described in Giertz et al (2010b). In order to link the scenarios of future water availability with future water demand, the results of the UHP-HRU model were used in the water management model WEAP in combination with water demand scenarios (Höllermann et al. 2009 and 2010).

Climate scenarios

The impact of Climate Change on water availability was simulated for the whole Ouémé catchment using the results of the regional climate model REMO, driven by the IPCC SRES scenarios A1B and B1 (Christoph et al. 2010 and Paeth et al. 2009). REMO is a regional climate model with a resolution of 0.5° x 0.5° that is nested in the global circulation model ECHAM5 (European Centre Hamburg Model). The simulations by Paeth et al. (2009) take into account the spatial patterns of future land use change according to FAO. For each scenario, three ensemble runs were simulated from 2001 to 2049, reflecting the uncertainties due to unknown initial conditions (Paeth et al. 2009). According to IPCC (2007), SRES scenario A1B describes a globalized world of rapid economic growth and comparatively low population growth. The use of fossil and non-fossil energy sources is balanced. SRES scenario B1 also characterizes a future globalized world with a low population growth. However, in this scenario, the economic structures change rapidly toward a service and information economy with reduced material intensity and the introduction of clean, sustainable technologies. Consequently, the predicted CO_2 emissions and temperature increases are lower than for the A1B scenario. Both scenarios are rather optimistic compared to the whole SRES scenario family (Christoph et al. 2010).

Current climate models cannot correctly represent the climatology of rainfall, but they are more reliable in terms of atmospheric circulation and thermodynamics. Therefore, the model results cannot be directly fed into hydrological models. In the case of REMO, the model systematically underestimated the amount and variability of rainfall over West Africa, including a shift in rainfall distribution toward more weak events and fewer extremes (Christoph et al. 2010). To address this, so-called Model Output Statistics (MOS) were applied in order to adjust the REMO rainfall data by using other near-surface parameters, such as temperature and sea level pressure wind components. A crossvalidated multiple regression analysis was used to adjust monthly data to the CRU (Climatic Research Unit) observational dataset (CRU dataset) (Christoph et al. 2010). As the resolution of the model is relatively coarse (0.5° x 0.5°), a statistical downscaling approach was used to create artificial station data for each rainfall and climate station in Benin (Christoph et al. 2010)

Hiepe (2008) has shown that the post-processed results of the REMO model show good correspondence with the measured ones. The climate scenarios based on the post-processed REMO results were simulated with the calibrated UHP-HRU 2.5 model for the Ouémé-Bonou catchment for the period 2001–2049. As with the calibration and validation period (Giertz et al. 2010a), spatially variable rainfall data were used for the climate scenarios for a better representation of the spatial heterogeneity, instead of the mean for sub-catchments, as in Giertz (2008). In order to take into account the variability of the REMO results, three model runs were simulated for each scenario with the hydrological model UHP-HRU based on the available REMO ensemble runs. For each scenario, the mean of the three runs was taken as the result of the scenario. The land use of 2000 remained constant for the whole simulation period of the climate scenarios.

As the annual variability of rainfall in the region is rather high and the results of the climate model are not sufficiently accurate to be evaluated within annual time steps, only the results of semi-decades or decades were analyzed. Figures 1 and 2 show the development of the rainfall and the total renewable water as a mean for semi-decades for climate scenarios A1B and B1. Table 1 summarizes the water balance for the reference period 1980-1999 and the five decades of the climate scenarios A1B and B1, as well as the relative change as compared to the reference period.

Table 1 Mean simulated annual water balance for the reference period and Climate Change scenarios A1B and B1 in the Ouémé-Bonou catchments. The results are averages of the three ensemble runs for each climate scenario. Absolute values and change in % from the reference period are presented.

	Precipitation [mm/y]	Etpot [mm/y]	Etact [mm/y]	Discharge [mm/y]	Recharge [mm/y]	Precipitation [Δ %]	Etpot [Δ %]	Etact [Δ %]	Discharge [Δ %]	Recharge [Δ %]
observed										
1980-1999	1118	1727	908	131	99	0	0	0	0	0
Scenario A1B										
2001-2009	1125	1953	921	105	84	0.6	13.0	1.4	-20.3	-15.5
2010-2019	1091	1971	907	105	83	-2.4	14.1	-0.2	-20.1	-16.6
2020-2029	1035	1988	895	83	58	-7.4	15.1	-1.5	-37.0	-41.0
2030-2039	1078	2010	909	96	70	-3.6	16.3	0.0	-26.5	-29.4
2040-2049	997	2053	877	74	47	-10.8	18.8	-3.5	-43.9	-52.2
Scenario B1										
2001-2009	1159	1915	908	132	103	3.6	10.9	0.0	0.8	3.7
2010-2019	1072	1973	916	90	67	-4.2	14.2	0.8	-31.3	-32.4
2020-2029	1069	1972	912	91	67	-4.4	14.2	0.4	-30.8	-31.9
2030-2039	1079	1992	908	99	72	-3.5	15.3	0.0	-24.5	-27.4
2040-2049	1065	2021	897	98	68	-4.8	17.0	-1.3	-25.2	-31.3

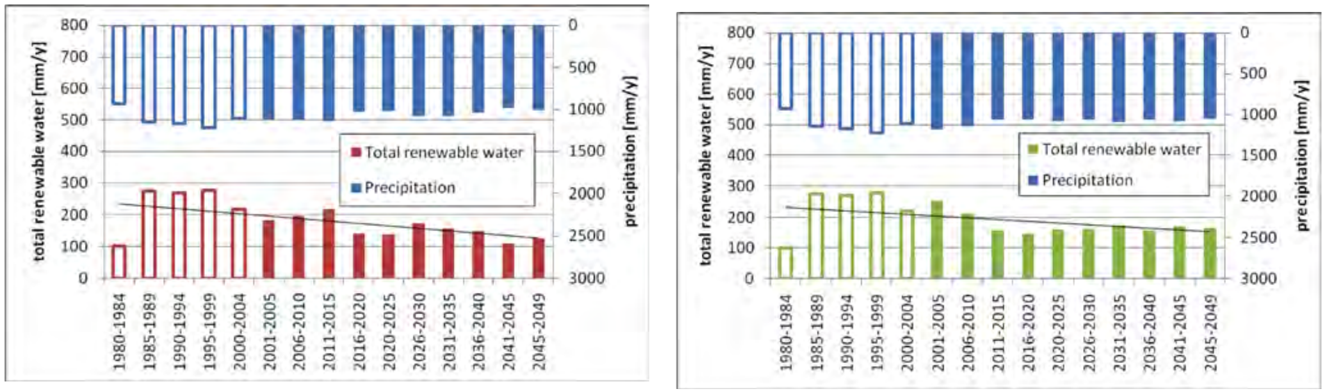
The results of the hydrological model reveal that the amount of renewable water decreases during the period 2001-2049 in both scenarios. The trend is more extreme in climate scenario A1B. In the latter, the discharge decreases by about 44% in the final decade as compared to the reference period, and a reduction of 52% was determined for the recharge. In the B1 climate scenario, the decrease still amounts to 25% for the discharge and 31% for the recharge. The decrease in renewable water can be explained by a decrease in precipitation and an increase in temperature until 2049 in both scenarios. Due to the higher amount of CO_2 in climate scenario A1B, the increase in temperature is higher than in climate scenario B1. This leads to higher potential evapotranspiration and a stronger decrease in renewable water in scenario A1B. However, figures 1 and 2 reveal that for both scenarios, the renewable water resources in the last semi-decade are still slightly higher than in the period from 1980-1984 which has been very dry.

The results of this interdisciplinary modelling approach have shown that – following the assumptions of climate scenarios A1B and B1 - a strong decrease in water resources can be assumed for the future in the Ouémé catchment.

The results of the scenarios must be interpreted with caution, as many uncertainties are included in the modelling process. In addition to the uncertainties of the hydrologic modelling (e.g., input data uncertainties, model-related uncertainties), the uncertainties of the scenario data must be taken into account. The evaluation of the REMO data from 1960-2000 has shown a good correspondence

Figure 1. Development of precipitation and renewable water resources (=total discharge + groundwater recharge) in the Ouémé-Bonou catchment for the climate scenario A1B (a) and B1 (b) simulated with UHP-HRU (mean for of the three ensemble runs; filled bars: UHP-HRU model results using post-processed REMO climate and precipitation data; unfilled bars: UHP-HRU model results using measured climate and precipitation data)

a b



to the measured data (Hiepe 2008). Therefore, the Climate Change sketched by the REMO model is assumed to plausibly represent the climate development of the region. Nevertheless, global circulation models (GCMs) show no clear rainfall trends for the Guinean Coast (IPCC 2007). The median from the 21 circulation models even show an increase in rainfall of about 2% from the period 1980-1999 to 2080-2099 for the region. The temperature trend is more obvious: all models predict an increase in temperature for the A1B scenario for the same period with an overall median of 3.3 °C for all models (IPCC 2007). As REMO incorporates the land use change in West and Central Africa into the modelling process, the simulated trend of increased temperature and decreased rainfall is more extreme than in simulations of other climate models. Using other IPCC scenarios could have led to significantly different results with regard to future water availability. This must be kept in mind when drawing conclusions from the model results and when defining management strategies.

Balancing future water availability and demand: WEAP application of the Ouémé catchment

Water management models are useful tools for improving water management practices and increasing water security. The WEAP system is a demand-, priority-, and preference-driven water management model. It aims at closing the gap between water management and catchment hydrology by addressing water demand and availability simultaneously. WEAP allows the simulation of changes in supply and demand structures, thereby discovering potential shortages and the impacts of different management strategies or development paths on water availability (Yates et al. 2005). As water availability could be transferred from the UHP-HRU model, the internal modules for calculating water availability in WEAP were not used. For modelling process with WEAP the Ouémé-Bonou catchment was subdivided into 27 sub-basins with an average area of about 2,000 km². The results of the UHP-HRU modelling provided localized information on surface water flows as well as on groundwater recharge for each of the sub-basins under two different model-based climate scenarios. To estimate the available groundwater the simple storage approach of WEAP was used. To analyze water demand and supply on the catchment level, it was necessary to disaggregate the information available on the commune level (Höllermann et al. 2009 and 2010)

Water demand scenarios

Benin's water demand has been studied and characterized comprehensively by Schopp (2004), Hadjer et al. (2005) and Gruber et al. (2009). Water demand scenarios for each sector (domestic, agricultural and industrial water demand) were developed, based on their findings, and taking into account the different development paths of the societal, economic, and ecological scenarios applied by IMPETUS (Höllermann et al. 2010). The socio-economic scenario B1, named "Economic growth and consolidation of decentralization," describes a scenario of political stability and economic growth. Socio-economic scenario B2, "Economic stagnation and institutional insecurity", sketches a development path of a continuing and mutually influencing spiral of political destabilization and economic depression. Socio-economic scenario B3, "Business as usual", extrapolates the current trends. A detailed description of the socio-economic scenarios is given Reichert and Jaeger (2010).

As a result of the different water demand scenarios, demand continuously increases over the simulation period. Consequently, scenario B1 shows the highest growth rates. Water demand particularly increases for the domestic and agricultural demand sites. Another important use of water is livestock, while industrial water use is projected to remain insignificantly small. While domestic and industrial water demand does not vary throughout the year, agricultural water demand shows a distinct monthly variation, influencing the intra-annual demand. Therefore, water demand is highest from December to March during the dry season, and it decreases with the start of the rainy season. The increased water demand during the dry season intensifies the competition for scarce surface water resources (Höllermann et al. 2010).

Balancing water demand and supply

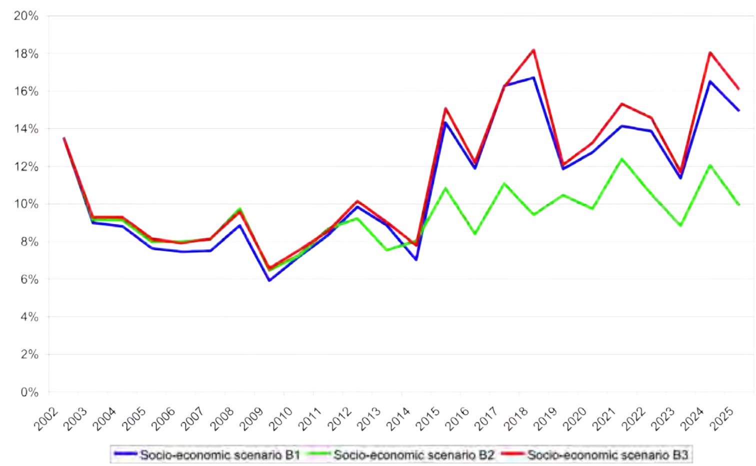


Figure 2. Unmet water demand of the Ouémé-Bonou catchment in percent of total water demand for the socio-economic scenarios B1, B2 and B3.

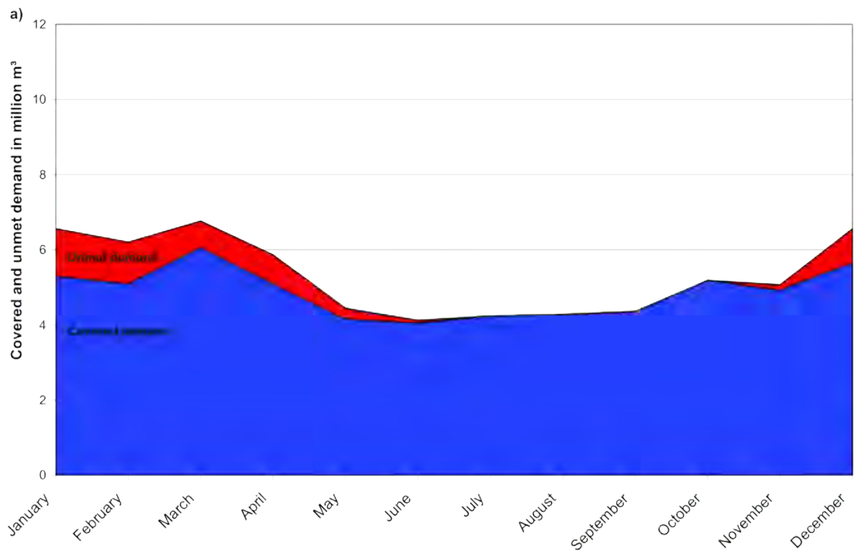
The water balance for the Ouémé-Bonou catchment was calculated for the period from 2002 to 2025, with 2002 as the base year for reference (Höllermann et al.2009 and 2010). The results show that the different climate scenarios A1B and B1 have a strong impact on water availability. A significant decrease in catchment inflow is observed for the period 2015 to 2025 in climate scenario A1B, while this effect is mitigated in climate scenario B1. The decreasing inflows affect the accessible groundwater and reservoir storage. While the groundwater aquifers tend to refill completely during the rainy season until 2014, the recharge rate from 2015 on is not high enough, and a decrease in storage is observed, leading to lower groundwater levels during the dry and rainy seasons (Höllermann et al. 2010). Less catchment inflow aggravates the refill capacity of larger reservoirs. Furthermore, growing water demand increases the pressure on reservoir water. This increase is more significant in climate scenario A1B under the IMPETUS socio-economic scenario B1, presenting the highest water extraction from reservoirs (Höllermann et al. 2009 and 2010).

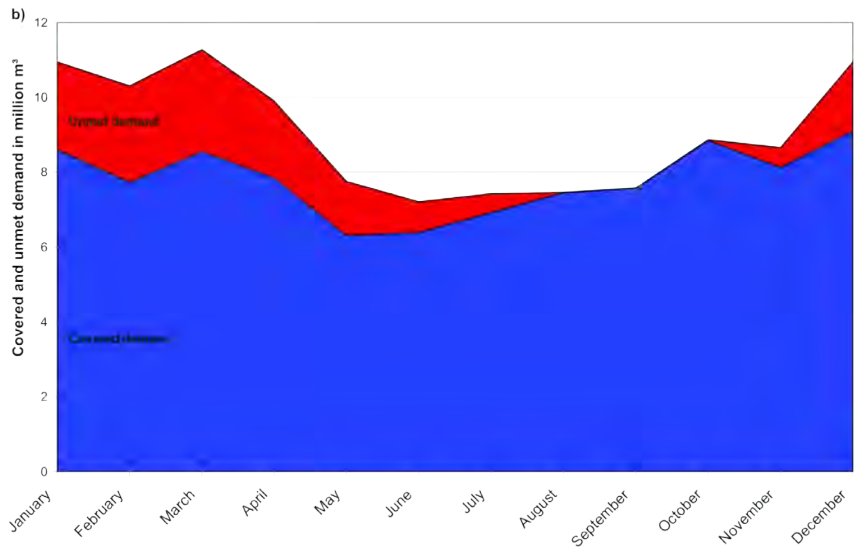
According to the effects of the climate scenarios, water scarcity is highest in the last decade of the study period. This becomes apparent from the above-average increase in unmet demand in the period 2015–2025 (see Figure 2), especially amongst demand sites that rely on water from rivers or reservoirs.

As the availability of surface water follows a monthly variation due to the changes from rainy to dry season, the shortages solely occur during the dry season. While the effects of the dry season with unmet demands can be found for about 8 months per year in the period of 2002–2014, these effects extend to 10 months per year for the period of 2015–2025 (see Figure 3).

The water balance results of WEAP imply that water supply security depends strongly on the water sources used. While the avail-

Figure 3. Monthly water demand of the socio-economic scenario B1 averaged over the periods 2002-2014 (a) and 2015-2025 (b). The water demand is distinguished into covered (blue) and unmet (red) demand.





able amount of groundwater is potentially high enough to satisfy demand, users relying on surface water from rivers and reservoirs experience shortages. As a result, the different user types relying on surface water are competing with each other. Especially in the northern parts of the study area, a distinctive competition between domestic water users and livestock watering is observed. Other competitors for surface water are the peri-urban irrigation sites, which double their demand during the dry season. The situation worsens with the projected changes in climate because the months with no unmet demand decrease from four months (2002–2014) to two (2015–2025). By contrast, the WEAP results imply that the water security for users relying on groundwater is high. However, these results must be treated with caution. Due to the simple groundwater modelling approach the uncertainties concerning the total amount of groundwater are quite high.

Furthermore WEAP does not simulate the socio-economic and institutional factors that prevent optimal exploration of groundwater.

Even though uncertainties and constraints exist, the WEAP results offer a solid basis for assisting planners in developing recommendations for future water resources management. The scenario analysis with WEAP has revealed potential conflicts over water, the occurrence of shortages, and the development of mitigation strategies. For example, increases in surface water efficiency as well as technical and organizational improvements in the rural infrastructure (e.g., reliable pumps, sufficiently deep wells, and improved management structures) can mitigate current and future shortages in water supply and therefore increase water supply security. However, one has to keep in mind that an improved infrastructure for exploring groundwater might also further deplete the groundwater.

Conclusions

The scenario analysis for the Ouémé catchment and its sub-catchment has shown that Climate Change, as well as the population growth and socio-economic changes will have a strong impact on the water resources. The increase of temperature and decrease in rainfall cause a decrease in total available water for both scenarios for the period 2001-2025/2049. With the WEAP water management model, it was possible to identify future problems of water supply in the Ouémé catchment by linking water availability with water demand. For the simulated climate scenarios, users relying on surface water from rivers and reservoirs, especially, will experience shortages in the future, while the available amount of groundwater is potentially high enough to satisfy the demand. Here the problems of poor access to the available groundwater must be kept in mind. The results of the presented studies are useful for supporting water management planning activities in Benin. As the IWRM-strategy is actually implemented in the water policy of Benin, reliable data concerning the development of available water resources and water demand on a catchment level are required. With the results of the water management model WEAP these data are provided for planners and decision makers in Benin in a user-friendly way.

References

» Christoph, M., Fink, A. H., Paeth, H., Born, K., Kerschgens, M., Piecha, K. (2010) Climate scenarios. In: Speth, P., Christoph M., Diekkrüger, B. (Eds.) Impacts of global change on the hydrological cycle in West and Northwest Africa. Springer, Heidelberg. 401-424.

» Falkenmark, M., Rockström, J., 2004. Balancing Water for Humans and Nature: The New Approach in Ecohydrology. Earthscan, London, Sterling.

» Giertz, S., 2008. Assessing the Impact of Climate and Land Use Change on Future Water Availability in the Ouémé Catchment. In: Judex, M., Thamm, H.P. (Eds) (2008) IMPETUS Atlas Benin: Research Results 2000-2007. 3rd edn.. Department of Geography, University of Bonn, Bonn, 37-38.

» Giertz, S., Diekkrüger, B., Jaeger, A., 2006. An interdisciplinary scenario analysis to assess the water availability and water consumption in the Upper Ouémé catchment in Benin. Adv Geosci 9, 3-13.

» Giertz, S., Hiepe C., Steup, G., Sintondji, L., Diekkrüger, B., 2010a. Hydrological processes and soil degradation in Benin. In: Speth, P., Christoph M. & B. Diekkrüger (Eds.) Impacts of global change on the hydrological cycle in West and Northwest Africa. Springer, Heidelberg. 167-196.

» Giertz, S., Hiepe, C., Höllermann, B., Diekkrüger, B., 2010b. Impacts of global change on water resources and soil degradation in Benin. In: Speth, P., Christoph M., Diekkrüger, B. (Eds.) Impacts of global change on the hydrological cycle in West and Northwest Africa. Springer, Heidelberg.

» Gruber, I., 2008. The impact of socio-economic development and climate change on livestock management in Benin. Doctoral thesis, University of Bonn, Bonn.

» Gruber, I., Kloos, J.R., Schopp, M., 2009. Seasonal water demand in Benin's agriculture. J Environ Management 90, 196-205.

» GWP, 2007. Global Water Partnership West Africa. Available at http://www.gwpforum.org/gwp/library/Regprof_2008_West_Africa.pdf. Accessed 12 January 2010

» Hadjer, K., Klein, T., Schopp, M., 2005. Water consumption embedded in its social context, north-western Benin. Phys Chem Earth 30, 357-364.

» Hiepe, C., 2008. Soil degradation by water erosion in a sub-humid West-African catchment a modelling approach considering land use and climate change in Benin. Doctoral thesis, University of Bonn, Bonn.

» Höllermann, B., Diekkrüger, B., Giertz, S., 2009. Bewertung der aktuellen und zukünftigen Wasserverfügbarkeit des Ouémé Einzugsgebiets (Benin, Westafrika) für ein integriertes Wasserressourcenmanagement mit Hilfe des Entscheidungsunterstützungsmodells WEAP. Hydrologie und Wasserbewirtschaftung 53 (5), 305-315.

» Höllermann, B., Giertz, S., Diekkrüger, B., 2010. Benin 2025—Balancing Future Water Availability and Demand Using the WEAP 'Water Evaluation and Planning' System. Water Resources Management. 24 (13), 3591-3613.

» IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

» Paeth, H., Born, K., Girmes, R., Podzun, R., Jacob, D., 2009. Regional climate change in tropical and northern Africa due to greenhouse forcing and land use changes. J Clim 22, 114-132.

» Reichert, B., Jaeger, A., 2010. Socio-economic scenarios. In: Speth, P., Christoph M., Diekkrüger, B. (Eds.) Impacts of global change on the hydrological cycle in West and Northwest Africa. Springer, Heidelberg, 425-440.

» Schopp, M., 2004. Wasserversorgung in Benin unter Berücksichtigung sozioökonomischer und soziodemograpischer Strukturen - Analyse der Wassernachfrage an ausgewählten Standorten des Haute Ouémé, Doctoral thesis, University of Bonn, Bonn.

Drivers of land use changes in the Amudarya river basin

Darya Hirsch

United Nations University-Institute for Environment and Human Security, UNU-EHS, UN-Campus, Hermann-Ehlers-Str. 10, 53113, Bonn

E-mail: hirsch@vie.unu.edu

Abstract

Land is a main factor of economic wealth and welfare of the population, a fundamental object of all economic sectors and agriculture in particular, where land is a principal means of production. The Central Asian region provides a vast territory consisting of deserts, steppes and mountains. Agricultural production in this region is constantly faced with complex climate-related low rainfall and irregular and extreme temperature changes. For productive agriculture, most Central Asian countries, especially the ones located downstream of the rivers, depend on irrigation.

The region has experienced drastic changes in political, societal and economic structures following the break-up of Soviet Union in 1991. The shift from centralized command economies to market-oriented systems has altered economic opportunities, induced technological changes and fostered rapid demographic processes. These changes tremendously affected land management and land-use decision making. Together, this triggered widespread land cover change. It increased for instance overgrazing and deforestation rates in the mountain regions of the basin, as well as processes of desertification in the downstream of Amudarya. Furthermore, Central Asia has become warmer more quickly than the global average. Changing climatic conditions and warm temperatures increase the risk of natural hazards posed by melting glaciers in the Pamir mountains of Eastern Tajikistan, which occupy an area around 17 950 km^2 and constitute a major source of runoff in the warm seasons. The melting processes will have a likely impact on river runoff.

The economies of the semi-arid former Soviet Union Countries located in the Amudarya River Basin thus strongly depend on the water resources of the river, which are mainly used for agricultural production downstream, but increasingly also for hydropower generation upstream. Nowadays, water management is largely subordinate to the agricultural sector. However, the upstream countries (Tajikistan and Kyrgyzstan), where most water is generated, will be increasingly claiming the water resources for themselves.

The purpose of this article is to outline the major uncertainties of climate, environmental change and other changes in the Amudarya river basin. Particular attention is paid to interactions between the effects of global change and regional changes such as the changes in the land use pattern due to the prioritization of domestic food security, water for hydroelectric generation versus irrigated farming and changes in socio-ecological systems.

Keywords
Central Asia, post Soviet environment, freshwater availability, agriculture, hydro energetics, large-scale irrigation systems, socio-ecological systems

Introduction

The Amudarya river basin (Figure 1) includes approximately 1,327 thousand km², of which 1018.6 thousand km² are located in the Central Asian states (Turkmenistan- 488.1thousand km², Uzbekistan-388.2 thousand km², Tajikistan -131thousand km² and Kyrgyz Republic- 11.3thousand km²). The rest of the basin's catchment area is in Afghanistan and Iran (Khudaiberganov, 2007).

In Soviet times, Central Asian Soviet Republics were interlinked within the centralized economic system. It was characterized by the specialization of each of these republics in producing one specific agricultural commodity according to prevailing agro-climatic and biophysical resources. For example, Uzbekistan has specialized in cotton production, while Kyrgyzstan has been a center for animal husbandry in the region.

The end of communism and the breakup of the Soviet Union have had a severe impact on the region and the Amudarya river basin by changing the entire socio-political and socio-economic situation. After gaining their independence in 1991, Central Asian Republics were faced with a break-up of previously existing trade arrangements and economic ties for production and distribution of agricultural products. With the collapse of this system, all the republics had to develop their own independent economies in which agriculture continued to play an important role in covering the local demand for food, such as wheat supply, while experiencing an increasing need to be more integrated into global markets.

In the Soviet agricultural production system, large collective and state farms controlled 95% of agricultural land and produced most of the commercially marketed products. Product markets and channels for agricultural exports were largely controlled by state organizations. After independence, the transition of the agricultural sector from a centralized command system to a market-based regulation has also been difficult. From their first days of independence the countries of Central Asia began to reform land use and agriculture. As a result of these reforms thousands of land (and water) users ap-

Figure 1. Amudarya River Basin (Source: www.cawater-info.net)

peared on the regional level replacing the former collective farms- kolkhozes and Soviet state farms - sovkhozes. Since the first reforms devoted themselves to the restructuring in land use and land tenure, little was done to coordinate the reform processes between land and water sectors (ICWC, 2004).This gap worsened the conditions of on-farm irrigation and drainage systems, especially in the downstream countries such as Turkmenistan and Uzbekistan.

The recent reforms in the agricultural sector in Central Asian countries have brought about many changes in peasants' lives. Peasants who previously were employees of former state collective farms and have now become private entrepreneurs in most cases do not have enough knowledge, skills and capital (Trevisani, 2008, ICARDA CAC Program, 2009). They face problems associated with poorly developed agricultural infrastructure, difficult access to markets as well as, in some countries, strict state control, ineffective institutions, conflicting laws and policies (ICARDA CAC Program, 2009).

Water sector reforms were not carried out parallel with changes in the agricultural sector and lagged behind the land reform process. Throughout most of the 1990s, water management remained unchanged. Reforms in the water sector were only slowly introduced from 2000 onward as a response to changes in the agricultural sector that made the Soviet water management administration unsuitable for serving thousands of newly established small and medium farms and thus water users (Zavgorodnyaya, 2006, Yalcin and Mollinga 2007, Schlüter and Herrfahrdt-Pähle, 2011). The result was the introduction of Water User Associations (WUAs) as the main water management organization at the local level. The reform processes created high levels of institutional uncertainty due to e.g. unclear position of WUAs at the different institutional levels. Through mismatch between sectors, e.g. the water and agricultural sectors, or between different levels, e.g. the regional and local, has contributed to high inefficiencies in water use and low agricultural productivity (along with the problems of soil salinization and deteriorating irrigation infrastructure).

While politically, especially in land and water management, the region has gone through far-reaching changes, in terms of the approach to water management, the situation has not changed significantly (UNECE/UNESCAP, 2004). The riverine countries of Amudarya started to develop independently their own water and energy management regimes, which led to a deterioration of common infrastructure, particularly for monitoring, as well as for the coordination of water use and monitoring. The lack of cooperation and coordination in the river basin manifests itself in the poor quality of runoff forecasts, but also in increasing conflicts over water use for irrigation versus hydropower. At the interstate level, the water division between the states is meanwhile carried out according to the common practice which was developed during existence of the USSR (Olimov and Kamoliddinov 1999, Abdullaev 2001, ICG 2002). Water quotas fixed by Moscow favored the downstream cotton-producers – Uzbekistan, Turkmenistan and Kazakhstan – at the expense of mountainous Kyrgyzstan and Tajikistan. Restrictions were imposed on irrigated agriculture in the latter two to maximize cotton output in their neighbors. Kyrgyzstan and Tajikistan, which have only limited gas and coal deposits, were keen to develop their hydropower potential. This, however, was not compatible with ensuring that sufficient water was available downstream for irrigation during spring and summer, which required that the reservoirs on the Syrdarya and Amudarya were let to fill up in autumn and winter – when electricity demand peaks in Kyrgyzstan and Tajikistan. Some changes have been brought in the existing agreement, as a result of bilateral summits. However, in all these agreements and protocols, the interests of Afghanistan and Aral Sea as equal water consumers are not considered. For instance, Afghanistan is not even included in structure of interstate Council. Apart from this, since independence, each Central Asian country has claimed ownership over water sources located in its territory (Abdullaev 2001). The lack of coherent water management between riverine countries of Amudarya will be further aggravated by increasing water consumption due to population growth and rapid economic development of the countries in the region, combined with declining inflows of water in the near future. Growing, predominantly rural, population demands reliable sources of income, wealth and a secure food supply under changing climatic and socio-political conditions. High population growth rates, especially in areas with arable land, will lead to the increased food demand and will prompt further expansion of irrigated lands, whilst increasing the risk of water scarcity and aggravating the battle for local resources: land, water and electricity.

This contribution refers to three specific effects of global change in the Amudarya River Basin: a) food security and connected changes in the land use pattern, b) so-called hydro-hegemony of riparian countries, i.e. use of available water resources for hydroelectric generation versus demand of down-stream countries for irrigation as well as livelihood loss and c) deterioration of rural living standards.

Discussion: drivers of land use changes

Food security connected to the economic and policy changes

Before independence in 1991, the Central Asian Republics were economically interdependent on each other and on the Soviet Union. The production of food and agricultural commodities were mainly organized through a central planning process, so-called economy of disorganization characterized by specificity of inputs and the breakdown of traditional domestic supply linkages. By that is meant that each republic of Soviet Union has to supply their agricultural production to the entire union's fund. Agriculture of Soviet Union was built on benefits of combination, composition of individual sectors, linked together by the fact that one sector uses waste of another; one culture in the crop rotation to increases the yield of the other. Therefore, to fully understand the geography of Soviet agriculture one has to consider specific combination of sectors in certain areas of agricultural specialization. Thus, entire USSR was divided into 9 zones.

The northernmost area, approximately coinciding with the tundra was a zone of reindeer production, sealing and fur farming. This zone lied entirely outside of agriculture. The main economic task of districts appearing in this zone was reindeer herding area.

The following zone is timber industry area, where main economic task was silviculture (timber trade). Agriculture in this zone due to forest dominance had consumer character, serving timber harvesting by food and fodder.

Further to the south stretched extensive third zone of flax, dairy and oil production. Areas entering into this zone specialized, mainly, on flax, giving together nearby 9/10 from its general production. The combination of branches in this zone is not incidental and based on reduction of shortcomings. Thus, flax exhausts soil very strongly; specialized farms are interested in occupying with flax most part of a cropland area. For this purpose plentiful manure fertilizer which gives by cattle breeding is necessary. Beside of this, introduction of sowed grasses in a crop rotation, which better prepare soil for flax cultivation and restore its fertility after flax.

The fourth zone was characterized by dairy farming and production of vegetables and potato. The zone was consisted from districts of suburban economy supplying industrial centers (Leningrad, Moscow, Ural Mountains).

Within Caucasus owing to sharp distinction of soil and environmental conditions, created by a mountain relief, division into districts had rather fractional character. Northern foothills specialized on a number of technical southern cultures. In Transcaucasia the strip of humid subtropics is allocated as unique area of tea, wine cultivation as well as farming of subtropical crops e.g. oranges, mandarins. On the other hand, low and hot, but dry parts have basis for irrigation culture of cotton and rubber-bearing plants. Areas of average foothills specialized on fruits and grapes; areas high-mountainous — on the Alpine cattle breeding, dairy farming, meat and wool production.

Beginning from dry steppes of Kalmyk autonomous region through the Aral-Caspian lowland to the borders of Kazakhstan and Central Asia spread zone of deserts and pastures and mountain and cattle breeding. The greatest district of this zone is district of meat and wool production. In this area in the west in a flood plain of the Lower Volga interspersed the area of vegetables, fruits and cotton production. South of meat and wool production district, in oases of the Central Asian republics located basic cotton area USSR.

Along southern border with Afghanistan and China on high-mountainous ridges from Pamir and Tjan-Shan up to Baikal was the zone of mountain cattle breeding with the specialization on meat, cheese and wool production.

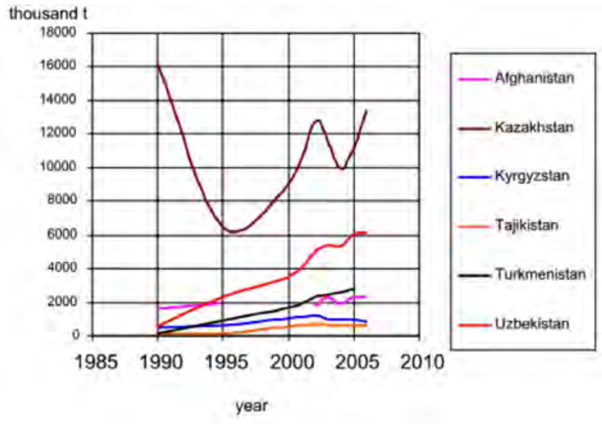
As seen from the description above, in the vast territory of USSR areas with predominance of grain, flax, cotton, cattle farming were developed depending on natural and economic conditions. Thus, specialization and location essentially reflect the same process of division of labour in agriculture. In terms of e.g. grain crops, some countries were net exporters (for example, Kazakhstan) and some countries such as Tajikistan were net importers (Babu, 2001, Brown and Belkindas, 1993).

Following independence and the breakup of the existing trading arrangements, the Central Asian Countries decided for food self-sufficiency in both food production and food security through a combination of own production and regional trade. After the collapse of the interregional trade, each country chose to produce only the amount of grain needed by its population, the so-called grain (wheat) independence. For countries that were previously net importers, that has meant increased domestic grain production accompanied by increased market prices and farming of grain crops in marginal lands. For countries that were previously net exporters, that has meant reductions in grain production and net decreases in prices and national export revenues from food production activities (Babu, 2001).

Production of major agricultural product ensuring minimal food security, i.e. of wheat in the region's countries strongly depends on available croplands. In this context, there are different conditions in the Amudarya river basin region's countries: Uzbekistan and Turkmenistan possessing enough irrigation area could organize production for a sufficient amount of cereals for their people during a short period of time. Difficulties with production of sufficient cereals remain in Kyrgyzstan and Tajikistan, which have the lowest unit irrigation area per capita in the region (Figure 2) (Yokubzod, 2008).

Thus, for example, in Uzbekistan, after the independence from the Soviet Union, a major goal of the agrarian reform was to "overcome the raw-material orientation of the republic through structural changes in the economy, and achieving energy and grain independence of the country" to ensure food self-sufficiency. As a result of it Uzbekistan officially attained grain independence, and since 2003 it even exports grain abroad in contrast to an import of 80% of grain during Soviet times. In many cases, grain self-sufficiency

Figure 2. Wheat Production in Central Asian Countries (Source: Yokubzod, 2008)



has been achieved through the conversion of crop area under cotton. It should be noted that the reduction of the cultivated area and total production of cotton by 10% led to a reduction of cotton production by 20-27 %. The negative impact of this policy was the loss of export earnings of the state, and a reduction of incomes of agricultural producers.

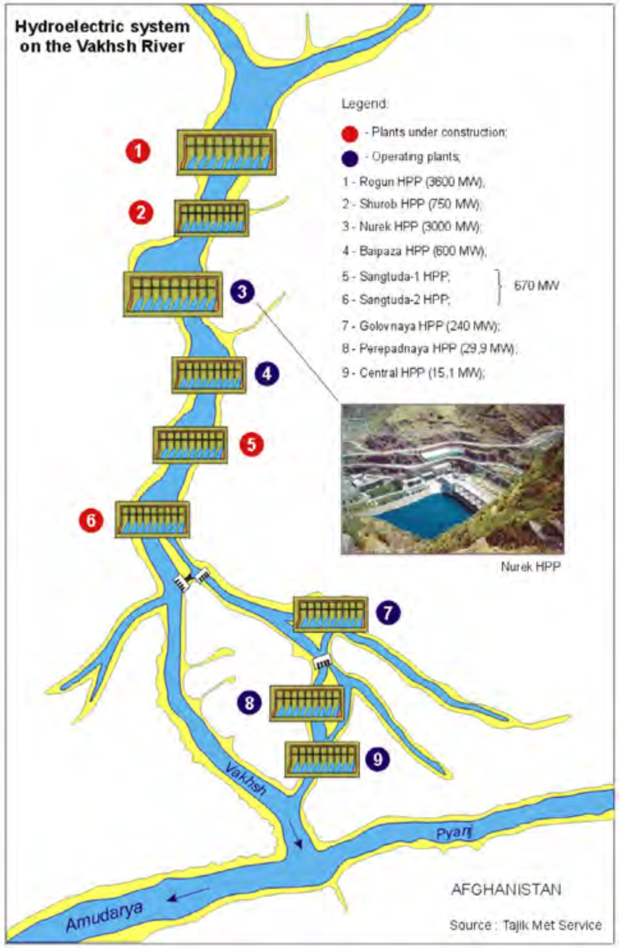
Besides this, wheat cultivation takes place mainly at the expense of alfalfa (Vlek at al., 2001). Originally, cotton was grown in rotation with alfalfa; three years of alfalfa followed by five or six years of cotton, which already leads to marginal and hardly sustainable soil management (FAO, 2009). The removal of alfalfa out of crop rotation has two major reasons: drastic reduction of winter wheat yield, which is strategically important crop (Baraev et al., 2007) and limited availability of cropping land. This change in land use has led to severe land degradation because the soil conservation effect of alfa-alfa rotations is missing. Today, wheat crops promote increased erosion, and due to the constant ploughing and fertilizing, soil exhaustion. Kyrgyzstan has already realized this necessity and is increasing the area under alfalfa. In Uzbekistan the trend is/goes to use fodder crops as double cropping after the wheat harvest but new zero-tillage technologies should be developed for this purpose (Suleimeinov and Oram, 2000). Increasing the area under alfalfa will improve soil fertility and provide better quality forage for livestock.

In the South-Eastern parts of Central Asia, more than 25% of the arable lands in the mountainous regions have slopes of more than 30%. Sloping lands are affected by a loss of soil fertility due to erosion, moisture deficits, run-off gullies, irrigation induced-erosion, and inadequate vegetative surface cover. There are indications that overgrazing together with relatively large geological movements of the soil in this highly motive region may lead to more heavy disruption of the vegetative cover (Reynolds et al. 2007b). Wind erosion is especially prevalent in areas where the climate is relatively dry with strong winds during cold periods. Soils in dry mountain steppes and semi-desert zones are naturally saline. Farmers have to switch to low-input subsistence agriculture and expand their fields to steep slopes. In the highlands of Kyrgyzstan and Tajikistan, at an altitude above 2000 m, potato represents the predominant crop contributing to more than 90% of household income (Pawlosky and Carli 2008). The change of land-use in this inherently fragile and dry mountain environment is resulting in severe land degradation (such as soil fertility mining, soil erosion, landslides, and loss of biodiversity), rangeland degradation due to overgrazing around villages, winter pastures, and deterioration of the unique mountain ecosystem ICARDA CAC Program, 2009).

Climate change and growing hydro-hegemony within the Amudarya river basin

The destruction of economic and trust relationships between the former Soviet Republics of Central Asia led to a widespread drop in production, reducing production of fuel resources. Streamlined operation of reservoirs and supply systems of energy resources began to falter. Central Asian states were faced with issues of water-resource -sharing in the region, which used to be managed from a single center in the past. Changes in economic and political situation in the region have caused sovereign states to use water resources,

Figure 3. Hydroelectric system on Vakhsh River (Source: http://enrin.grida.no/htmls/tadjik/vitalgraphics/eng/html/u27.htm)



primarily in their own national interests at the cost of riparian states sharing the river basin.

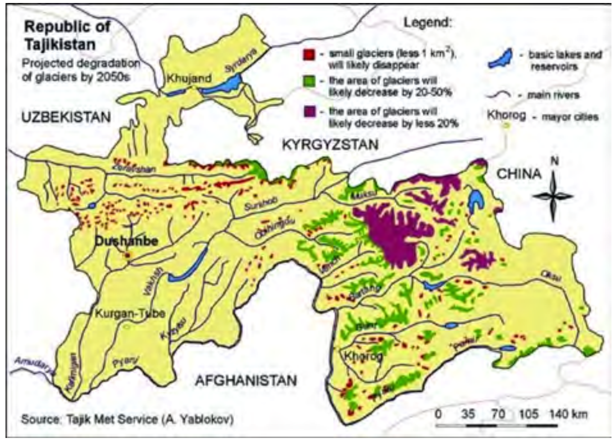
Tajikistan and Kyrgyzstan, being the territories from where more than 80% of the water that ultimately flows into the Aral Sea originates, are more interested in using the available water resources for hydroelectric generation. Whereas countries further downstream, such as Kazakhstan, Turkmenistan and Uzbekistan, demand those resources for irrigation. Upstream countries have an interest in discharging maximum volumes of water in winter time when power shortages occur, while downstream countries need an optimal discharge in summer for irrigation.

Tajikistan is planning to restart the construction of the Rogun Reservoir (3,600 MW), 100 km northeast of the Tajik capital, which was started already during the Soviet period but was suspended during the Tajik civil war, and the Sangtuda dam (670MW) in the Vakhsh Basin (Figure 3).

The Uzbek Government is very critical of the Rogun Dam because it would 'put Tajikistan firmly in control of the river.' Experts in the region discuss that international financial institutions would not support these plans of constriction unless Tajikistan's neighbours would agree.

The lack of agreement from Uzbekistan let Tajikistan to seek financial support for the infrastructure construction from Iran and Russia. Parts of the investment are earmarked for the completion of the hydroelectric projects in the Vaksh Valley. The construction of the Rogun Dam will allow Tajikistan to have/gain high control over the flow of the Vakhsh River, and therefore might put Tajikistan into a similar position as Kyrgyzstan, that is already demanding cost-sharing for her reservoirs power balance from the downstream riparian states Kazakhstan and Uzbekistan. Kyrgyzstan regularly raises the issue on optimization of water use in the Central Asian region. The essence of their proposals is as follows: Since resources are shared, Uzbekistan,

Figure 4. Projected degradation of glaciers by 2050 (Source: Yablokov, 2006)



Kazakhstan and Turkmenistan on certain degree have to share maintenance costs of power structures within their regional neighbours. Uzbekistan, Kazakhstan and Turkmenistan, in their turn, refer to the fact that power facilities in Kyrgyzstan and Tajikistan were built in Soviet times and they have contributed their shares already and there is no need to talk about annual payments.

Moreover, over the past decade (2000-2010), the glaciers in Tajikistan lost a third of their volume, while the population has increased many times over. According to the observations of scientists, these phenomena show a sustained trend lead to a significant reduction in runoff of the river in medium-long term (Figure 4).

Considering intensive development of economies of the region, which will lead by 2030 to increased water consumption by at least 15-20%, the trend towards a reduced runoff is certainly a serious concern. An alternative to the glaciers as natural water freshwater storage is active storage capacity of water reservoirs for multiannual

Figure 5. Main water consumers in the Amudarya River Basin, %
(Source: Fröbrich et al., 2006)

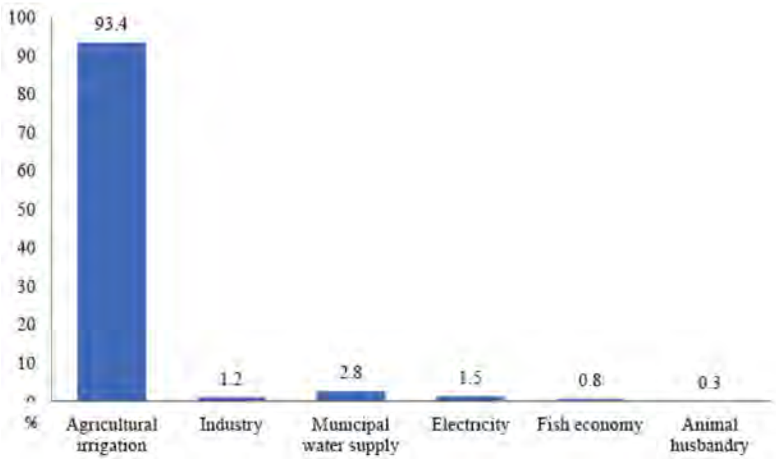
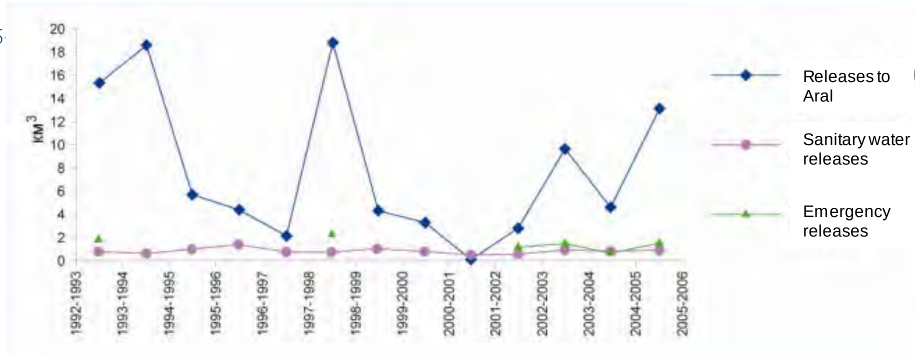


Figure 6. Satisfaction of water needs in Aral Sea and environmental flows in 1995-2005 (Source: BVO 2006)



regulation. If the Syrdarya River's flow is regulated by 95% and available water resources along the river greatly exceed its annual natural runoff, the Amudarya River's flow regulation amounts to only 35%. This indicates the great development potential for the basin countries, preconditioned a construction of an adequate total volume of reservoirs in mountain canyons (Figure 5).

Demographic pressure and mounting poverty due to loss of livelihoods and deterioration of living standards

Water is a basic resource for agriculture, which is traditionally the largest source of livelihoods. If this livelihood is no longer available, people are often forced to search for job opportunities in the cities or turn to other, often illicit, ways to make a living. Migration—induced by lack of water, sudden droughts and floods, infrastructure construction (dams), pollution disasters, or livelihood loss—can produce tensions between local and incoming communities, especially when it increases pressure on already scarce resources (Carius et al., 2005).

Linked to change in land use (wheat instead of alfalfa) described in the section "food security" of this paper, the effect from lacking alfalfa rotations lead to decrease in forage for livestock, which caused a reduction in livestock numbers. As a result of it, the rural population lost income, as well as livelihood and pastures were increasingly overused. Apart from that, changes in the climate, mentioned in the section "Climate change and growing hydro-hegemony within the Amudarya river basin" above, will not only have an impact on water, land, and forest resources and on biodiversity, but also on human health and the condition of livestock in terms of animal health, nutrition, husbandry and fodder availability.

The bulk of cattle in the Amudarya river countries, are kept high proportion by very small household farms. Livestock production in these farms plays a significant social role as it constitutes the main asset for the livelihoods of rural communities.

Deteriorating environmental conditions, combined with recurring drought, have resulted in agricultural and fisheries production declining by as much as 50%, equivalent to an economic disaster for almost 3 million people (including those in areas of Turkmenistan and Kazakhstan near the Aral Sea), whose main source of income was agriculture. The aggregate losses in Uzbekistan associated with mass migration from provinces near the Aral Sea between 1970 and 2001, are estimated to be above US$20 million. Many people still living in the high-migration areas, suffer protein and vitamin deficiencies resulting from malnutrition and extreme poverty. In addition, as the migrants have generally been young the birth rate has decreased significantly.

The livelihoods of this population, especially in the river delta, strongly depend on the provision of ecosystem goods and services from its semi-natural ecosystems. The importance of the deltaic wetlands as an additional income source has even increased after the retreat of the Aral Sea as well as the socio-economic changes following the independence of the riparian nations from the former Soviet Union. One of the serious consequences of the Aral disaster is the loss of the largest fisheries of the country, provides 20 tons of fish per year. Re-orientation of fishing from the sea to lake systems of Aral Sea could not hold a steady fall in fish production in the region. Therefore, fisheries shifted to pond fish production and use of all, for this purpose suitable reservoirs, primarily Aydar-Arnasai lake system. Due to this change fish production and fishery redistributed their roles. A significant decline in fish production (in 51%) happened in 1992 - 1995 due to economic difficulties. The role of deltaic wetlands has become very evident during a severe drought in the years 2000/2001, when water deliveries to the northern delta were reduced to 18% of the mean (Figure 6). The most devastating loss in the history of fisheries in Aral Sea was observed in 2003, when volume of fish production has decreased to 131.6 ton.

Conclusions

To conclude, over the above mentioned three topics recommendations could include the following.

Food Security Connected to the Economic and Policy Changes: Continuing the food self-sufficiency policy will result in further deterioration of the natural resource base and food insecurity. The continued misuse of natural resources will also in its turn reduces productivity and farm incomes and increase rural poverty. Therefore, more emphasis should be put on sustainable land use practices land management (indigenous and introduced), such as traditional agro forestry, fencing with stones/trees, reclamation of steep hills for orchards, crop rotation, nursery development as well as establishment of agro service and consulting centers (extension services) to support farmers.

Climate Change and Growing Hydro-Hegemony within the Amudarya River Basin: Since the independence of the Central Asian states, their interaction in regard to politics of water has been dynamic, presenting simultaneously cooperative and controversial tendencies. Instead of forming a strong union, the states are today yearning to break free from the regional interdependencies. However, the development of the societies, the state of the environment and regional stability stay at risk in Central Asia as long as the states are not capable of moving away from quarrelling about water allocations and towards sharing benefits beyond the river. Interstate water management in Central Asia has been constrained for major reasons such as the lack of financial, technical, organizational and professional capacities, lack of effective control and sanctions' mechanism, the lack of political will for cooperation and the willingness to compromise external apportioning of blame instead of internal reforms. As water issues and water-energy linkages will likely remain high on the political agendas of the states, the coming years will show whether they will be able to cooperate on developing common water policy in the future.

Demographic Pressure and Mounting Poverty Due to Loss of Livelihoods and Deterioration of Living Standards: Economic and demographic trends have a critical influence on natural resources use-poverty linkages. Rural poverty is closely linked with unsustainable land use leading to a decrease in soil fertility and loss of productive capacity of land. Peasant's welfare could be raised through improved management of land and natural resources. However, this requires often more material and financial resources. Abolishment of state subsidies to agriculture after the collapse of the Soviet Union, poor material and technical base of households and individual farms as well as growth of rural poverty led to that fact that population got fewer possibilities to implement sustainable practices of economic activities. As result, unsustainable agricultural practices have led to land degradation as well as lower agricultural production and, consequently, contributed to the mounting poverty of the rural population. Increased deterioration of natural resources requires adoption of immediate steps. In this case, besides an introduction of new technologies for recovery and sustainable maintenance of soil fertility, retrieval and dissemination of traditional skills and knowledge, which for centuries helped to keep the land from degradation, are essential. Apart of this, search for suitable alternative income generation for the rural population could be an option. Increased income for farmers will lead to growing demand for services in the villages and, thereby, to natural formation of a better labour market.

References

» Abdullaev, I., 2001. "Preventing Conflicts through Water Management in Central Asia " Beyond Transition The Newsletter About Reforming Economies Juli-August-September 2001: 28-29.

» Babu, S.C. and Tashmatov, A., 1999. Attaining food security in Central Asia — emerging issues and challenges for policy research. Food Policy 24 4, pp. 357–362

» Babu, S., P. Pinstrup-Andersen, 2000. Achieving food security in Central Asia — current challenges and policy research needs Food Policy 25(6): 629-635

» Babu, S., 2001. Food Security in Central Asia: Economic Opportunities, Policy Constraints, and Future Challenges. Keynote paper prepared for the UNCTAD Regional Workshop on "Food Security and Agricultural Diversification in Central Asia." Almaty, Kazakhstan, 12-13 November 2001.

» Baraev, F., A. Sherov, K. Isabaev, A. Baraev, S. Kasymbetova, 2007. Improvement of ecologic state of cropland based on introduction of bio-artificial drainage systems. Central Asian International Scientific-Practical Conference dedicated to 15th Anniversary of ICWC , 24-27 April 2007 Almaty, the Republic of Kazakhstan

» Brown, Stuart S. and Misha V. Belkindas, 1993. Who's Feeding Whom? An Analysis of Soviet Interrepublic Trade. In The Former Soviet Union in Transition, edited by Richard F. Kaufman and John P. Hardt. New York: M.E. Sharpe.

» Carius,A., G. Dabelko, A. Wolf, 2005. Water Conflict and Cooperation. United Nations Policy Briefing

» FAO, 2009. Conservation agriculture in Uzbekistan. Fao Crop and Grassland Service Working Paper 2: 1-38.

» Gupta, R., K. Kienzler, C. Martius, A. Mirzabaev, T. Oweis, E. de Pauw, M. Qadir, K. Shideed, R. Sommer, R. Thomas, K. Sayre, C. Carli, A. Saparov, M. Bekenov, S. Sanginov, M. Nepesov, and R. Ikramov, 2009. Research Prospectus: A Vision for Sustainable Land Management Research in Central Asia. ICARDA Central Asia and Caucasus Program. Sustainable Agriculture in Central Asia and the Caucasus Series No.1. CGIAR-PFU, Tashkent, Uzbekistan. 84 pages.

» ICG, 2002. Central Asia: Water and Conflict. Asia Report. Osh/ Brussels, International Crisis Group (ICG): 1-45.

» Khudaiberganov, Yu, 2007. Particular characteristics of integrated water resources management (IWRM) in the Amudarya River Basin. Implementing Integrated Water Resources Management in Central Asia NATO Science Series, 77 (2): 35-43

» Naygaard, D., C. Hendriks, D. Dzhumakhonov, 2005. Strategies of development and food security in mountain regions of Central Asia. Document 1: Use of possibilities for development and food security support in the mountain regions of Central Asia (in Russian).International seminar 2005, 06.06.-10.06. 2005, Dushanbe, Tajikistan

» Olimov, M. and A. Kamoliddinov, 1999. Regional cooperation on use of water and energy resources in Central Asia (in Russian). Central Asia and the Caucasus 2(3): 3-15

» Pawlosky, I. and C. Carli, 2008. Enhancing individual incomes and improving living standards in Khatlon and Sughd Regions, Tajikistan. EuropeAid/126-844/L/ACT/TJ.

» Pomfret, R., 2000. Agrarian reform in Uzbekistan: Why has the Chinese model failed to deliver? Economic Development and Cultural Change 48: 269-284

» Reynolds, J.F., D.M. Stafford Smith, E.F. Lambin, B.L. Turner, M. Mortimore, S.P.J. Batterbury, T.E. Downing, H. Dowlatabadi, R.J. Fernández, J.E. Herrick, E. Huber- Sannwald, H. Jiang, R. Roessner, and S.H.U. Wetzel, 2007. Tektonisch und klimatisch bedingte Massenbewegungen in Kirgizstan – Naturgefahren mit hohem Risikopotential. Presentation, Deutscher Geographentag 2007, 29.9.-5.10.2007, Bayreuth, Germany.

» Schlüter, M., E. Herrfahrdt-Pähle, 2011. Exploring Resilience and Transformability of a River Basin in the Face of Socioeconomic and Ecological Crisis: an Example from the Amudarya River Basin, Central Asia Ecology and Society 16(1): 32

» Spoor, M., 1998. Upheaval along the Silk Route: the dynamics of economic transition in Central Asia. Journal of International Development 9 (4): 579–587.

» Suleimenov, M. , P. Oram, 2000. Trends in feed, livestock production, and rangelands during the transition period in three Central Asian countries. Food Policy 25 (2000) 681–700

» Trevisani T., 2008. Land and power in Khorezm. Farmers, communities and the state in Uzbekistan's decollectivisation process. Institut für Ethnologie, Politik- und Sozialwissenschaften, Berlin, ZEF Bonn / Freie Universität Berlin. 300p.

» UNECE/UNESCAP, 2004. Diagnostic report on water resources in Central Asia, Download at, http://www.unece.org/speca/energy/energ_he.htm.

» Vlek, P. C.Martius, P. Wehrheim, A. Schoeller-Schletter, J. Lamers, 2001. Economic Restructuring of Land and Water Use in the Region Khorezm (Uzbekistan) (Project Proposal for Phase I) ZEF Work Papers for Sustainable Development in Central Asia 1: 1-75

» Wehrheim, P. and C. Martius, 2008. Farmers, Cotton, Water and Models: Introduction and overview. Pages. 1-16 In: Continuity and change Land and water use reforms in rural Uzbekistan – Socio-economic and legal analyses for the region Khorezm (P. Wehrheim, A. Schoeller-Schletter, and C. Martius eds). Leibniz Institute of Agricultural Development in Central and Eastern Europe (IAMO). Studies on the Agricultural and Food Sector in Central and Eastern Europe, Vol. 43. Download at: http://www.iamo.de/dok/sr_vol43.pdf

» Wilson, R.T., 1997. Livestock, pastures, and the environment in Kyrgyz Republic, Central Asia. Mountain Research and Development 17 1, pp. 57–68

» Yablokov, A., 2006. Climate change impacts on the glaciation in Tajikistan. In: Assessment report for the Second National Communication of the Republic of Tajikistan on climate change. Tajik Met. Service, Dushanbe

» Yalcin, R., and P. P. Mollinga, 2007. Water users associations in Uzbekistan: the introduction of a new institutional arrangement for local water management. Amu Darya case study - Uzbekistan. NeWater project. Zentrum für Entwicklungsforschung (ZEF), Bonn, Germany.

» Yokubzod, S., 2008. Food security and the improvement of water use efficiency Workshop "Socio-Economic Stability and Water Productivity: Food and Water Security in Central Asia" Tashkent, 18-20 March 2008

» Zavgorodnyaya, D., 2006. Water User Associations in Uzbekistan: theory and practices. PhD Dissertation. Cuvillier. Göttingen, Germany. 201pp.

Diverse impacts of climate change on streamflow in Alberta, Canada

Stefan W. Kienzle[1,3], Michael Nemeth[1], Katherine Forbes[2] & James M. Byrne[1]

[1] *Department of Geography, University of Lethbridge, Alberta Water & Environmental Science Building, 4401 University Drive, Lethbridge, Alberta, T1K 3M4, Canada*

[2] *Department of Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta, T2N 1N4, Canada*

[3] *E-mail: stefan.kienzle@uleth.ca*

Abstract

Impacts of climate change on water availability can change over a short distance within central and southern Alberta, Canada, depending on the climate and hydrological dynamics of the watershed. The impacts of climate change were investigated for two distinctly different watersheds. The Beaver Creek watershed is 254 km^2 large, relatively undisturbed, located in the foothills region in south-western Alberta, and has an arid climate with a runoff coefficient of 5%. The Cline River watershed constitutes the headwaters of the upper North Saskatchewan River basin, has a runoff coefficient of 58%, with 8% of the streamflow contributed by glacier melt. The ACRU agro-hydrological modelling system was set up and extensively verified for the 1961-1990 base period. The simulation of climate change impacts was based on predicted precipitation and air temperature changes from five selected GCMs for three future periods, 2010-2039, 2040-2069, and 2070-2099. Results revealed a shift in the hydrological regime to higher streamflows in winter and spring with a subsequent decline in summer and fall. While the Beaver Creek watershed had relatively stable water yields in the future, the Cline River watershed exhibited an increase due to increased precipitation.

Keywords

watershed simulation, climate change impacts, hydrological cycle, water resources

Introduction

Unknown regional impacts of climate change increase the typical uncertainties of future water availability associated with normal climate variability. The availability of water resources in the province of Alberta is of concern due to growing water demands by agriculture, industry, and a rapidly increasing population. Therefore, the understanding of predicted climate change on the hydrological cycle within a watershed and its subsequent hydrological regime is essential for future water resources planning.

Trends in historical climate records indicate that, over the 20th century, the Canadian Prairies experienced an increasingly warmer and, to a lesser extent, drier climate (Gan, 1998). Modelled projections of the future climate in the Canadian Prairie Provinces indicate that the mean annual air temperature may further increase between 4°C and 5°C by 2050, relative to conditions of the 1961-1990 period (Wheaton, 2001). For the entire province of Alberta, mean annual air temperature is projected to increase between 3 and 5°C by the 2050s (Barrow and Yu, 2005).

The projected future changes in precipitation in the Prairie region are variable, similar to projections at the global scale (IPCC, 2007). In Alberta, mean annual changes in future precipitation are expected to be between -10% and +15% (Barrow and Yu, 2005). In hybrid watersheds both snowmelt and rainfall events occur, and consequently the watershed behaviour is dominated by contrasting hydrological processes, and may respond uniquely to changes of the future climate (Loukas and Quick, 1996; Whitfield et al., 2003).

The hydrological response to climate change has been studied through the application of watershed-scale hydrological models driven by GCM-derived scenarios of future climate (e.g. Loukas et al., 2002; Schulze and Perks, 2003; Toth et al., 2006; Nurmohamed et al., 2007). Physically-based, spatially distributed hydrological models are an effective means to assess the impacts of climate change on hydrological response, as they are able to capture the spatial variability of hydrological processes throughout complex watersheds (Bathurst et al., 2004). The ACRU agro-hydrological modelling system (Schulze, 1995, updated; Smithers and Schulze, 1995) was applied in this study as it is a physical-conceptual, distributed hydrological modelling system designed to be responsive to changes in land use and climate.

Objectives

This research focused on quantifying the impacts of climate change on the hydrology of two distinctly different watersheds. The objective of this research was to quantify climate change impacts by setting up a physically-based hydrological model for the baseline period (1961-1990), verifying simulated output against a range of observed hydro-climatological data, and then simulating the hydrological behaviour of the two watersheds for a range of GCM-derived scenarios for the future periods 2010-2039, 2040-2069, and 2070-2099.

Study areas

The Beaver Creek watershed (BCW) has an area of 254 km^2, is relatively undisturbed, and located in the foothills region of south-western Alberta, Canada (Figure 1). Elevations range from 1100 m to 1500 m, with a mean annual precipitation (MAP) of 460 mm (1961-1990), of which 218 mm falls as snow, and with a mean annual potential evapotranspiration (PET) of 959 mm. The BCW is characterized by the transition from montane forest to aspen parkland and prairie grasslands.

In contrast, the Cline River watershed (CRW) has an area of 3,856 km2 and consists of alpine, subalpine, and foothills landscapes located on the eastern slopes of Alberta's Rocky Mountains. Elevations range from 1300 m to just under 3500 m at the continental divide. The MAP of the CRW is 1002 mm (1961-1990), ranging from 1408 mm in the upper reaches to 510 mm at the outlet. About 8% of the mean annual streamflow is produced by glacier melt, and about 60% is produced by snow melt. The CRW is an important head watershed feeding the North Saskatchewan River and contains the largest hydro power reservoir in Alberta (Figure 2).

The ACRU model

The ACRU agro-hydrological modelling system has been developed at the School of Bioresources Engineering and Environmental Hydrology (formerly the Department of Agricultural Engineering) at the University of KwaZulu-Natal, Pietermatitzburg, Republic of South Africa, since the late 1970s. ACRU is a multi-purpose, multi-level, physical-conceptual model that can simulate total evaporation, soil water and reservoir storages, land cover and abstraction impacts, snow water dynamics and streamflow at a daily time step (Figure 2). The ACRU model revolves around multi-layer soil water budgeting with specific variables governing the atmosphere-plant-soil water interfaces. Surface runoff and infiltration are simulated using a modified SCS equation, where the daily runoff depth is proportional to the antecedent soil moisture content. The ACRU model is further described by Schulze (1995), Smithers and Schulze (1995), and Kiker et al. (2006).

Recent improvements, conducted at the University of Lethbridge, Alberta, Canada, include the estimation of daily mean air temperature for each hydrological response unit as a function of GIS derived radiation input and land cover, allowing for different daily air temperatures in areas with diverse aspect and shading. ACRU contains dynamic snow routines, where precipitation is separated into rain and snow based on daily air temperature (Kienzle, 2008), and

Figure 1. The Beaver Creek Watershed

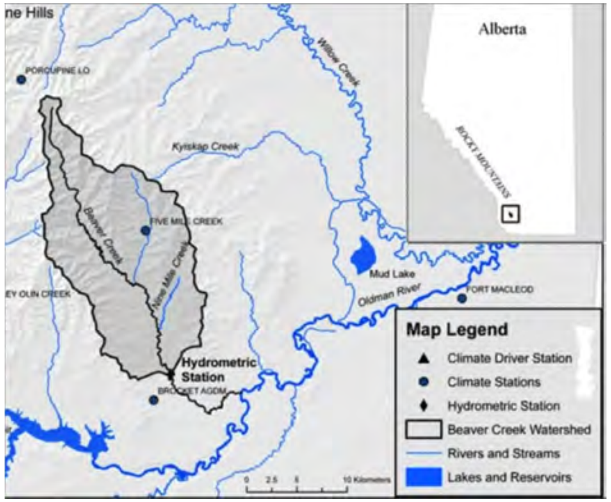


Figure 2. The Cline River Watershed

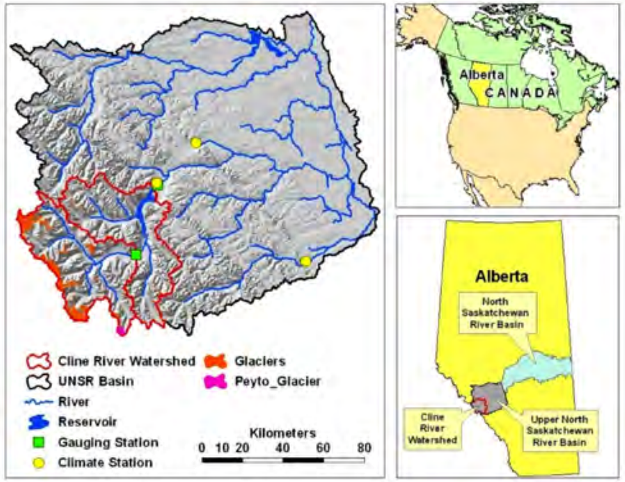
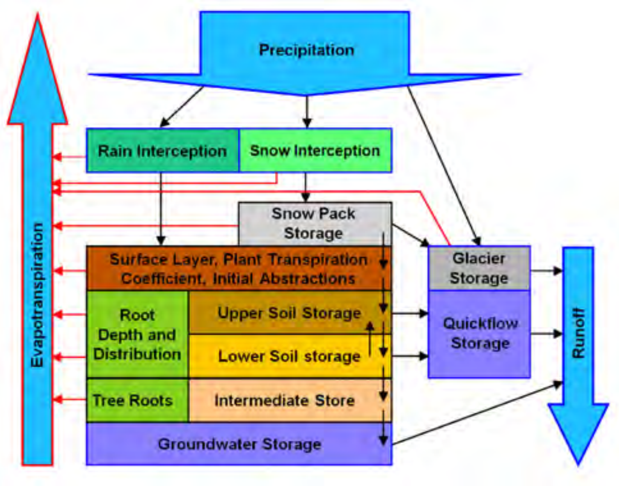


Figure 2. Key elements of the ACRU agro-hydrological modeling system



the snow melt is derived dynamically as a function of net radiation and albedo (Kienzle, 2010). For this study, the authors have added a simple glacier routine, which contains a dynamic glacier melt function and a routine where both glacier depth and glacier area change as a function of glacier mass balance.

Verification analyses

Simulation results for the 1961-1990 baseline period were verified against streamflow time series in the BCW, and available observed key elements of the hydrological cycle, including air temperature, snow pack, glacier melt, potential evapotranspiration, and streamflow in the CRW. The comparison of simulated against observed streamflow in the BCW and CRW revealed a coefficient of determination for daily (CRW: r^2 of 0.82) and monthly (r^2 of 0.78 and 0.91) streamflows respectively (Forbes et al., 2010). The differences between simulated and observed streamflow variance were 2.1 and 3.9% respectively, indicating realistic simulations of peak and low flows. ACRU simulated the mean annual hydrograph reasonably well in the BCW, and very well in the CRW, and in both cases the shapes of the hydrographs very well. The annual water yields of the two watersheds were replicated for the verification periods with a mean overestimation of 3.5 and 2.6%, respectively. The Nash-Sutcliff coefficient of efficiency was 0.80 for daily and 0.91 for CRW monthly streamflow simulations (0.77 for the BCW), indicating a strong association between observed and simulated values (Nemeth et al., 2010).

Within the larger, 20,000 km^2, upper North Saskatchewan River watershed, which contains the CRW, additional verification analyses were carried out. Air temperatures, observed at 18 fire observation towers were well simulated across the UNSRB, with an average overestimation of 0.37°C, and excellent representation of seasonality. Taking into account the difficulties of representative snow measurements within a watershed, snow water equivalent (SWE) was reasonably well simulated using snow pack time series, with a total of 8507 daily observations (r^2 of 0.63, under-estimation by 6.1%, and difference in variance of 4.0%). PET was simulated to range from about 500 mm to about 1000 mm and compared both spatially and in magnitudes very well against available from the Hydrological Atlas of Canada (1978). The seasonality of PET was validated against a total of 100 months (May to October) of observations at three A-pan stations in the vicinity of the watershed (r^2 of 0.78, difference in variance of 2.5%, slope of the regression line 0.87).

Based on the verification analyses it was determined that ACRU was representing the 1961-90 baseline period correctly in terms of spatial and temporal hydro-climatological behaviour of the watersheds. Most importantly, the verification analyses revealed that streamflow was simulated for the right reasons, as for the CRW all verified hydrological elements could be confirmed by comparing the results against independent observed datasets (Nemeth et al., 2010). This provided the fundamental conditions to allow the consequent estimation of impacts of climate change in the two watersheds.

Global climate model scenarios

Climate change scenarios were downloaded from the Pacific Climate Impacts Consortium (PCIC). Three future time series were assessed: 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). The observed daily climate time series for 1961-90 was used as the baseline period. IPCC (2007) recommended using more than one GCM in impact assessments to demonstrate how a range of air temperature and precipitation changes may affect a given region. In order to provide sensitivity analyses of predicted climate change impacts on streamflow, five scenarios were selected using the method developed by Barrow & Yu (2005). These scenarios were chosen from the 41 climate scenarios provided by PCIC containing both air temperature and precipitation predictions. Following Barrow & Yu (2005), the climate scenario selection was based on mean air temperature change and percent precipitation change for the 2050 spring (March – April - May) time period. Figure 3 presents the selection method presenting data for the CRW. The selection of GCM scenarios is based on the creation of four quadrants separated by the median air temperature change (here: +1.75°C) and the median precipitation changes (here: +12.0%). Five scenarios from GCM output were selected based on their projection of the range of possible future climates: for the BCW hotter-drier, hotter-wetter, median, warmer-drier, warmer-wetter, and for the CRW hotter-wetter, warmer-wetter, median, hotter-wettest, and warmer-wettest (Figure 3). Rather than using just one climate scenario, these five scenarios were needed to provide a representation of the range of predicted possible future climates in the respective study area, thus enabling the simulation of future streamflow scenarios without prejudice.

Due to the large size of the GCM climate grid cells of 400 by 400 km, the GCM output needed to be downscaled to a regional climate to evaluate climate change impacts at a watershed scale. To con-

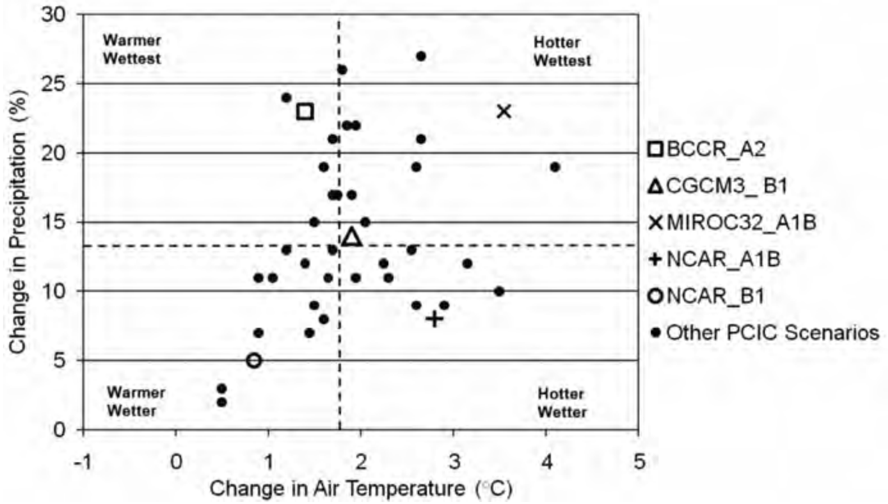


Figure 3. Selection of five GCM scenarios

Table 1. Mean annual water balance components for the Beaver Creek watershed (all values in mm).

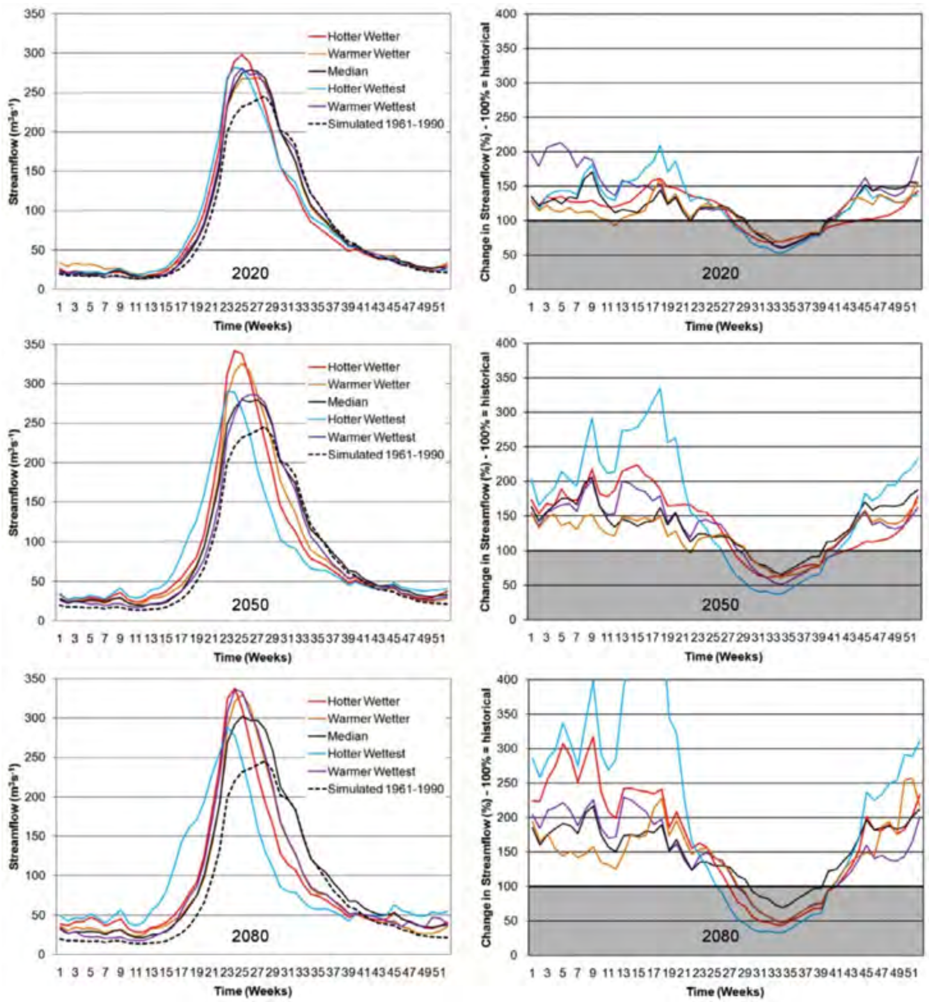
	Period	Rain	Snow	Total P	PET	AET	Q
Baseline	1961-90	218	242	460	959	431	25
HD		228	207	435	1111	411	20
HW		245	221	466	1106	435	28
MD	2010-39	250	212	462	1089	433	25
WD		245	203	448	1089	422	22
WW		282	212	494	1085	461	29
HD		252	207	459	1156	430	26
HW		242	218	460	1180	423	34
MD	2040-69	266	202	468	1141	440	25
WD		269	198	467	1216	436	28
WW		281	209	490	1106	460	27
HD		240	203	443	1208	415	26
HW		267	220	487	1245	444	40
MD	2070-99	280	195	475	1179	445	28
WD		310	187	497	1302	463	32
WW		303	231	534	1116	493	38

struct regional climate change scenarios based on GCM output, a widely used procedure, the delta method, was applied (Hay et al., 2000). The delta method of downscaling uses projected monthly changes in air temperature and precipitation based on results from each selected scenario (Figure 3) to perturb the observed 1961 to 1990 climate record.

Results

Whilst a wide range of variables and behaviours were analysed (Forbes et al., 2010; Nemeth et al, 2010), only a few key results are reported here. For the BCW, the mean annual simulation results are summarized in Table 1. The water balance components (Precipiation = Actual Evapotranspiration + Runoff) do not sum up to 100%, as there are storage changes in the watershed for groundwater, soil moisture, and snow pack. Annual precipitation volume increased in the majority of scenarios, except those scenarios which projected a decrease in annual precipitation (HD in the 2020s and 2080s scenarios, WD in the 2020 scenario). In all scenarios, a greater volume of the rainfall was simulated, while concurrently snowfall was simulated to be reduced The proportion of snowfall to total precipitation decreases from the historical (1961-1990) 48.9% to an average of 41.7% for 2010-2039, an average of 39.8% for 2040-2069, and an average of 38.1% for 2070-2099. In all scenarios, potential evapotranspiration was simulated to increase above the baseline simulation, which can be attributed to the increase in mean annual air temperatures across the scenarios. In all scenarios, the changes in AET are related to the changes in precipitation (Table 4). This is an interesting result, as it indicates that in this semi-arid, water limited region future changes in AET depend more on precipitation changes than on air temperature changes. In this environment, actual evapotranspiration is limited by available soil moisture rather than atmospheric demand. The simulated changes in mean annual streamflow (Q), relative to the baseline, showed an increase for most simulations. This is due to an increase in precipitation with a concurrent lesser increase in actual evapotranspiration.

Figure 4. Simulated future weekly mean streamflows and percent changes



There is strong shift in seasonality. With a few exceptions, the future streamflow regime is simulated to change towards much increased streamflow in winter, a smaller increase in spring, a decline in summer, and a potentially severe decline in fall.

For the CRW, results are summarized in Figure 4. Peak streamflows are simulated to increase and occur earlier in all five scenarios and all three time periods. Also, starting approximately in Week 40 (early October), and lasting until approximately Week 12 (late March), baseflow is simulated to increase significantly. Of importance is the period between approximately Week 27 (mid July) and Week 39 (late September), when future streamflow is reduced, ranging from between about -25% in the 2020s period to about -33% in the 2080s period. As expected, simulations further in the future result consistently in a wider spread of predicted streamflow behaviour, resulting in increased uncertainties. While PET is simulated to increase from an average of all five scenarios of 11.5% in the 2020s to 27% in the 2080s, AET is projected to increase from 2.5% to 8.5% respectively.

Soil moisture is simulated to very slightly increase (from an average 0.5% in the 2020s to an average of 2.6% in the 2080s). Groundwater recharge is projected to increase from an average of 1.6% in the 2020s to 8.0% in the 2080s, resulting in higher baseflow and increased low flows (Figure 4). Snow water equivalent is simulated to strongly decrease, from an average of -47% in the 2020s to -66% in the 2080s. This results in a shift from a hydrological regime that is snow melt dominated to one that is dominated by stormflows. While mean annual water yields are simulated to increase by 1.1% in the 2020s, ranging from an increase of 3.7% to a decrease of 2%, they are projected to increase by an average of 11.5% in the 2080s, ranging from 7.5% to 17.8%.

Discussion

In the Beaver Creek watershed, water yield was simulated to be quite stable, despite future increases in air temperature. This is explained by the limitation of actual evapotranspiration due to restrictive soil moisture availability. Both watersheds exhibited an increase in precipitation during the winter and spring, and either a decline (BCW) or lesser increase (CRW) in precipitation during the summer and fall. This resulted, in the BCW, in a decrease in soil moisture and subsequent decrease in groundwater recharge, with sunsequently lower baseflow during summer and fall. Whilst groundwater recharge was simulated to be increased in the CRW, it happens also much earlier, with the consequence of being exhausted in the summer and early fall, resulting in a decline in summer and fall streamflows. The BCW, with a runoff coefficient of just 5%, is vulnerable to climate change. In contrast, the CRW has a runoff coefficient of 58% and is predicted to receive increased precipitation, making it more resistant to harmful climate changes. The CRW streamflows are also influenced by the declining glacier melt contributions, as the peak in glacier melt was likely surpassed about a decade ago, and the steadily declining glaciated area and glacier volume will result in a declining glacier melt contribution, until all glaicers have completely melted.

A major problem in simulating climate change is the shortcoming of all GCMs in their current ability to predict changes in terms of frequency (number of days with precipitation) and intensity (amout of rainfall or snowfall on a given day). As most hydrological processes are non-linear, a change in either intensity or frequency (or both) would change elements of the hydrological cycle. For example, a shift towards more frequent, but less intensive, precipitation events would result in increased evapotranspirational losses, drier soils, and less runoff; and vice versa.

Another deficiency of the GCMs applied here is their inability to simulate the impacts of the Pacific Decadal Oscillation (PDO), which has an approximate 60-year cycle and a major influence on the weather in southern Alberta, as do other cycles such as the Arctic Oscillation and the El Nino Southern Oscillation (ENSO). All of these long-term cycles are associated with distinct long- to medium term weather patterns (drier or wetter, warmer or colder) within the study watersheds, which can temporarily (for a year or up to several decades) override the long-term climate change trends. Failure to incorporate these multi-decadal cycles increases the inherent uncertainties associated with global climate models.

Only when future climate models successfully integrate these long-term cycles and include future changes of precipitation intensities and frequencies, we can expect to simulate more reliable future predictions of climate change impacts on watershed behaviour.

References

» Bathurst, J.C., Ewen, J., Parkin, G., O'Connell, P.E., Cooper, J.D., 2004. Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses. Journal of Hydrology, 287 (1-4), 74-94.

» Barrow, E., Yu, G., 2005. Climate Scenarios for Alberta. A Report Prepared for the Prairie Adaptation Research Collaborative (PARC) in co-operation with Alberta Environment. Alberta Environment, Regina, Saskatchewan.

» Forbes, K.A., Kienzle, S.W., Coburn, C.A., Byrne, J.M. and Rasmussen, J., 2010. Modelling the impacts of selected GCM derived climate scenarios on the future hydrology of a hybrid watershed in the Oldman River watershed, Alberta, Canada.

» Gan, T.Y., 1998. Hydroclimatic trends and possible climatic warming in the Canadian Prairies. Water Resources Research, 34(11), 3009–3015.

» Hay, L.E., Wilby, R.L., Leavesley, G.H., 2000. A Comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. Journal of the American Water Resources Association, 36(2), 387-397.

» IPCC (2007) Climate Change, 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

» Kienzle, S.W., 2008. A new temperature based method to separate rain and snow. Hydrological Processes, 22: 5067-5085.

» Kienzle, S.W., 2010. Effects of area under-estimations of sloped mountain terrain on simulated hydrological behaviour. Hydrological Processes.

» Kiker, G.A., Clark, D.J., Martinez, C.J., Schulze, R.E., 2006. A Java-based, object-oriented modeling system for southern African hydrology. Transactions of the ASABE, 49(5): 1419-1433.

» Loukas, A., Quick, M.C,. 1996. Effect of Climate Change on Hydrologic Regime of Two Climatically Different Watersheds. Journal of Hydrologic Engineering, 1 (2), 77-87.

» Loukas, A., Vasiliades, L., Dalezios, N.R., 2002. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. Journal of Hydrology, 259, 163-188.

» Nurmohamed, R., Naipal, S., De Smedt, F., 2007. Modeling hydrological response of the Upper Suiname river basin to climate change. Journal of Spatial Hydrology, 7(1), 1-22.

» Schulze, R.E., 1995. Hydrology and Agrohydrology: a text to accompany the ACRU 3.00 agrohydrological modelling system. Report TT69/95. Water Research Commission, Pretoria, RSA.

» Schulze, R.E., Perks, L.A., 2003. The Potential Threat of Significant Changes to Hydrological Responses in Southern Africa as a Result of Climate Change: A Threshold Analysis on When These Could Occur, and Where the Vulnerable Areas are. In: Schulze, R.E. (Ed.) Modelling as a Tool in Integrated Water Resources Management: Conceptual Issues and Case Study Applications. Water Research Commission, Pretoria, RSA, WRC Report 749/1/02. Chapter 14, 250-258.

» Smithers, J., Schulze, R.E., 1995. ACRU Agrohydrological Modelling System User Manual. WRC Report TT 70/95, Water Research Commission, Pretoria.

» Toth, B., Pietroniro, A., Conly, F.M., Kouwen, N., 2006. Modelling climate change impacts in the Peace and Athabasca catchment and delta: I-hydrological model application. Hydrological Processes, 20, 4197-4214.

» Wheaton, E., 2001. Limited Report. Changing Climates: Exploring Possible Future Climates of the Canadian Prairie Provinces, SRC Publication No. 11341-3E01, Government of Canada.

» Whitfield, P.H., Fraser, D., Cohen, S., 2003. Climate Change Impacts on Water in Georgia Basin / Puget Sound – Special Issue. Canadian Water Resources Journal, 28(4), 523-529.

Physical heterogeneity and socio-economic differences as determinants of change in the Danube basin

Hans-Peter Nachtnebel

Institute for Water Management, Hydrology and Hydraulic Engineering
Department of Water-Atmosphere-Environment

University of Natural Resources and Life Sciences, BOKU, Muthgasse 18, A-1190 Vienna, Austria.

E-mail: hans_peter.nachtnebel@boku.ac.at

Abstract

The objective of this paper is to identify and assess anthropogenic and environmental changes and their impacts on the water system in the Danube basin. Considering the period of the last 25 years, political and subsequent socio-economic changes had substantial impact on the state of water resources and environment. The basin exhibits a large physical heterogeneity, with mountainous headwaters rich in rainfall while in the lowland part hot and dry summers are dominating. Besides the physical gradients there is also a distinct upstream-downstream gradient in socio-economic development. Also the expected regional climate change signals are very likely more pronounced in the lower parts of the basin. These gradients are seen as the key factors for water related changes and the governance regime.

The paper is structured in the following way utilizing the terminology from DPSIR concepts. First, the physical settings in the basin are described with the emphasis on the hydro-meteorological and environmental state of the system. The major driving forces are reflected by socio-economic changes and by expected climate changes. Major impacts on the water resources and the environment originate from water pollution and the hydraulic infrastructure. Water shortage is likely to become more pronounced in several regions of the lower Danube basin. Natural hazards like floods and draughts caused substantial and increasing damages in the last decades although it is difficult to conclude that there is an increasing frequency in natural hazards. Finally, the political changes and the economic response are analyzed together with the modifications of the governance structure during the last twenty years. It can be concluded that economic pressures are dominant and the major drivers are seen in the heterogeneity in the basin and the socio economic gradients

Keywords:
Danube basin, water resources, integrated river basin management, climate change, governance regime

Introduction

In general, larger river basins exhibit clear trends in hydro-meteorological indicators from upstream to downstream. The headwaters are usually located in mountainous regions rich in rainfall. Erosion processes together with landslides along the steep slopes constitute major risk besides torrential floods. The discharge of the main river is quickly increasing downstream, exhibiting a large carrying capacity for sediments. Further downstream the river morphology is characterised by an unstable braiding river section which changes its course after major floods. Along the river extended flood plains covered by forests are found which depend on frequent flooding to maintain their characteristic ecological features. These flood plain forests constitute one of the most productive global ecosystems although annual precipitation is moderate. In the low land parts of the basin annual rainfall is low and the major water resource is the inflow from upstream. The river morphology is driven by sandy sediment transport, a meandering structure of the river and extended sedimentation processes which create large dynamic Delta areas.

With respect to land and water resources utilisation it can be concluded that timber harvesting and animal grazing dominate in the headwater areas. The hydropower potential is quite important and is utilised by both run-of-river and reservoir-type schemes. Navigation does not play anymore an important role. Historically, regional navigation was relevant for the transport of salt, ore, timber, although several obstacles had to be managed because of steep slopes and high flow velocities. Usually, water availability is in excess with excellent water quality.

In the middle part of the basin agriculture becomes more important and industrial complexes together with large agglomerations are found along the main river which provides also acceptable navigation conditions. Due to this fact the cities are historically located closely to the river and are thus exposed to flood risk.

Proceeding downstream to the low land area agriculture is becoming even more important but it has to face lower precipitation amounts with pronounced drought periods. Irrigation schemes are widely developed which are fed via long distance distribution systems from numerous reservoirs and rivers. At the same time, extended swampy areas along meandering rivers and in the delta, which were subjected to major drainage works in the past, accompanied by flood protection measures such as extended dike systems. Floods and droughts constitute the main natural hazards in such regions. The extended flood plains and the huge wetlands exhibit a large bio-diversity and are of high ecological value. As long as they are not separated from the main river by technical structures, they are efficient nutrient traps and contribute substantially to the self-purification capacity of the river system.

Finally, the river discharges its runoff together with all the nutrients and pollutants delivered from the basin and its inhabitants into the sea. The receiving water body and the adjacent coastlines are suffering from reduced inflow of water and high pollution loads.

This general description is a prototype model for several river basins like the Rhine, the Danube, the Nile, The Aral Sea basin, the large Chinese rivers, although local geographical features may modify this scheme.

This scheme also describes the physical gradients from upstream to downstream: decrease of precipitation, decrease in specific runoff, increase in total runoff, change from a gravel bed river to sandy river bed, increase in wetland and flood plain areas, increase in flood risk, increase in irrigated land, increase of the importance of navigation, increase of accumulated pollution.

But there are numerous gradients directed in the opposite direction. Due to the fertile soil and the climatic conditions, downstream countries are usually benefiting from more favourable conditions for agriculture. They export these products upstream. Also navigation is based on a long lasting experience in the downstream part and thus the downstream countries may dominate ship based transport along the whole river. Other natural resources, like and oil and gas, are usually found in the sedimentary basins which are mostly located in low land areas, along the sea coast and at the continental shelf. The efficiency of these opposite gradients depends also on the technological and economic state of the involved states. And this is the pivotal point where economy defines the strength of the gradient. Of course, the technological progress defines the level of economic efficiency, to a large extent the intensity of water management and the level of environmental pollution.

This paper is based on the physically justified hypothesis that gradients determine the intensity of flows, such as water flows but also migration processes, and flows of products. The efficiency in controlling these processes depends on the political and economic system, the cooperation within the basin characterised by the governance regime.

The state of the Danube basin

The state of the Danube basin is described with respect to the physical features of the basin including the main hydro-meteorological indices, then the ecological status is summarised. A description of the economic and political situation completes this chapter. Most of the information can be found in ICPDR (2005, 2009) and in Nachtnebel (2000).

Hydro-climatology of the basin

The Danube river basin includes major parts of South Central and South Eastern Europe with 18 riparian states. The river flows over a distance of 2 857 km and it drains an area of 817 000 square kilometers. The major tributaries to the Danube are also international rivers with several riparian countries (Figure 1).

According to the geomorphologic structure and the longitudinal profile of the Danube the basin can be conveniently divided into three regions (Table 1). Sometimes, the Delta is considered as a separate unit because of its unique ecological value..

Figure 1. The Danube basin with river network and national borders (from ICPDR, 2005)

Table 1. Characteristics of the three main parts of the Danube catchment

(from Stancik and Jovanovic; 1988)

Main parts of the catchment	Gauging station	Stream location	Catchment area	Mean annual discharge	
		(km)	(km²)	(m³/s)	(mm)
Upper basin	Bratislava	1869	131 338	2 020	485
Middle basin	Orsova	955	576 232	5 699	312
Lower basin	Ceatal Ismail	72	817 000?	6 550	256

The annual precipitation in the high Alpine parts and in the Carpathians averages about 2 000 mm. In the plains of the lower Danube, precipitation is only 500-600 mm/year, falling to less than 400 mm/year in the Delta. In some years there is no precipitation over the summer period at all. Evaporation is important for the water balance in the catchments. In lower regions the mean annual evaporation varies between 450 mm and 650 mm. In the highest altitudes values of about 100 mm occur.

Low flows in the upstream part occur in winter time while they are dominant in late summer in the downstream section where they may constitute an obstacle for navigation. It is estimated that the Danube River discharges 25-80 million tons of sediment each year into Black Sea. At the river's mouth, suspended material makes up more than 98% of the total sediment load of the river. Total sediment transport has declined in recent years. Due to the limited monitoring it is difficult to determine the relative influence of hydropower stations and flood regulation reservoir which were implemented since the mid-seventies.

Ecological State of the Danube basin

Major environmental problems have been identified in sub-basins while the main river, the Danube, still exhibits a large self-purification capacity and resilience to local effluents from urban areas. The pollution level in some tributaries basin is critical. However, water quality indicators for the main stem show good result compared to other major rivers in Europe, like the Rhine and the Volga.

Because the Danube River basin has a broad variety of landscapes, it is outstandingly rich in biodiversity. In 1967, 103 fish species were recorded in the Danube (IUCN, 1994). This taxonomic richness can be related to the number of endemic species and to the remaining high diversity of floodplain biotopes. However, the local structure and distribution of the fish communities reflect the impact of human modifications of the system, such as in the German-Austrian section (ICPDR, 2005; 2008a). Furthermore, the Iron Gate dam has stopped the upstream movement of migratory species.

Major wetlands are found along the Austrian section downstream of Vienna which have been designated in 1996 as a National park. Then, the Hungarian Szigetköz and Slovak Csallóköz along the border between Slovakia and Hungary and the Gemenc area in lower Hungary comprise exceptional wetland areas. . The Kopacki Rit, which represents some 50 000 ha lying between the Drava and the Danube, is the richest floodplain of the Danube.

The delta and the banks of the Black Sea were designated by UNESCO as a "Biosphere Reserve" which includes an area of 591 000 ha. A part of the delta (53% or 312 400 ha) has been declared a "wetland of international significance" in 1991 and designated as a "World Heritage" site under the Ramsar Convention (1971). The filtering capacity of both, wetlands in general and the Danube Delta specifically, is an important factor for improving the water quality and for buffering suspended sediment load. Due to impoundment works and intensive agricultural activities the ecological functions of the Delta area have declined in the last fifty years.

Demographic state in the Danube basin

Today, about 82 million inhabitants live in the basin. The catchment area of the Danube River presently covers parts of territories larger than 2 000 km^2 of the Federal Republic of Germany, Austria, the Czech Republic, the Slovak Republic, Slovenia, Hungary, Croatia, the Federal Republic of Serbia, Bosnia-Herzegovina, Ukraine, Romania, Bulgaria, and Moldova. Additionally, some smaller parts of the catchment are located in Switzerland, Italy, Poland, Albania and Macedonia.

Drivers and pressures on water systems

Different drivers and pressures were identified in the Danube basin. Starting with water users and their management practice, pressures on the river regime, on soil and water bodies are identified. Most of the impacts originate from agricultural activities which constitute an important part of the national economy of the downstream countries. But also the non-consumptive uses such as navigation and flood protection exhibit often severe impacts on the ecosystems. Ad-

Table 2. Territory and inhabitants in the Danube basin *(from PCU, 1999; Annexes, 1.4 and 1.5)*

Country	Total area	Area in basin	Total population	Population in the basin
	(km2)	(km2)	(Mio)	(Mio)
Germany	356 974	56 240	82,1	9,1
Austria	83 855	80 565	8,1	7,7
Czech Rep.	78 866	21 119	10,3	2,8
Slovakia	49 036	47 064	5,4	5,2
Hungary	93 030	93 030	10,2	10,2
Slovenia	20 253	16 842	2,0	1,7
Croatia	56 542	34 404	4,8	3,2
Bosnia-Hercegowina	51 129	38 719	3,8	2,9
Serbia	102 173	88 919	10,4	9,0
Romania	238 391	232 200	22,6	21,2
Bulgaria	110 994	46 896	8,3	3,9
Ukraine	603 700	32 350	50,9	3,1
Moldova	33 700	12 025	4,3	1,1

Table 3. Major water users in the Danube basin (Aquastat database, 2011)

	Share in % of total water use			Irrigated land (103 ha)				
Countries	Agriculture 2000.	Industries 2000	Domestic 2000	1979-81	1989-91	1999-01	2002	2003
Austria	0,9	64,0	35,1	4	4	4	4	4
Hungary	32,1	58,6	9,3	190	201	223	230	230
Serbia & Montenegro						23	32	32
Ukraine	52,5	35,4	12,2			2393	2262	2208
Romania	57,0	34,4	8,6	2301	3124	3082	3077	3077
Bulgaria	18,8	78,2	3,0	1189	1251	624	592	588
Moldova	32,9	57,6	9,5			303	300	300

Figure 2. Longitudinal profile of the Danube: altitude (m), specific capacity (E in kW/km) and mean annual discharge Q (m^3/s) versus stream kilometre

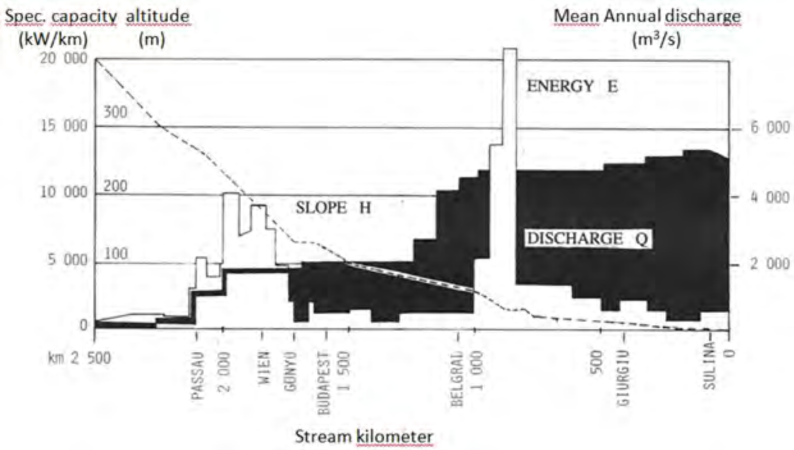


Table 4. Electricity generation in the Danube River Basin: total and electricity generation divided by origin (data from 2002; ICPDR;2005)

Country	Total electricity generated (TWh)	Share hydro-power (%)	Share thermal power (%)	Share nuclear power (%)
Austria	60	67,2	32,5	0,0
Slovakia	31	18,6	18,6	62,8
Hungary	35	0,5	57,5	40,7
Serbia and Montenegro	33	33	67	0,0
Romania	51	28,5	61,0	10,5
Bulgaria	22,6	8	10,9	82,3

ditionally, the climate variability associated with long lasting drought periods puts pressure on agriculture.

Main users of water resources

Consumptive uses refer mainly to agriculture, then to industrial and drinking water demand. In the lower basin a large number of reservoirs has been constructed along the tributaries to satisfy water requirements. Only in Romania more than 400 major dams and reservoirs have been built. In some countries, like Ukraine and Romania, the agricultural sector still requires more than 50 % of total water consumption. In Hungary and Moldova the share is above and around 30 % of total consumption (Table 3).

The challenges and problems of multipurpose water allocation have been growing in recent years. The water flow in 1993 was the lowest in a century and also the 1994 discharges were quite low. In several sub-catchments extreme low flows were also observed the year 2003. An important non-consumptive use with severe ecological implications constitutes hydropower utilisation. Based on the longitudinal profile of the Danube the relevant sections for hydropower use can be easily identified (Figure 2). They are located in the upstream part, mainly in Austria, and at the Iron Gate.

Austria has the highest percentage in coverage of its electric demand from hydropower generation which is recently about 60 % (2010). In Austria and the former Yugoslavia, hydroelectricity could theoretically cover 100 % of electricity consumption while in Czechoslovakia it could only take a 6 % share, the figures for the other countries totaling between 12 % and 54 %. Only 40.5 % of the total hydroelectric potential is currently being exploited (79.4 TWh).

Several proposals developed at the national level exist to increase the utilized rate (IUCN, 1994). In the upstream part run-of-river schemes are dominating. Major reservoir type schemes are the Iron Gate at the Serbian-Romanian border and the Gabcikovo scheme in Slovakia. Numerous multi-purpose reservoirs are additionally operated on tributaries, which have a significant impact on the discharge

Table 5. Percentage of Population Linked to Sewerage (Haskoning, 1994; ICPDR, 2005)

Country	Percentage of Population linked to Sewerage		
	1960	1990	2005
Germany (Bavaria)	40	88	93
Austria	35	70	85-88
Czech Republic	35	71	74-80
Slovakia	19	51	53-60
Hungary	21	52	60-74
Slovenia	20	47	65
Croatia	18	41	50-60
Serbia	?	25 ?	33
Bulgaria	25	45	66
Romania	15	40	50
Moldavia	5	10	10
Ukraine	39	55	??

pattern. According to the roof report (ICPDR, 2005) more than 700 large dams are located on the tributaries.

Hydropower schemes provide also some support for navigation because they increase the navigable depth and they reduce the flow velocity. Further, navigation channels were built in the last decades in Hungary and in the Delta area to facilitate the navigation of larger vessels.

Waste Water Treatment Capacity

Limited linkage to sewer systems and (Table 5) and even lower capacity for waste water treatment are an evident problems in several countries, especially in Moldova, Bosnia-Herzegovina, Serbia, and Romania. Many agglomerations in the lower part of the basin lack still from acceptable wastewater treatment technology and are therefore key contributors to organic pollution. Untreated industrial waste water increases the pollution level, especially in the tributaries, while the main stem has still a remarkable self-purification capacity. Polluted surface and groundwater systems together with lacking or insufficient water purification led to health problems of the population in several regions of the basin, especially in the lower part of the basin.

Climate change impacts

Within the CC-WaterS project a climate change data base was established for the Danube region (Nachtnebel et al. 2010). The A1B emission scenario was selected as the common scenario for all analyses and Regional Climate Models (RCM) applying this scenario were used from the ENSEMBLES project. The models have a 25x25 km resolution and their A1B scenario runs are available for the entire 21st century. A comparison of three models for the period 2021-2050 and of two models for 2071-2100 was considered sufficient for an estimation of the uncertainties. As RCM simulations for control runs show quite considerable differences compared with observations, the raw model data sets were bias corrected by a quantile mapping approach (Déqué, 2007).

Based on the simulation runs the following changes in precipitation and temperature can be expected for the Danube basin. Figure 3 and Figure 4 show the changes for the mid of the century, while Figure 5 and Figure 6 provide information for precipitation and temperature for the end of the century.

In Central Europe (Austria and Czech Republic) the simulation runs from all RCMs indicate no apparent changes in seasonality and variance in temperature, but a clear increase in the mean of between 1.1 to 2.2 C between the reference period 1961-1990 and 2021-2050 and of approximately 3.3 °C until 2071-2100. In the last period, summer extreme temperature increased more than the mean. The changes in precipitation are in general small but different trends can be derived dependent on the selected RCM.

In the Southern countries like Romania and Bulgaria the increase in temperature may be even more pronounced and may go up to 4,1-4,5 0C until the end of this century. Changes in precipitation are unclear and dependent on the chosen RCM even opposite trends may be found. Towards the end of this century even precipitation is not very clear, the variability between various models is quite high, indicating high uncertainties. More consistent results were obtained for the summer period for the period 2071-2100 when a decrease of about 25% is expected in several areas. Supported by numerous regional studies, it can be concluded that the climate changes, and in consequence the hydrological changes, increase from North to South. In Austria (Nachtnebel et al., 2010) the mean annual surface runoff is supposed to decrease between 5-15 % in the major river basins. In Hungary, the higher evaporation rates will reduce surface runoff contribution.

In several regions of Serbia (Dimkić et al., 2011) the runoff is expected to decrease by about 20-25% until the end of this century. The climate signals in the RCMs are similar and the change in temperature dominates the hydrological cycle. In Romania, due to the heterogeneity of the landscape, different results are reported, but overall substantial decreases in runoff are expected until the end of the century. The climate change signal for Romania can be summarized as follows: for the period 2021-2050, a moderate increase of the mean temperature of about 1.5 °C in winter and 1.8-2.1 °C in summer is expected compared to 1961-1990. For the period 2071-2100, the mean temperature is expected to increase by 3°C and in summer even larger changes between 3,5-4 °C are simulated.

It can be concluded from several regional climate models that by the end of this century the increase in the mean annual temperature will be about 2,5 -3,5 °C in the upper region and above 4,0 0C in the lower part. The rainfall is expected to decrease in the South-East by about 15-20 %, especially in Serbia, Romania, and Ukraine, while in the upper part the annual rainfall amount seems to remain stable. The precipitation in spring and summer is expected to decrease while the winter precipitation should be stable or even increase. Droughts are expected to occur more frequent and over longer pe-

Figure 3. Simulated bias corrected changes (%) in mean annual precipitation until 2050 for different RCMs

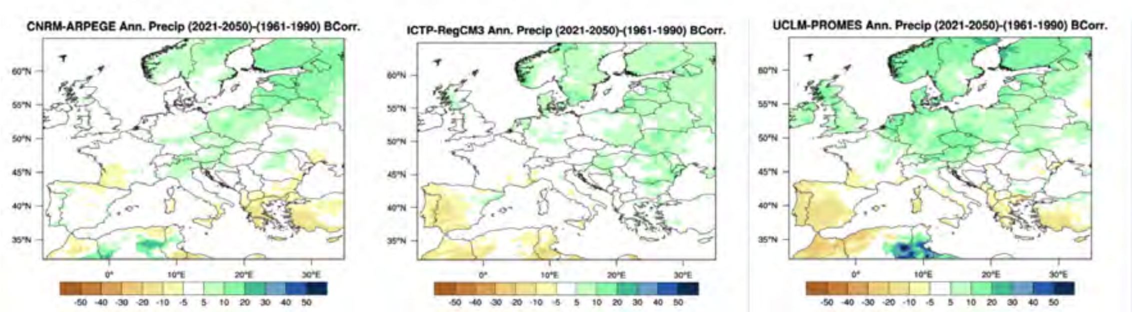


Figure 4. Simulated bias corrected changes (⁰C) in mean annual temperature until 2050 for different RCMs

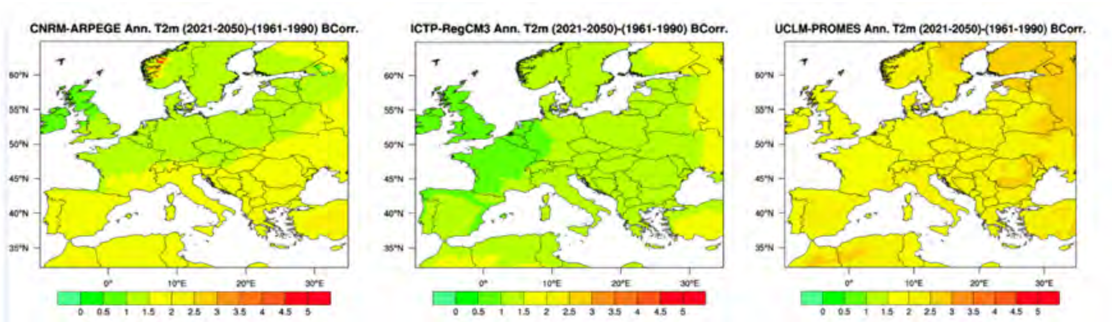


Figure 5. Simulated bias corrected changes (%) in mean annual precipitation until 2100 for two RCMs

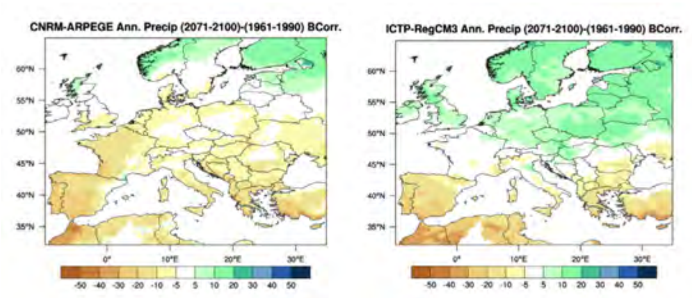
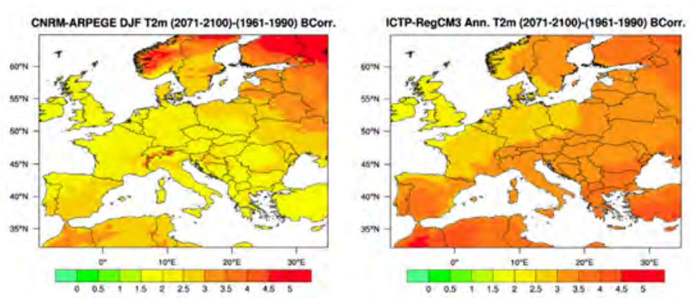


Figure 6. Simulated bias corrected changes (⁰C) in mean annual temperature until 2100 for two RCMs



riods. Implications of climate change on the water sector are seen in an increase of irrigation schemes which would put surface and groundwater systems under increased pressure.

Impacts

The main impacts on the water resources originate from nutrient emissions and organic pollution. Overall, due to modified agricultural practice and stepwise improvement of the waste water treatment capacity, nutrient loads have significantly decreased over the past 20 years, although they are still well above the levels of the 1960s. The relatively high percentage of untreated waste water in the middle and downstream area caused pollution of surface and groundwater systems, locally severely amplified by industrial wastes. Accidental spills from navigation are also considered as a major impact.

Further impacts refer to morphological changes due to river engineering works mostly related to flood protection, hydropower generation and navigation. Thus, the number of surface water bodies identified provisionally as heavily modified is very high throughout the entire basin. These activities reduced flood plains and wetland areas and modified adversely the sediment regime.

Impacts on groundwater quality

Ground water resources are essential for drinking water supply and large groundwater bodies are found in the flatland areas along the Danube and the major tributaries. Shallow groundwater bodies, which together with deep-layered aquifers, supply a high percentage of the population (8095 % varying from country to country) with drinking water, are exposed to impacts from agriculture, landfill sites, inefficient sewage systems and interaction with polluted surface water systems. Additionally, vulnerable karstic water resources are of special importance for drinking water supply.

Many of these water bodies are highly polluted by fertilizers and chemicals (chloride, ammonium, sulphates and phenols) due to agricultural practice and point pollution from former large-scale livestock farming and uncontrolled dumping sites. Major cities along the main river and the tributaries cover their drinking water demand by bank-filtered waters. Nonpoint pollution from agriculture is a major issue in the whole basin. Thus, only four of the 11 important transboundary groundwater bodies have been identified as not at risk concerning chemical status.

Impacts on surface water quality

The main problems are in organic micro pollutants, nutrient loads, and in heavy metals loads. Organic matter exhibiting biochemical oxygen demand (BOD) is a source of food for microorganisms, thereby causing microbial heterotrophic growth and oxygen uptake. Most recent data about water quality are available from the 1st and 2nd Joint Danube Survey (ICPDR, 2002, 2008a). The saprobity along the sites down to Budapest may be classified as moderately polluted (II) while downstream of Budapest several times the class II-III (critically polluted) was found, indicating significant organic pollution. Further downstream, especially downstream of the big cities in Romania and Bulgaria, an increase in the level of destruents, bacteria and detritus feeders was found, and even sites with toxic effects seem to exist.

Nutrient concentrations (nitrate and phosphate) increase along the river course and are at least doubled in the lower sections of the Danube (Figure 7). The input from diffuse sources into the drainage network of the basin is of about 450 ktons/a of total N and 40-50 ktons/a of total P (ICPDR, 2007). The major nutrient loads originate from Romania and Serbia and then from the upstream countries Germany and Austria (Figure 7). In the upstream part high fertilizer application (Table 6) and high runoff amount generate major nutrient loads although the waste water treatment capacity is quite high. In lowland and flat countries like Hungary even high applications of fertilizers are not reflected in nutrient loads of surface systems because erosion processes are not relevant and large extended groundwater bodies collect the nitrate input.

Figure 7. Longitudinal Profiles of Nitrate and Phosphorous Loads (ICPDR, 2005)

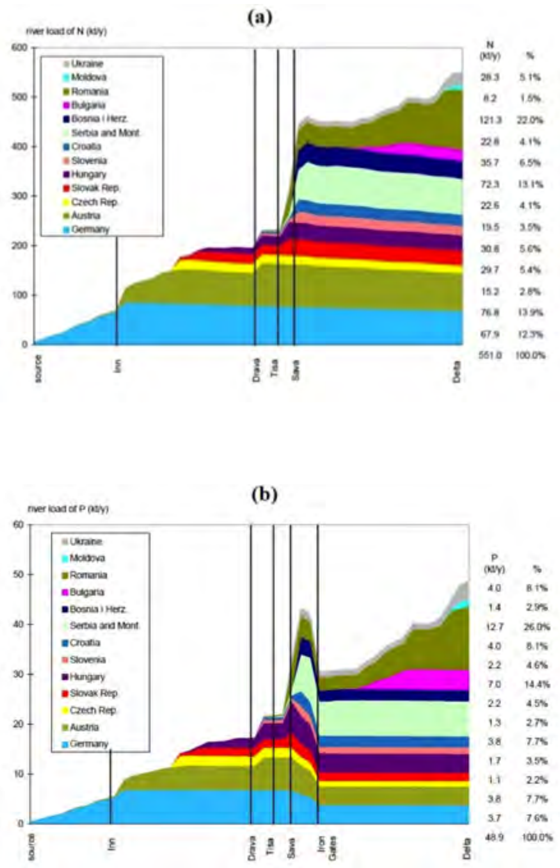


Table 6. Irrigated land and specific fertilizer application (from Aquastat data base, 2011)

Country	Percentage of agricultural land	Fertilizer consumption (kg/ha)
	2002-2007	2002
Germany	-	224
Austria	1,4	154
Slovakia	1,3	
Hungary	2,1	99,3
Serbia	0,5	73,2
Ukraine	5,3	15,4 ?
Romania	2,4	35,5
Bulgaria	1,4	50
Moldova	9,2	8,6 ?

Impacts from accidental hazardous spills

‚Baia Mare' (UNEP-OCHA, 2000) and‚Baia Borsa' (UNDAC, 2000), both located in the upper Tisza basin in Romania, are terms referring to the accidental spill of cyanide in particular and/or heavy metals from sedimentation ponds in the mining industry. During the Baia Mare event about 100,000 m^3 of sludge contaminated with cyanide and heavy metals reached via Szamos and Lapos rivers the Tisza. These events in 2000 clearly showed that an accident in one state will have huge transboundary effects over distances of hundreds of kilometres. Due to extreme loads of hazardous substances during the first accident at Baia Mare it was estimated that 1 200 tons of fish were killed and the total damage was about 874 million HUF. The second spill had lower impacts on the biology but the overall impact of these two events was classified as considerable for the fauna and flora of Hortobagy National Park in Hungary.

Some detailed chemical analyses from 1992, long before these disastrous events took place, indicate background concentrations for As and Pb already 100- to 1,000-fold, respectively, above the quality goal of the river Rhine. The Cd concentrations were by a factor ten above the respective chemical standards of the Rhine (UNEP-OCHA, 2000). For the Baia mare spill the maximum cyanid concentration ranged between 18,6 and 32,6 mg/l at the Hungarian border. The peak of copper pollution was reported from the Romanian side from Cicarlau with 10,5 mg/l.

Due to a dam break near Kolontar (Hungary), where mining deposits were stored, mud and alkaline slurry were released and polluted about 1 000 acres of land in October 2010. The amount of the emitted pollutants was about 0.9–1 million cubic meters. Ten fatalities were reported and almost 150 injured, including local residents and the participants in the rescue operations (Javor and Hargitai, 2011). The alkalinity of the spilt liquid approached a pH value of 13 combined with high concentration of metals (arsenic, mercury, among others). Hungary declared a state of emergency in three counties and due to immediate counter measures the impacts could be restricted to the tributary basin of the Danube.

Morphological changes and losses of aquatic habitats

Hydro-morphological alterations of the river systems originate from flood protection measures cutting off the former flood plain from the rivers, from hydropower development with weirs and impoundments along the river banks, from channeling rivers to support navigation, and from agricultural activities which had severe impacts on the minor rivers. Additionally, a complex hydraulic structure was developed in the last decades including more than 800 large dams and reservoirs with a capacity over 5 million m^3 and many smaller seasonal reservoirs. Thus, hydro-morphological alterations have been identified as a basin-wide significant water management issue in the Danube River Basin. The longitudinal assessment (Figure 8 and 9) showed that the situation in the Lower Danube is better than in the upper part. About 40% of the investigated Danube was satisfactory, meaning that there are still many healthy ecological areas. Good conditions remain in some breakthrough/gorge reaches in the

Figure 8. Longitudinal bank assessment of the Danube (taken from the ICPDR 2008a, p. 36)

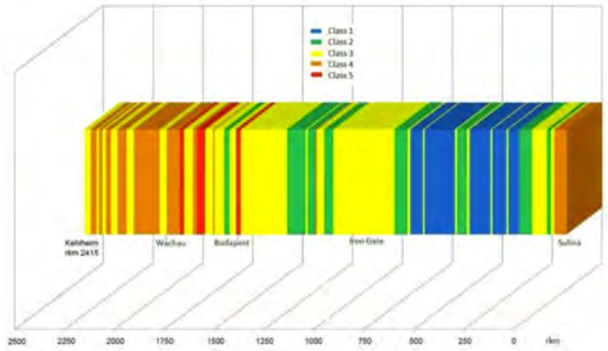
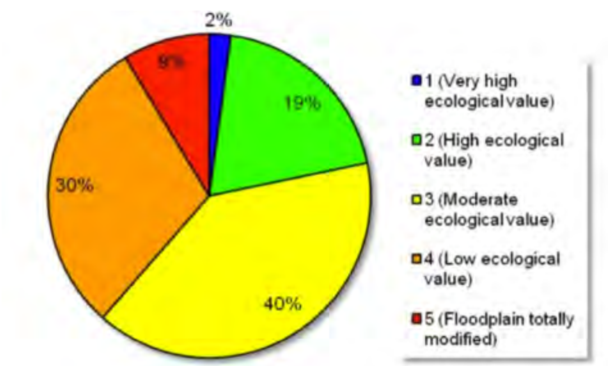


Figure 9. Total figures for the flood plain assessment (taken from ICPDR,2008a, p. 36)



upper and medium part when they are not affected by hydropower stations and in lowland stretches in upper Serbia, and mainly along the Romanian-Bulgarian stretch.

Natural alluvial flood plain areas have declined from about 26 000 square kilometres to about 6000 square kilometres within the last fifty years. Compared with the 19th century, less than 16% of the former floodplain area of 41 605 km² remained.

Natural hazards (floods and droughts)

In the last 20 years several extreme events like floods and droughts hit the basin. Romania suffered 2004, 2005 and 2006 (ICPDR, 2008b) from extreme flood events. The upstream part was exposed to heavy rainfall events and subsequent flooding in 2002 (Nachtnebel, 2005), and partly in 2005. Considering the flood damages in 2002 in Bavaria, Austria and Slovakia, economic losses added up to 3,75 billion € from which 3,1 billion € were reported from Austria. In some studies for the downstream areas it is concluded that uncontrolled deforestation and poor maintenance of hydraulic structure aggravated flood impacts.

Responses: Political and socio-economic changes

This chapter summarizes briefly the political changes which took place during the last few decades. These changes were accompanied by outstanding economic and institutional changes. The emphasis is here on the water and land use related transformation processes.

Political changes

During the period of the cold war Europe was divided into an Eastern and Western part. Concerning the Danube Germany and Austria belonged to the Western part with a free market economy while the majority of the Danubian countries including Czechoslovakia, Hungary, Yugoslavia, Romania and Bulgaria developed a state controlled centralized economy. The "Iron curtain" separated the two upstream countries from the rest of the basin and trade, political cooperation and cultural exchange were reduced to a minimum level. Austria, becoming in 1955 an independent neutral country between the Eastern and Western block, could use its political peculiarity to re-establish its links to its neighbors, especially Hungary, Yugoslavia and finally to Czechoslovakia. The collapse of the socialist regimes at the end of the 1980'ties created once more severe tensions in the central part of the Danube basin. The former federal state Yugoslavia broke into pieces and the new independent states Slovenia, Croatia, Serbia with Montenegro, and Bosnia and Herzegovina entered the political scene. Also on the territory of the former Czechoslovakia two new states, Czech Republic and Slovakia, were established in 1993. Luckily this segregation happened in a peaceful way. In 1999 a civil war started among different ethnic groups in Kosovo in Southern Serbia and so far this conflicted could be calmed down but no sustained political solution has been yet achieved.

Several countries including Germany, Austria, Czech Republic, Slovakia, Slovenia, Hungary, Romania and Bulgaria are members of the European Union. Germany, Austria, Slovakia, and Slovenia have already introduced the Euro. Croatia will become an EU member in 2013. Negotiations about the integration of Serbia, Bosnia-Herzegovina, Montenegro are slowly progressing.

Table 7. Agricultural production expressed in value added in % of GDP (World Bank, 2011)

Country	1986-1990	1990-1995	1995-2000	2000-2005	2007
Germany	2	2	2	1	1
Austria	4	3	2	2	1
Slovakia	7	6	5	3	4
Hungary	18	8	7	6	4
Serbia	24		20 ?	13-20	10
Ukraine	22	20	16-20	14	12
Romania	24	21	18	13-15	9
Bulgaria	13	13	18-20	11	7
Moldova	36 ?	35-40	32	22	12

Changes in agriculture

Agriculture in Europe was exposed to pronounced structural changes throughout the last 20 years. In contrast to Western European countries, where these changes took place over a comparatively long period of time, the changes in the East European countries were rapid and fundamental. Large collective agricultural production units fell apart and agricultural land was given back to private farms lacking modern equipment and technology. Fertilizer consumption dropped rapidly to about one third of previous application. Typical examples are Romania, Ukraine, Moldova and Bulgaria. Still today, a high percentage of people is working in the agricultural sector which also contributes a substantial percentage to the national gross domestic product.

As it was pointed out in the introduction, downstream countries show in general more favorable condition for agricultural production than upstream countries. As can be seen from Table 7 there is also an ongoing remarkable transformation process in the agricultural sector. The former socialist countries had quite an important contribution of the agricultural production to the GDP but this percentage is continuously decreasing although it is still above respective figures from the upstream countries.

Economic changes

There is a large North-South and West-East gradient in GDP per capita and also in political stability. The GDP per capita of the upstream countries is about 10 times higher compared to those in some downstream countries. The economic growth rate is larger in the downstream region although these markets are quite volatile. Migration pressures in the past originated in armed conflicts and in civil war, as in Croatia, Bosnia-Herzegovina, Serbia-Kosovo, and Moldova. Besides loosing people through migration, Ukraine has a negative population balance. Moldova suffers under extreme poverty. More than anything else, migrants and their remittances contributed to the economic transformation and restructuring of several states in the Danube basin, particularly in Moldova, Bosnia-Herzegovina, Serbia and Montenegro. Analyzing the development of the GDP in the various countries (Table 8) it can be concluded that the new EU members like Romania and Bulgaria could substantially increase their productivity while Ukraine, starting in 1992 at a comparable level, shows a much slower increase in GDP.

Changes in water and environmental management

Water management tries to satisfy human requirements such as protection from floods and droughts, provision of water in adequate quantity and quality for different purposes at different locations, and provision of water for non-consumptive uses. The Danube Action Programme encourages the promotion and harmonisation of changes in water policies and land-use practices, as well as environmental protection and nature conservation, in order to improve flood management and also meet the targets and measures of Integrated River Basin Management. The efficiency of the utilisation of resources has been improved over the last two decades in the downstream part but a further increase in production efficiency is required.

Table 8. GDP per capita in purchasing power parity (current international $) from World Bank (2011)

Country	1992	1995	2000	2005	2010
Germany	20613,8	22490,3	25753,4	31114,5	37260,2
Austria	21563,3	23504,0	28900,6	33604,0	40005,2
Slovakia	6476,1	8309,0	11004,6	16174,8	23422,8
Hungary	8090,3	8985,1	11880,0	16974,6	20028,7
Serbia			5768,1	8525,1	11280,8
Ukraine	5059,4	3171,9	3276,4	5583,4	6721,0
Romania	4432,8	5374,7	5660,9	9370,3	14287,3
Bulgaria	4950,3	5540,7	6309,2	9818,7	13779,8
Moldova	2073,9	1503,3	1469,0	2362,0	3109,8

Only in some segments of water management, for instance navigation, international agreements exist since decades. Then, in the 1980'ties it was recognized that the pollution of the surface water systems requires joint efforts. 1986 the Danube countries signed the Bucharest declaration which had the objective to initiate programs to improve the water quality of the Danube and to establish a network for standardized water quality measurements. But until 1990 the Danube countries managed their water and environmental resources on a national and local level (Buijs, 1991; Westing, 1989). On a bilateral basis expert groups met twice a year to discuss water issues between adjacent upstream and downstream countries and to agree on joint solutions.

The main trigger for the collaboration throughout the Danube basin is seen in the political and economic changes of the former socialist countries which started towards the end of the 1980s. Privatization of industries and of farmland and the establishment of a market orientated economy required new legislation and administrative structures. Also, the establishment of a monitoring system and of new environmental standards became an important issue. The riparian countries together with interested members of the international community met in Sofia in September 1991 and it was agreed to develop and implement the Environmental Programme for the Danube River Basin, including priority actions and studies in preparation for the eventual agreement on a new convention. In addition, the countries agreed to form a Task Force to oversee this programme. In parallel, two conventions related to environmental problems in the basin were prepared, of which one, the Convention and Cooperation for the Protection and Sustainable Use of the Danube River, has been signed by all Danube countries in June 1994. This convention specifies three major goals referring to the

- sustainable and equitable water management, including conservation, improvement, and rational use of surface and groundwater;
- control of hazards originating from accidental spills of hazardous substances, and natural phenomena such as floods and ice;
- reduction of the pollution load to the Black Sea.

The development of the Strategic Action Plan, which supports and complements the convention, has been a major task in the early phase of cooperation, for the first three years.

Immediate actions were taken under the programme to address environmental problems of acute concern and obvious high priority including areas of known health hazard or areas where environmental values and critical resources such as water supplies are threatened irreversibly. They include municipal and industrial waste water, solid waste, and surface and ground water pollution from point and non-point sources.

Another important activity within the short term actions was the development of an effective accident warning, alarm, and response system to minimize the serious environmental harm caused by industrial accidents such as oil spills and discharges of toxic and hazardous wastes, radioactivity and risks related to hydro-technical works. Further priority actions referred to capacity building and strengthening of authorities, organizations and individuals involved in environmental management in the Danube Basin. The activities are until today related to the establishment or improvement of inventories, the development of tools for analysis and the planning and environmental management in the basin.

Although the private income is quite low in some countries it was agreed to reduce immediately pollution and to stimulate the application of new technologies utilizing the resources more efficiently.

Another important principle, regional cooperation, means the full participation in and utilization of regional mechanisms and structures for international cooperation, consultation and coordination on policy and action.

Tödtling (2010) underlines the importance of the Global Environment Facility (GEF) as a source of international funding. In 1994 the World Bank established the GEF as a permanent mechanism, becoming the largest multilateral donor for global environmental issues. This also applies to water-related projects. The fund aims to help states to overcome obstacles for regional cooperation and to pave the way for a transnational approach, for example the management of transboundary rivers (Gerlak 2004). Other donors like EBRD, EU, USAID, UNDP and some member states provided financial support fostering the political cooperation in the Danube river basin. Tödtling (2010) stresses the importance of international funds for the mutual exchange as the basis for the drafting of the convention as well.

The appearance of ecological issues in the former socialist countries was the first sign of a political movement which was tolerated by the power loosing socialist parties. Later, in the early 1990s, the former socialist states faced severe problems during their transition phase from a centralized economy to a market oriented economy. They had a profound interest to get closer to Europe and the European Union. Especially, membership in the EU and NATO became a priority of the Central and Eastern European countries. Several countries adopted EU environmental standards and management principles as a precondition for an accession. With the help of EU funds, the Czech Republic, Slovakia, Hungary and Slovenia developed quickly and were able to ensure the financing of activities for a more sustainable use of the Danube. Bulgaria and Romania are undergoing the same development now (Tödtling, 2010) as can be seen also from the growth of GDP (Table 8).

Since its creation in 1998 the ICPDR has promoted policy agreements and the setting of joint priorities and strategies for improving the state of the Danube and its tributaries. The work of the ICPDR is based on the Danube River Protection Convention, the major legal instrument for cooperation and transboundary water management in the Danube River Basin.

States are even today the dominant players in the governance of the Danube basin, but the cooperative efforts which were achieved under the guidance of the ICPDR are impressive. A basin wide water management plan, several inventories including hot spots as well as information about the ecological state of the system, have been elaborated and adopted by the partners. The Danube protection convention has been signed and ratified by 15 parties. Still, some water related conflicts, such as the case of the hydropower station Gabcikovo, have not been solved.

Summary and conclusions

In this paper the main pressures on the water resources in the Danube basin were analyzed. It can be concluded that nutrient emission from agriculture and organic loads from untreated waste water constitute a threat to health of large groups of the population, especially in the downstream countries. Additionally, major sections of the technically modified river systems are classified as heavily modified water bodies. Water scarcity is already an issue in some downstream countries and it can be expected that climate change will aggravate this problem. These pressures originate from the different economic capacity of the countries and their younger political development in the region characterized by a transition from a centralized to a market oriented economy in the last two decades. Both, the physical heterogeneity as well as the socio-economic gradients in the basin can be considered as the driving forces for changes in the management of water resources in the basin. During the last 15 years the principles of the EU water framework directive have been adopted by most of the riparian states in the Danube basin.

References:

- Aquastat, 2011. Food and agricultural organisation of UN, Rome, Italy. http://www.fao.org/nr/water/aquastat/countries_regions/index.stm
- Buijs, P.H.L., 1991). Environmental Management Programme for the Danube River Basin. Background Document for the Technical Expert Meeting, September 1991, Sofia
- Déqué, M., 2007. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values, Global and Planetary Change 57: 16–26.
- Dimkić, A.M., M. Milovanović and D. Dimkić, 2011. Sustainable and Adaptive Water Management: Case Study of Water Management in Serbia. Water Research and Management, Vol. 1, No. 4, 9-19
- Gerlak, A.K., 2004. The Global Environmental Facility and transboundary wter resources management. New institutional arrangements in the Danube river and Black Sea region. J. Environment and Development, 13 (4), 400-424.
- Haskoning, 1994. Danube integrated environmental study. Haskoning Royal Dutch Consulting Engineers, Phare Contract ZZ 92110101 B003.
- ICPDR, 2002. 1st Joint Danube Survey. Technical Report of the ICPDR. International Commission for the Protection of the Danube River, Vienna, Austria.
- ICPDR, 2005. The Danube River basin District, Part A- Basin wide overview. International Commission for the Protection of the Danube River, Vienna, Austria.
- ICPDR, 2007. The ICPDR Joint Action Programme 2001-2005, ICPDR; Vienna, Austria.
- ICPDR, 2008a. 2nd Danube survey: Final scientific report. Liška, I., F. Wagner, and J. Slobodník (eds.) International Commission for the Protection of the Danube River, Vienna, Austria.
- ICPDR, 2008b. The analysis of the Danube flood 2006. Final report by Wachter K. Toth S. and l.iska. pp. 54. ICPDR, Vienna, Austria.
- ICPDR, 2009. Danube River Basin District Management Plan. Part A – Basin-wide overview. International Commission for the Protection of the Danube River, Vienna, Austria.
- IUCN, 1994. Analysis and synthesis of national reviews. IUCN report, Gland, Switzerland.
- Javor, B. and M. Hargitai (eds.), 2011. The Kolontár Report: Causes and lessons from the red mud disaster. Pp. 156, Budapest, Hungary.
- Nachtnebel, H.P. , 2000. The Danube river basin environmental programme: plans and actions for a basin wide approach. Water Policy 2, 113-129.
- Nachtnebel, H.P., 2005. Revised strategies for flood risk management, In Proc. NATO Advanced Workshop on Extreme Hydrological Events: New Concepts of Security, Nowosibirsk, 2005. Vasiliev, O.F.; Gelder, P.H.A.J.M. van; Plate, E.J.; Bolgov, M.V. (Eds.).Vol. 78, p. 417-435. Springer 2007.
- Nachtnebel, H.P., Stanzel, P. and H. Formayer, 2010. Report WP3 of CCWaterS: Climate change in South East Europe. http://ccwaters.eu/
- PCU, 1999. Danube Pollution Reduction Programme. Transboundary Analysis Report. Programme Coordination Unit & UNDP/GEF Assistance, Vienna, Austria.
- Ramsar Convention, 1971. The Convention on Wetlands of International Importance especially as Waterfowl Habitat, Ramsar, Iran.
- Stancik, A. and S. Jovanovic, 1988. Danube: Hydrology of the river. Publishing House Priroda, Bratislava, Slovakia.
- Tödtling, T., 2011. Water governance. From a global and national perspective. Master thesis, Univ. Vienna, Austria. pp. 138.
- UNDAC, 2000. Mining waste spill from the Baia Borsa processing complex in Romania. Assessment Mission to Hungary and Romania. UNDAC Mission Report, United Nations Environment Programme, UNEP / Office for the Co-ordination of Humanitarian Affairs, OCHA,Geneva, March 2000, pp. 32.
- UNEP-OCHA, 2000. Cyanide Spill at Baia Mare, Romania. United Nations Environment Programme, UNEP /Office for the Coordination of Humanitarian Affairs, OCHA. Assessment Mission to Romania, Hungary, Federal Republic of Yugoslavia, pp. 60.
- Westing, A.H., 1989. Environmental Security for the Danube Basin. Environmental Conservation 16, S. 323-329, Geneva, Switzerland.
- World Bank, 2011. The World Bank Data base. URL: http://data.worldbank.org/data-catalog/world-development-indicators.

Global change is more than climate change

Circulation of water through its atmospheric, terrestrial and marine domains and in different phases (liquid, vapor and ice) reflects not only the energy balance of the planet but also its sensitivity to water and land use patterns and pollution, as well as to a large number of changes which are taking place including in some seemingly disparate sectors of human activities and earth processes. It is certain that the likely temperature and carbon dioxide increases, due to the multitude and increasing intensity of human influences over the next few decades will directly or indirectly lead to substantial shifts between fluxes and storage throughout the hydrological cycle at all spatial and temporal scales. Water demands will need to be satisfied in the future from a resource with more uncertain and variable occurrence in time and space.

In the contemporary scientific, public and political debates climate change has the highest visibility and emphasis. However, climate change is rather expected to exacerbate the more direct and more significant anthropogenic impacts of water use than being the primary driver of change. Even the more alarming climate change predictions imply longer time scales of change and relatively more modest percentage shifts in average values of climate parameters and their potential consequence on the hydrological cycle, than for example the almost certain increase of the world population. In the next 40 years the number of people will increase by about 40%. Most of them will be born in already water stressed areas.

Population growth and the inherent increase of water use, the justified need to rectify social inequities and other socioeconomic aspirations, food and energy security requirements are imminent, grow faster than climate change indicators and influence the water cycle more directly. In fact, climate change is rather a consequence of these very changes than being an independent component of "global change".

Atmospheric processes significantly influence what will happen in the underlying terrestrial compartments of the hydrological cycle. Thus ultimately global change will affect everything and everybody. The atmospheric system is vulnerable to local-scale effects that can have wide-scale ramifications. High per capita emission of CO2 and other gases from a few countries increases greenhouse gas concentrations globally. Subsequent warming increases water vapor in the atmosphere, and thereby greatly increases the greenhouse effect, exacerbating climate change. This may explain why human-induced climate change is perceived by many as a primary global threat to humanity and to the ecology of the Earth System rather than blaming unsustainable human practices and resource wastage directly. We have already experienced and further projected changing precipitation patterns, increasing intensity of precipitation and longer dry spells, and higher evapotranspiration leading to increases of climatic extremes such as floods and droughts. More precipitation falls as rain rather than snow and the seasonality of runoff is changing. Consequences include changing air quality, increased wild fires, and changes in ground water recharge and river flows. Atmospheric teleconnections, as with the ENSO phenomenon, demonstrate the potential impact of regional climate variability on meteorological and hydrological processes half a globe away from the core Pacific region. Human influences on climate will have major consequences for the terrestrial part of the hydrological cycle as its spatial and temporal characteristics change.

Considering the mere quantitative dimension of freshwater use is of little help to address its consequences as far as water quality is concerned. Deterioration of water quality is a major feature of global change. The excessive use of agrichemicals to secure crop yields, increasing husbandry and aquaculture to satisfy the animal protein requirement of gradually more affluent societies, and the release of untreated or inadequately treated sewage and industrial waste waters into lakes and rivers have caused serious degradation of the quality of a resource that, in many parts of the globe, is already in short supply (Vörösmarty et al., 2010). This is evident from the presence of poisonous agrichemicals, persistent organic pollutants (POPs) in the water cycle, high nitrate levels in ground waters, heavy metals in river sediments, increasing water temperature, algal blooms and low levels of dissolved oxygen in many streams and lakes. As an unexpected side effect of improving health care and affluence, residues of medicines and cosmetic products enter recipient water bodies even through treated municipal sewage.

Irrespective of scientific, technological and medical achievements, social progress of the world of today is not yet a just place. Well-being, social and environmental justice, access to basic services, food, freedom, wealth and other amenities the world has been able to generate so far are not shared equitably. Inequalities imply conflict potential and are detrimental to good stewardship of our planet.

In spite of many political declarations and genuine efforts, the world still faces a staggering number of problems, each affecting at least a billion people.

- One billion people suffer hunger.
- Two billion people live with nutritional deficiencies.
- One billion people live in so called "informal" urban settlements.
- A further one billion subsistence farmers may respond to the pressures of poverty, the asymmetric competition with commercial and energy agriculture by joining the rural exodus and thus further contributing to unregulated urbanization.
- Two billion people live with nutritional deficiencies.
- Around one billion people will still remain without access to safe drinking water and more than two and a half billion will still lack basic sanitation, even if MDG 7 would be met.
- Over two billion people do not have access to modern energy services.

Obvious double or triple counting notwithstanding it is a fair guess that about one third of humanity does not participate in a process we may call "progress". The fact that we expect at least an additional 3 billion people on earth by 2050 emphasizes the magnitude and time scale of the inherent problems. The inherent humanitarian, social and political challenges are ultimately water challenges. While climate change forecasts predict marked changes rather for 2070 – 2100, other aspects of global change do not allow us decades to respond.

Land cover and its change has also a major influence on the terrestrial part of the hydrological cycle, and even atmospheric feedbacks and precipitation patterns depend largely on it. Massive profit oriented land-use changes like deforestation of the tropical rain forest, land conversion to grow "energy crops" do not only devastate biodiversity but contribute to global vulnerability through monocultures. It is cautioned (Marengo, 2010) that if the conversion of the Amazonian rain forest exceeded 30% of the original area, the consequences would be felt even in the Parana basin. Decreasing rainfalls due to massive land use changes and, in turn reduction of the moisture flux to the atmosphere could ultimately undermine both hydropower production, agriculture and related industries. Forests have higher value while standing than cut. Land use and water resources are intertwined and should not be managed without multiple scale integration.

References:

- Bogardi, J. J., Dudgeon, D., Lawford, R., Flinkerbusch, E., Meyn, A., Pahl-Wostl, C., Vielhauer, K., Vörösmarty, C., 2011. Water Security for a Planet under Pressure: Interconnected challenges of a changing world call for sustainable solutions. Current Opinion in Environmental Sustainability, 4:1-9.
- GWSP IPO, 2011. Water Security: Challenges for Science and Policy – Interconnected problems of a changing world call for sustainable solutions.
- Marengo, J., 2010. Climatic change: implications for ecosystem and environmental services in Amazonia. Global Water News No.9 pp.21-22
- Vörösmarty, CJ. et al, 2010. Global threats to human water security and river biodiversity. Nature, 467: 555-561

Global sustainability

A recent assessment of whether planet Earth is on a sustainable trajectory has revealed that several, "planetary boundaries", based on scientific consensus and assigned to selected dimensions of the Earth-system process (see Table 1), have already been transgressed due to unsustainable practices (Rockström et al, 2009a, 2009b).

The failure to achieve sustainability and earth system related security objectives without synchronized strategies is shown not only through the transgression of planetary boundaries like in the case of the nitrogen and the phosphorus cycles, but also through the extremely high biodiversity extinction rate and the climate change dynamics. While the world is characterized as being on an unsustainable trajectory, our scientific knowledge is still not comprehensive enough to predict whether, how much, how long and how many planetary boundaries can be violated without triggering irreversible change and potentially fatal consequences.

As shown in Figure 2 freshwater use, at least at global scale, is fortunately not yet among the most critical threats for global sustainability. The present global water withdrawal is approximately 4000 km^3 annually (or about 10% of the annual renewable water flux through overland flow, streams and ground water to the oceans), of which an estimated share of 2600 km^3 water is consumed annually (the difference accounts for transfer losses between withdrawal and consumption). While the global freshwater use is below the threshold proposed in Table 1, it does not offer any reason for complacency. In terms of aquatic biodiversity loss, water systems are among the most heavily impacted. (Vörösmarty et al. 2010). As the largest future population growth is expected to occur in countries that are already water stressed, these problems are likely to become more severe. Following the historical trend is not an option. The twentieth century experienced a threefold growth of the world population while water withdrawals sextupled. We need a critical look. Not only on how much water we use, but on how and what for we use it.

Beyond doubt "business as usual" would keep the world on an unsustainable trajectory with unpredictable consequences for humanity and its natural environment. Our limits of knowledge and imagination coupled with a great degree of uncertainty could jeopardize predictions of possible futures. However it is more and more evident that even well researched

Table 1. State of the indicators and proposed planetary boundaries (after Rockström et al 2009a)

PLANETARY BOUNDARIES

Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1-1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5-9.5	-1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis		To be determined	
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof		To be determined	

Boundaries for processes in red have been crossed. Data sources: ref. 10 and supplementary information results, such as the IPCC reports, fail to provide impetus for changes to society. Consequently, sustainability issues are not being addressed. While technological fixes are welcomed, there is no fundamental mentality change, new social value systems, or novel development paradigms adopted by world leaders that are needed as basis for change. Concepts and aspirations to change production systems are certainly key contributors towards a more sustainable world. However, realizing their potential needs a broad-based political and social acceptance and trust. Without a long term and intensive cooperation of social and natural sciences, engineering, politics and policy we cannot expect to succeed.

During the last two decades water problems have started to receive public attention. However and irrespective of the urgency of the related challenges and the multitude of links of water security to other concern areas like human and ecosystem health, food and energy security as well as population growth and land use changes the primary focus of the global debate on the temperature-CO_2-climate change nexus certainly overshadows water issues. In spite of its known regulating role even in the climate system water was seen as a sector and hence subject to "sectoral adaptation" This classification disregards the ethical imperatives inherent in addressing the water challenges as emphasized by the recent decision of the UN General Assembly declaring water as a human right. Political stability, economic equity and social solidarity are very closely related to water, its management and governance. For the sake of a sustainable world ahead, water problems have to be brought to the light! The future should be viewed first through "water" rather than a "CO_2" lens.

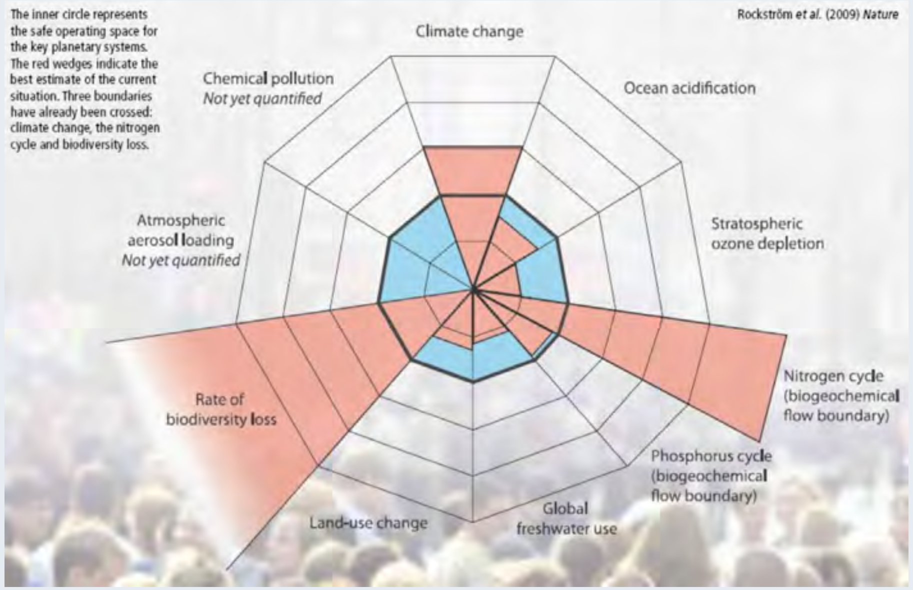


Figure 2. Proposed planetary boundaries and the current situation (after Rockström et al, 2009b)

References

» GWSP-IPO, 2011. Water security: Challenges for Science and Policy – Interconnected problems of a changing world call for sustainable solutions.

» Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley., 2009a. Planetary boundaries: exploring the safe operating space for humanity. Ecology and Society 14(2): 32, URL: http://www.ecologyandsociety.org/vol14/iss2/art32/.

» Rockström J, Steffen W, Noone K, Persson Å, Chapin FSI, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber H, Nykvist B, De Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sorlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson D, Crutzen P, Foley JA, 2009b. A safe operating space for humanity. Nature 461:472-475.

» United Nations General Assembly, 2010. Resolution 64/292: The human right to water and sanitation, 3 August 2010. URL: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/64/292.

Downscaling in climate change studies

Global Circulation Models (GCMs) are used to estimate global consequences of climate change. They have a spatial resolution of about 0,25*0,250 which corresponds in Europe to a grid length of a few hundred kilometres. Obviously, this resolution is insufficient for regional impact studies, especially to study hydrological impacts at the basin scale (Wood et al., 2004) which is usually in the range of a few thousand square kilometres. To bridge the gap in spatial resolution different downscaling techniques have been elaborated in the last two decades. These downscaling approaches can be grouped into dynamic, statistical and stochastic techniques.

Dynamic downscaling utilises the GCM data as boundary conditions for a regional domain with a higher spatial regional resolution. Typical grid scales of regional climate models (RCMs) refer to 25*25 km (van der Linden and Mitchell, 2009). For Central Europe the REMO-UBA model is available which exhibits a 10*10 km grid. The benefits of the RCMs are seen in the higher spatial resolution of the digital elevation model and the more detailed information contained in land use maps. The bias from GCMs is also introduced via the boundary conditions. This should be considered in interpreting RCM climate data.

In general, statistical downscaling methods (Buishand et al., 2004; Wilby et al., 2004; Fowler et al., 2007) are based on the statistical relationship between large scale climate features, such as air pressure fields, and local phenomena usually described by rainfall and temperature patterns within a catchment. Sometimes the pressure fields are classified according to a catalogue of circulation patterns (CP) and then a relationship is established among each CP type and season with the local observations (Wetterhall et al., 2006; 2008). It is assumed that the established relationship for the past will also hold under climate change.

Stochastic downscaling techniques (Busuioc and von Storch, 2003) are closely related to weather generator methods. First, a time series of a key variable is modelled and subsequently other relevant meteorological variables, such as temperature and solar radiation, are generated dependent on the key variable. In many case studies daily precipitation is selected as a key variable which may be dependent on CP types and/or on the season. Others recommend using a Markov type model for wet and dry days (Bellone et al., 2000; Robertson et al., 2004).

Each of these techniques has its benefits and limitations (Schmidli, et al., 2007). The main benefit is in the higher spatial resolution which is a prerequisite for regional impact studies and which is achieved by analysing additional information such as terrain data, local observations, etc. The deficit of RCMs originates from bias in the boundary conditions and secondly from the still unsatisfactory grid scales of 25*25 km which is still to course for impact studies in a heterogeneous environment, such as mountainous catchments. Analysing RCM data for the control period 1960-1990 it can be concluded that the long-term averages and the seasonal patterns exhibit large differences compared to observations. In mountain areas the error in precipitation data may reach 50-100% of long-term mean values (Déqué, 2007; Themeßl et al., 2011). The error in temperature may be in the range of expected climate change signals and in several cases a bias in temperature data was found. At lower altitudes the temperature is overestimated while in high mountain zones the temperature is underestimated. To compensate this errors several bias correction methods have been developed which correct the RCM data in the first and sometimes also in the second statistical moment, too. This data adjustment procedure is subsequently applied to time series of future climate (Panofsky and Brier, 1968; Déqué, 2007).

Other experts suggest using ensembles (Tebaldi et al., 2005; Christensen and Lettenmaier, 2006) of RCMs, favourable are RCMs driven by different GCMs, for hydrological simulations to learn about the variability in the hydrological model outcomes. Considering that RCMs may exhibit quite large deviations from observations, also for long-term mean values, it is questionable if this technique is useful.

Statistical and stochastic downscaling techniques assume that some large scale features, such as air pressure patterns, are reasonably well reproduced by GCMs. Data analysis indicates that the frequency of historically relevant pressure fields contained in weather type catalogues is not reliably reproduced by the climate simulation models.

It can be summarised that all climate change impacts studies reflect the bias in the climate simulation model which implies that the uncertainty increases with improved spatial resolution, especially in a heterogeneous environment. This is particularly the case for changes in hydrological extremes which, by definition, are represented only by a small subsample of the whole simulation period.

References:

- Bellone, E, Hughes, J. P. and P. Guttorp, 2000. A hidden Markov model for downscaling synoptic atmospheric patterns to precipitation amounts. Climate Research, 15: 1-12.
- Buishand, T.A., Shabalova, M.V. and T. Brandsma, 2004. On the choice of temporal aggregation level for statistical downscaling of precipitation, Journal of Climate, 17, 1816-1827.
- Busuioc, A. and H. von Storch, 2003. Conditional stochastic model for generating daily precipitation time series, Climate Research, 24: 181-195.
- Déqué, M., 2007. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values, Global and Planetary Change, 57: 16–26.
- Fowler, H.J., Blenkinsopa, S. and C. Tebaldib, 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. International Journal of Climatology, 27: 1547 - 1578.
- Christensen, N. and D. P. Lettenmaier, 2006. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. Hydrology and Earth System Sciences, 3: 3727 - 3770.
- Panofsky, H. A. and G. W. Brier, 1968: Some applications of statistics to meteorology. State College, Pennsylvania State University Press, 268 pp.
- Robertson A W..Kirshner, S. and P. Smyth, 2004. Downscaling of Daily Rainfall Occurrence over Northeast Brazil Using a Hidden Markov Model. Journal of Climate 17: 4407-4424.
- Schmidli, J., Goodess, C.M., Frei, C., Haylock, M.R., Hundecha, Y., Ribalaygua, J. and T. Smith, 2007. Statistical and dynamical downscaling of precipitation: An evaluation and comparison of scenarios for the European Alps. Journal of Geophysical Research, 112: D04105.
- Tebaldi, C., Smith, R.L., Nychka, D. and L.O. Mearns, 2005. Quantifying Uncertainty in Projections of Regional Climate Change: A Bayesian Approach to the Analysis of Multimodel Ensembles. Journal of Climate, 18: 1524 - 1540.
- Themeßl, M.J., Gobiet, A. and G. Heinrich, 2011. Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. Climatic Change.
- Wetterhall, F., Bárdossy, A., Delian, C., Halldin, S. and X. Chong-Yu, 2006. Daily precipitation downscaling techniques in three Chinese regions. Water Resources Research, 42: W11423.
- Wetterhall, F., Bárdossy, A., Delian, C., Halldin, S. and X. Chong-Yu, 2008. Statistical downscaling of daily precipitation over Sweden using GCM output. Theoretical and Applied Climatology 42.
- Wilby, R.L., Charles, S.P., Zorita, E., Timbal, B., Whetton, P. and L.O. Mearns, 2004. Guidelines for use of climate scenarios developed from statistical downscaling methods. 27 pp.: http://ipcc-ddc.cru.uea.ac.uk.
- van der Linden P., and J.F.B. Mitchell (eds.) 2009: ENSEMBLES: Climate change and its impacts: Summary of research and results from the ENSEMBLES project. 160pp. http://ensemblesrt3.dmi.dk/

Interbasin transfer of water between river basins or to demand centers outside of the basin

Locations of water availability (frequently high mountain watersheds well endowed with precipitation of orographic origin) and that of considerable water needs (agricultural areas, human settlements) are usually not identical. It is increasingly frequent, especially under semi-arid and arid climatic conditions that this spatial mismatch cannot be easily resolved within the same river basin or/and by using the underlying aquifer as source of water. This situation has emerged most frequently in case of large irrigation areas and megacities.

Interbasin water transfer (IBWT) which conveys water physically over the borders of the basin of its "origin" is a technical solution which has been applied both within the same (national) jurisdictions (like in South Africa or Sri Lanka or Tunisia, or water supply of Mexico City) but also across national borders (like in the case of the Lesotho Highland Water Project). While not strictly interbasin transfers, navigational links across river basin boundaries like the Rhine-Main-Danube Canal can also be mentioned in this context.

As of present in the international water debate over IBWT the option "can do" is not identical with the "should be done". IBWTs are expensive infrastructure projects. Furthermore solving water scarcity problems by supply side management (like providing water through inter-basin transfer) could discourage water saving technologies to be introduced in the recipient basin. In addition, ecosystem security could be seriously jeopardized through invasive species which may enter the recipient basin through the transferred water.

The issue of IBWT was discussed in depth by a multiple stakeholder workshop organized by the International Hydrological Programme of UNESCO in 1999. The outcome of this workshop was a set of recommendations providing a guide to decide on the ethical justification, ecological and economical feasibility of this type of projects. These recommendations are reproduced here in an abbreviated form as they provide a good checklist of potential critical areas, dimensions of debate and issues to be addressed by planners of water resources projects in general and IBWTs in particular.

Technical and economic feasibility

- IBWT can be a sustainable solution to cover water demand in water-scarce areas
- IBWT is comparable with other water management infrastructure system elements and thus should not be excluded from considerations
- Requirements for new infrastructure, including IBWT solutions, can be eased by water demand management; yet, these measures must be viewed in their complexity, including social and political impacts, where economy is not always the determining factor
- Technical problems are usually not the limiting factors to IBWT

Environmental appraisal

- Environmental considerations should not be an addendum, but an organic part of the project; to ignore or belittle environmental impacts can backfire;
- Transfer of species between the two basins should be considered and assessed
- Improvement of the ecological balance in the recipient basin may be a valid reason to support IBWT
- Environmental valuation differs between countries: environmental sensitivity is more prevalent in industrialized societies, while developing countries tend to give preference to economic and social progress.

Ethical concepts

- No ethical barrier is justified against IBWT as such
- Water is generally considered a national patrimony or a common good; the sharing of that resource with neighbors is a sign of goodwill and a token for peace, cooperation and partnership; IBWT may be part of such efforts
- IBWT can help to sustain cultural and emotional values, associated with a water course or water body
- Unethical, selfish attitudes are sometimes disguised as environmental concern, or hidden behind catchy slogans
- The paramount ethical value of water supporting life, society and development is not in opposition with its practical use in everyday life
- Professional ethics oblige to use true arguments in the debate;
- Ethics is not universal; it is value-, belief- and culture-bound.

The legal context

- Legal barriers against IBWT as such are not justified and can hinder development;
- Water law is a major factor in the prospects of IBWT;
- River basin authorities with legal status have particular competence in approving or opposing IBWT decisions, which sometimes need to be overruled by higher instances;
- Transboundary water transfer is hampered by the lack of internationally agreed and ratified legislation;
- The size of the IBWT project is relevant for the need and scope of legal intervention.

Partcipation and transparency

- Participation in all stages of planning IBWT is essential: omissions may come back with vengeance;
- Participation requires transparent factual information of all who take part in the decision making process;
- Compensation of affected stakeholders is an essential component of IBWT projects;

Institutional models

- Depending upon the ethical and social valuation, IBWT can be:
  - an enterprise of selling and buying water;
  - an act of solidarity between two regions, of which one suffers from water shortage and the other has a reasonable surplus of water;
  - a joint venture of sharing water resources, respecting the interests of both partners and compensating the provider basin for the transferred resource.
- Each solution needs an adequate institutional model, which can range from simple commercial agreements, to joint resource management, through different types of intermediate institutions (joint commissions, treaties, etc.).

Decision support

- IBWT projects may efficiently be supported by modeling tools for multi-criteria decision making of different kinds; an essential feature of these is the possibility to assess uncertainty and estimate the value of social and economic criteria;
- Professional analyses should support the decision making process and provide unbiased information to the decision makers and the general public;
- The ultimate decision in complex matters such as IBWT is political.

The real issue: shared water management

Interbasin water transfer is ultimately "only" the technical tool; the real issue is the sharing of water resources between the receiving basin and the area of origin of the water. The physical linkage between hitherto separated water systems (basins) should become a facilitating element of shared water management in the interest of both basins. The shared management should promote sustainability, respond to common ethical values, generate mutual benefits and be administered by suitable institutions.

Sustainability:

- The impetus for inter-basin water sharing should come from an unsustainable situation: lack of water security and shortages reduce the quality of life, hamper economic development and social progress; the objective is to improve the situation through interbasin water transfer
- In the donor basin, the water transfer must not affect negatively
- the sustainability of water management (the abstraction of water must not cause environmental, social and cultural damage)
- Sustainable development will have to be promoted in both basins, owing to the shared economic and social benefits from the project
- The respect of future generations obliges to put time limits to water sharing agreements;
- Water transfer agreements should foresee monitoring and periodical assessment with the possibility of adjustments of the contractual obligations, including potential decommissioning of IBWT.

Inter-basin solidarity:

- In both basins, the same ethical values are shared as regards to basic human rights, equity, life and consumption
- In both basins, good neighborhood is a lasting principle of cooperation
- In the receiving basin, the water users acknowledge the advantages of the water transfer and are willing to share the benefits with the donor basin
- In the donor basin, stakeholders willingly contribute to the well-being of their neighbors, without resentment as regards to the advantages these may generate from the water received.

Institutional solutions:

- The realistic assessment of the water deficit is the onus and responsibility of water management in the receiving basin, which is responsible for the right use of transferred water under the agreed conditions;
- The realistic assessment of water availability is the onus and responsibility of water management in the donor basin, which is responsible for its delivery in agreed quantity and quality;
- Equitable sharing of the benefits of the water transfer are secured by the agreements and guaranteed by mutually agreed institutions;
- The agreement on water transfer is included into a wider scope of cooperation on issues other than water;
- Cooperation between the two basins can lead to sustainable integrated water management of the shared resources, if confirmed by the general development and environmental conditions in both basins.

Reference

- Bogardi, J.J., Bruk, S., 2000. In Lieu of Conclusions: Some Answers and Many Questions. In: Interbasin Water Transfer, UNESCO-IHP Technical Documents in Hydrology No. 28 pp 9-16, Paris

Foto: Irrawaddy River, Bjørn Christian Tørrissen (wikipedia)

Estimating green-blue water availability and needs for global food production

Dieter Gerten[1], Jens Heinke[1] & Holger Hoff[1,2]

[1] Potsdam Institute for Climate Impact Research (PIK), Research Domain II: Climate Impacts and Vulnerabilities, Telegraphenberg, 14473 Potsdam, Germany
E-mail: gerten@pik-potsdam.de

[2] also at Stockholm Environment Institute, Kräftriket 2B, 10691 Stockholm, Sweden

Abstract

This study compares per person water availability and requirements for global food production (crop and livestock products), for the present and for future climate and population change (climate scenarios from 17 General Circulation Models, A2 emissions and population scenarios, 2070-2099 period). The dynamic vegetation and hydrology model LPJmL was used to calculate green and blue water availability per capita, water requirements to produce a balanced diet (3,000 kcal cap^{-1} d^{-1}, consisting of 80% vegetal food and 20% animal products), and a new water scarcity indicator that compares the two at country scale (assuming that inhabitants benefit equally from water resources in a country rather than in a river basin). Water scarcity was assumed if water availability was lower than water requirements, which is according to our results already the case in North and East Africa and in southern Asia in particular. In the future, however, water availability is very likely to be lower than today in many regions. Yet, the water requirements for producing the target diet are suggested to decrease concurrently, due mainly to the effect of rising atmospheric CO_2 concentration on crop water productivity – this effect, however, is unlikely to be fully realized in poorly managed agro-systems. As a net effect of climate, CO_2 and population change, water scarcity will aggravate in many countries and river basins, and a number of additional countries/basins may lose their food self-sufficiency by the end of this century.

Keywords

water scarcity, water stress, climate change, food production, crop yields, livestock water use, LPJmL model

Introduction

Knowledge of how freshwater availability for food production and scarcity will evolve in the future under climatic and socioeconomic changes is of outstanding importance. Until recently, most assessments and projections of worldwide water resources (e.g. Vörösmarty et al. 2000; Arnell 2004; Alcamo et al. 2007) were focused on the blue water (BW) offered by rivers, lakes, reservoirs and aquifers while disregarding the green water (GW) available in the soil. Hence, both green and blue water need to be included in water availability and scarcity analyses, which has been initiated only recently by use of macro-scale hydrological, ecological and crop models (e.g. Liu et al. 2007; Rost et al. 2008; and Hoff et al. 2010, who provide an overview of recent efforts).

It remains a challenge to unambiguously define the GW resource and to represent it consistently with BW in indicators of water availability and scarcity. Rockström et al. (2009) developed a first variant of such an enhanced water scarcity indicator, assuming the GW resource to be the evapotranspiration (ET) from grazing land and cropland (including the non-BW fraction on irrigated areas) in a country and relating it to the country's population. If the value of this modified "Falkenmark index", or "water crowding" index, was <1,300 m^3 cap^{-1} yr^{-1}, green-blue water scarcity was assumed to prevail. One can further assume that countries with <1,300 m^3 cap^{-1} yr^{-1} of green-blue water resources cannot produce a "healthy" diet of 3,000 kcal cap^{-1} d^{-1} with shares of 80% vegetal and 20% animal products (Rockström et al. 2007). While this threshold may represent a global average, significantly more, or less, water is required in individual regions for producing the specified diet. The reason is that the crop water productivity (CWP)—the ratio between crop yield and ET during the growing period—differs significantly among regions due to different climatic and management conditions (Liu et al. 2007; Fader et al. 2010).

This presentation provides an estimation of GW and BW availabilities for countries (with outlooks on river basins) and compares these to the country-specific water requirements for producing a diet of 3,000 kcal cap−1 d−1 (with 80% vegetal products) calculated from local CWP. The resulting new water scarcity indicator is applied for the present situation and for a number of climate change scenarios (from 17 General Circulation Models (GCMs), including direct CO_2 effects on plants; A2(r) emissions and population). All calculations were done at high spatial resolution (0.5° global grid) and high temporal resolution (daily, up to 2099), while results are presented as 30-yr country averages (blending results for rainfed and irrigated land) for the present (1971–2000) and for a future time slice (2070–2099 or "2080s"). Most material presented here is taken from the study by Gerten et al. (2011submitted).

Methods and data

We used the global ecohydrological model LPJmL (Bondeau et al. 2007; Rost et al. 2008), which simulates the growth, production and phenology of 9 "plant functional types" (representing natural vegetation at the level of biomes), grazing land, and 11 "crop functional types" (CFTs, representing the world's major food crops; see Bondeau et al. 2007 for detailed description). The fractional coverage of grid cells with CFTs was prescribed using a dataset of present cropland distribution combined with a dataset of maximum monthly irrigated and rainfed harvested areas of individual crops (see Fader et al. 2010 for data and further details).

Water requirements and water consumption—and thereby the CWP—of irrigated and rainfed CFTs are distinguished, also on irrigated land. We assumed that the irrigation water requirements of the CFTs as controlled by their water limitation and by country-wide irrigation efficiencies can always be fulfilled (details in Rost et al. 2008). Seasonal phenology of CFTs was simulated based on 20-yr average climate, allowing for adaptation of varieties and growing periods to climate change (Bondeau et al. 2007). Management/yield was calibrated using statistical data for the period around 2000 by sequentially varying parameters for cropping density and other management features (Fader et al. 2010). We assumed that neither changes in management nor in the extent of agricultural land will occur in the future.

The BW resource and the GW resource (both in m^3 yr^{-1}) were computed at the grid cell level and then summed up for the respective country, presuming that the food produced with this water is distributed evenly within a country rather than produced and consumed within individual grid cells or within river basins. For determining the BW resource, we computed the runoff generated in a river basin and redistributed it across all cells within the basin in proportion to their accumulated discharge. This way, cells with a high share of discharge relative to the basin's total discharge were assigned a relatively high BW resource. The BW resource per country was given by the sum of this runoff for all grid cells. We also assumed that just 40% of this resource are actually available for food production, e.g. to account for environmental flow requirements (further details in Gerten et al., 2011submitted).

The GW resource was computed as the precipitation water that evapotranspires from crop and pasture areas within a country. GW contribution from grazing land was constrained either by total grassland ET or by the global average water requirement of 251 m^3 cap^{-1} yr^{-1} from grazing land. The GW resource also reflects the extent of agricultural area, meaning that countries with a large agricultural area may show a relatively high GW resource. The total green and blue water resource GWBW (m^3 yr^{-1}) was calculated as the sum of the GW and BW resources in a country.

GWBW availability (in m^3 cap^{-1} yr^{-1}) was calculated by relating the annual GWBW resource to the number of people inhabiting a country, assuming that they benefit uniformly across the country from its total water resource. Subsequently, GWBW scarcity was computed for each country as the ratio between the GWBW availability and the water requirement for food production (see the following).

Water requirements for producing a healthy diet of 3,000 kcal cap^{-1} d^{-1} with 20% calories from animal products were estimated from the water needs for producing vegetal calories on a country's present cropland and from a hypothetical livestock sector. Details can be found in Gerten et al. (2011submitted) and only a short summary is provided here. Water needs for the vegetal part were estimated by relating the total amount of calories produced on cropland (inferred from simulated yields using calorie conversion factors from the FAO's Food Balance Sheets) to the total amount of GWBW consumed on cropland during the growing period, yielding to a global requirement of 0.409 m^3 1,000 $kcal^{-1}$. Following Rockström et al. (2007), the eightfold amount of water is required to produce an equivalent amount of animal calories. This results in a global average of 1,075 m^3 of water per capita and year required for the above specified diet (358 m^3 cap^{-1} yr^{-1} for the vegetal share plus 716 m^3 cap^{-1} yr^{-1} for the animal share). Water needs to produce the animal share were attributed to cropland and grazing land assuming a mixed livestock system with a non-grazing and a partly grazing sub-system, each consuming 50% of the water (as in Rockström et al. 2007; see also Gerten et al. 2011submitted). As a result, 840 m^3 cap^{-1} yr^{-1} are required to produce food and feed on cropland, and, respectively, 251 m³ cap⁻¹ yr⁻¹ to produce grazed biomass. For the water requirements from grazing land we used for each country the global average of 251 m³ cap⁻¹ yr⁻¹, assuming that grassland management and grazing intensity are not related to cropland productivity.

LPJmL was forced for the period 1901–2000 by monthly values of air temperature, precipitation amounts, number of wet days and cloud cover, taken from the CRU TS 3.0 climate database (Mitchell and Jones 2005; http://badc.nerc.ac.uk/data/cru/). Climate projections for the transient simulations up to 2099 were derived from 17 GCMs under forcing from the SRES A2 emissions scenario (overview of models in Gerten et al., submitted), as follows. First, the individual GCMs' monthly mean temperatures, precipitation sums and mean cloudiness were brought to 0.5° resolution and smoothed using a 30-yr running mean. Second, anomalies relative to the 1971–2000 mean were calculated for each month of 2001–2099 and applied to the observed 1971–2000 baseline (additive for temperature, and using mixed additive-multiplicative approaches for precipitation and cloudiness, see Gerten et al. (2011). Third, annual CO_2 concentrations until 2099 were taken from the Bern CC carbon cycle model. To quantify the net physiological and structural effects of atmospheric CO_2 concentration and thus on water scarcity, we ran additional LPJmL simulations in which CO_2 was held constant at the year 2000 level. Finally, we used population projections consistent with the emissions and climate projections to determine future per capita water availabilities. In the case of A2 we chose the revised "A2r" scenario (Grübler et al. 2007).

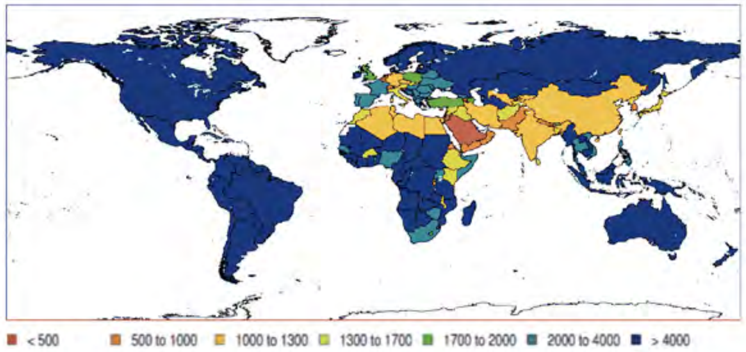


Figure 1. Availability of green plus blue water, illustrated at the country level (values in m³ cap⁻¹ yr⁻¹ and averaged over 1971–2000). Modified after Gerten et al. (2011).

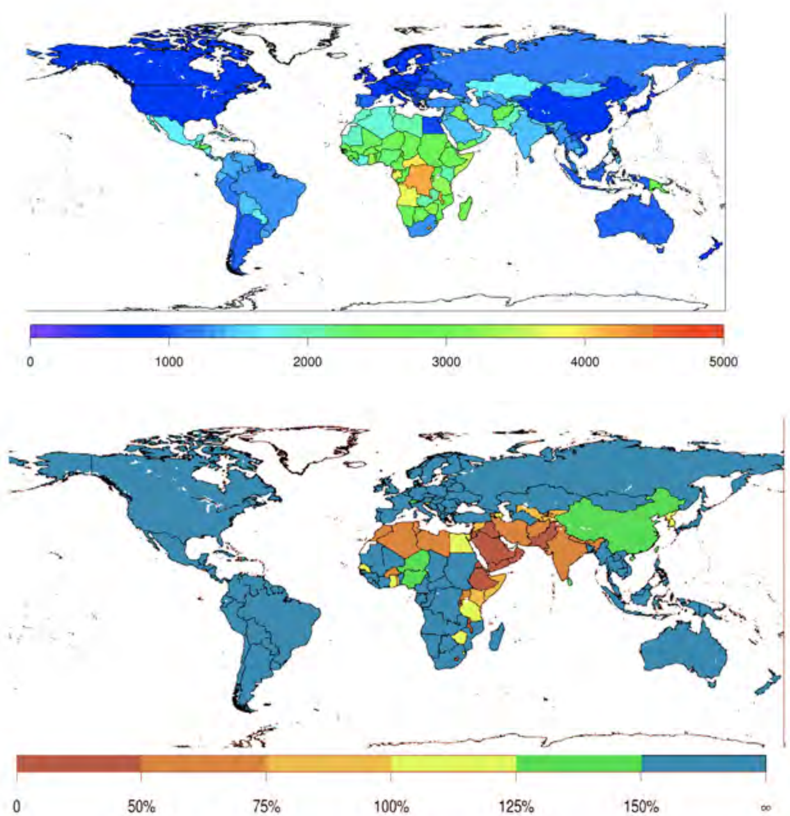


Figure 2. Country-level GWBW requirements (m³ cap–1 yr–1, 1971–2000 average) for producing 3,000 kcal cap⁻¹ d⁻¹ with 80% vegetal and 20% animal products (top), and water scarcity defined as the percentage ratio between GWBW availability (cf. Figure 1) and these requirements (bottom). © American Meteorological Society – used with permission.

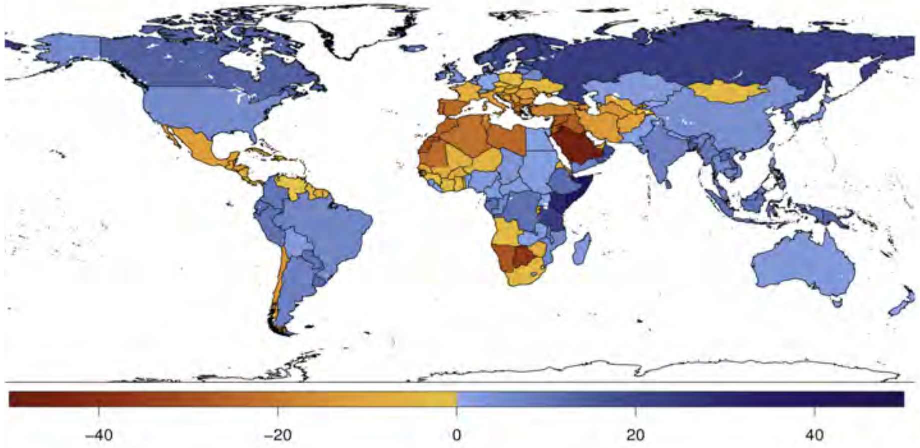


Figure 3. Relative changes in GWBW availability by the 2080s. Shown are medians across all climate scenarios, with CO_2 effect, and assuming the SRES A2 emissions scenario. Population numbers held constant at the year 2000 level.

Results and discussion

Current green-blue water availabilities, requirements and scarcities

BW availability is presently rather low (e.g. <1,700 m^3 cap^{-1} yr^{-1}) not only in many physically water-poor countries in subtropical regions but also e.g. in Central Europe (data not shown). When the GW resource is added to the BW resource, water availability appears to be much higher, but nevertheless many countries stay at a level <1,700 m^3 cap^{-1} yr^{-1} (Figure 1). Most countries at high latitudes and in the humid tropics, or countries with little resources but low population (e.g. Australia), are characterised by high per capita water availability (>4,000 m^3).

Based on our computations of CWP (and our assumptions for the livestock sector), the water requirements for a balanced diet of 3,000 kcal cap^{-1} d^{-1} vary considerably between countries (Figure 2a). We find that many countries e.g. in Europe and North America need less water to produce this diet than suggested by the global average (1,095 m^3 cap^{-1} yr^{-1}), while elsewhere the respective needs are calculated to be much higher (up to >2,500 m^3 cap^{-1} yr^{-1}). This regional pattern results from differences in CWP, which in turn are controlled mainly by differences in climatic conditions, yield levels, and management intensity (see Fader et al. 2010 and Gerten et al. 2011, for more detailed analyses).

Relating these water requirements to GWBW availability gives the degree of water scarcity, and it appears that GWBW scarcity varies among countries as well (Figure 2b). Many European countries classified as chronically water-scarce according to the 'standard' Falkenmark indicator (see Figure 1), however, do no longer appear as being water-scarce when using the new indicator, since comparatively little water is needed there for producing a unit of crop and livestock. Likewise, other countries showing GWBW scarcity according to the conventional analysis (Figure 1; e.g. South Africa, China, Japan) actually have enough water to produce the specified diet.

Future changes in GWBW availability and water-for-food requirements

GWBW availability is simulated to change significantly in the future under the suite of climate models considered, even if population changes are not considered (Figure 3). The change patterns are different for BW and GW (data not shown). The regional pattern of relative change in GWBW availability results from the complex interplay of impacts of changing precipitation, temperature, CO_2 concentration (all of which affect potential ET and soil moisture), and from changes in the CFT's growing periods. Hence, climate change will decrease GWBW resources and availability in many regions, in particular where the sign of change in GW and BW is the same.

Climate change by the 2080s alone (without CO_2 effects) will increase the water requirements for growing food crops in many regions (data not shown, but see Gerten et al. 2011). This is attributable chiefly to the higher evaporative demand induced by the warming. In parts of Europe, western Asia and southern Africa, however, water requirements are projected to decrease as a consequence of e.g. prolonged growing seasons enabling higher annual yields while consuming the same amount of water year-round. Water requirements decrease in most regions if the direct CO_2 effects are included (data not shown).

Water scarcity under climate and population change

Figure 3 (bottom map) implies a high likelihood for many countries that owing to climate change, per person GWBW availability will decrease by the 2080s (>70% likelihood for a decrease by >10% in southern Europe and significant parts of Africa; Gerten et al. 2011). However, only a few countries presently not water-scarce are suggested to turn to a water-scarce status by the 2080s due to climate and CO_2 change. Given both climate (incl. CO_2) and population change, however, there is a very high probability that GWBW availability will decrease in many regions, such that countries and basins in Africa, the Near East and the Middle East that are presently water-scarce will remain so in the future (compare Figure 2, bottom). In addition, a number of countries presently able to produce 3,000 kcal d^{-1} for their inhabitants will probably lose this ability by the 2080s, whereas most countries in the Americas and also Australia will still have enough GWBW resources for this purpose (Gerten et al. 2011). But, regional differences are masked by the country-scale analyses, such that it may well be that water resources in a number of Australian (and other) river basins may not suffice. If both climate and population change are accounted for, the global number of people living in water-scarce countries will rise to approx. 6 billion, respectively (only 3.4 billion, however, if the B1 scenario was chosen; Gerten et al. 2011). The number of people living in water-scarce countries is lower if the new indicator is used instead of the fixed threshold of 1,300 m^3 cap^{-1} yr^{-1}.

In sum, the present study contributes to developing a water scarcity indicator that compares per person GWBW availability and GWBW requirements for food production at country scale, based on pixel-scale computations of the underlying processes. An application of this new indicator demonstrates that applying a fixed threshold (here, 1,300 m^3 cap^{-1} yr^{-1} for a balanced diet of 3,000 kcal cap^{-1} d^{-1} with 80% vegetal products) may give a biased view on water constraints to food production as this method tends to overrate water scarcity. The reason is that due to differences in CWP more, or less, water is actually required in individual regions to produce the specified given diet. We also find that water scarcity, even if GW is considered in addition to BW, will exacerbate in many countries, especially in parts of Africa and Asia. This will be driven primarily by population growth and only secondarily by climate change, which is in accordance with findings from earlier studies based on blue water only (Vörösmarty et al. 2000; Arnell 2004). Note, potential future land use changes and their effects on GW (and BW) resources were not considered here. Also, while the beneficial effect of rising CO_2 concentration especially on C_3 plants was considered, nutrient limitation was not, such that the CO_2 effect found here is unlikely to be realized especially in low-managed systems.

Next steps towards a more complete account of water limitations to food security will have to consider both the actual diet composition and the origin of the consumed products. This will require a more detailed account of the water requirements for livestock products (e.g. by considering livestock feed baskets), and ultimately an integration of virtual water trade by accounting for the actual and potential future global pattern of production and consumption of agricultural products and the underlying green and blue freshwater resources. Yet, the present study represents a major step towards a more comprehensive and spatially explicit assessment of the water needs and limitations for producing the food for a growing world population.

References

- Arnell, N. W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. 14, 31–52.
- Bates, B. C., Z. W. Kundzewicz, S. Wu, J. P. Palutikof (Eds.), 2008. IPCC Technical Paper VI. Geneva, 210 pp.
- Bondeau, A., et al., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. , 13, 679–706.
- Fader, M., S. Rost, C. Müller, and D. Gerten, 2010. Virtual water content of temperate cereals and maize: Present and potential future patterns. , 384, 218–231.
- Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008. Causes of change in 20th century global river discharge. , 35, L20405.
- Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, K. Waha, 2011. Global water availability and requirements for future food production, early online.
- Grübler, A., B. O'Neill, K. Riahi et al., 2007. Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. , 74, 980–1029.
- Hoff, H., M. Falkenmark, D. Gerten, L. Gordon, L. Karlberg, J. Rockström, 2010. Greening the global water system. , 384, 177–184.
- Liu, J. G, J. R. Williams, A. J. B. Zehnder, H. Yang, 2007. GEPIC – modelling wheat yield and crop water productivity with high resolution on global scale. 94, 478–493.
- Mitchell, T. D., P. D. Jones (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. , 25, 693–712.
- Rockström, J., M. Lannerstad, M. Falkenmark (2007) Assessing the water challenge of a new green revolution in developing countries. , 104, 6253–6260.
- Rockström, R., M. Falkenmark, L. Karlberg, H. Hoff, S. Rost, D. Gerten (2009) Future water availability for global food production: The potential of green water for increasing resilience to global change. , 45, W00A12.
- Rost, S., D. Gerten, A. Bondeau, W. Lucht, J. Rohwer, S. Schaphoff (2008) Agricultural green and blue water consumption and its influence on the global water system. 44, W09405.
- Rost, S., D. Gerten, H. Hoff, W. Lucht, M. Falkenmark, J. Rockström (2009) Global potential to increase crop production through water management in rainfed agriculture. , 4, 044002.
- Vörösmarty, C. J., P. Green, J. Salisbury, R. Lammers (2000) Global water resources: vulnerability from climate change and population growth. , 289, 284–288.

The impact of water pricing in an arid river basin in Morocco considering the conjunctive use of ground- and surface water, water quality aspects and climate change

Claudia Heidecke [1] & Thomas Heckelei [2]

[1] Johann Heinrich von Thünen-Institut, Bundesallee 50, D-38116 Braunschweig, Tel: +49 531 596 5519, Fax: +49 531 596 5599, E-mail: claudia.heidecke@vti.bund.de

[2] Institute for Food and Resource Economics, University of Bonn, Nussallee 21, 53115 Bonn Germany, E-mail: thomas.heckelei@ilr.uni-bonn.de

Abstract

Climate change is likely to lead to more unreliable water supply in the future, especially in arid regions of the world. A hydro-economic river basin model is used to analyse the effects of an IPCC climate change scenario on water use and agricultural income in the arid Middle Drâa river basin in Morocco. The model considers problems of irrigation water salinity and the conjunctive use of surface and groundwater and their interconnections. We use REMO model data provided by the IMPETUS project (Speth et al. 2010) to derive a maximum likelihood density estimate of current and future water supplies that are introduced as a random variable into the mathematical programming approach for Monte Carlo simulations. The paper extends the work by Heidecke and Heckelei (2010) by simulating management options taking water pricing as an example. The effects on water use and different economic indicators are evaluated. Results show that climate change impacts negatively on irrigation water availability, and hence leads to a reduction in farm income. The effects of water pricing as a management option analysed depend on the assumptions of water quality of irrigation water, overall water supply and the scope of the water charge.

Keywords

climate change, conjunctive water management, hydro economic river basin models, water quality

Introduction

The impact of climate change on land use and water use has received increasing attention in research, especially with more data available from the IPCC (2007) report. According to IPCC by 2080 an increase of "5 to 8% of arid and semi-arid land in Africa is projected under a range of climate scenarios" (IPCC 2007: 50). The Middle Drâa valley in Southern Morocco is already facing semi-arid to arid weather conditions and is heavily relying on irrigation water for agricultural production in the six oases. Irrigation water is mainly drawn from the Mansour Eddabhi reservoir that is centrally managed to distribute water to the six oases along the Drâa River. During the last centuries water available from the reservoir has been decreasing due to less rainfall but also due to more demand and higher evaporation rates. Therefore, farmers have shifted to more groundwater use for irrigation. Groundwater is available from shallow aquifers below each oasis, which are connected due to a hydraulic gradient with each other (Klose et al., 2008). The specific setting of surface and groundwater availability and the interactions of groundwater aquifers as well as groundwater and surface water provide a challenging and complex system of conjunctive water use in the Middle Drâa valley. The economics of the conjunctive use of water have been analysed by economists since the sixties starting with simplified analysis by Buras (1963) and Burt (1964). The theoretical approach has since then been applied to various settings e.g. by Feinerman and Knapp (1984), Provencher and Burt (1994), Roseta-Palma (2006) and Gemma and Tsur (2007).

The conjunctive use of water in the Middle Drâa valley has been analysed with an optimization model by Heidecke et al. (2008) who set up an optimization model that allocates irrigation water between the six oases in an economic optimal manner. Heidecke and Heckelei (2010) used the model to analyse the effect of water quality and changing water inflow distributions under the assumptions of two climate change scenarios of the IPCC. In this paper we extend the work by Heidecke et al. (2008) and Heidecke and Heckelei (2010) to analyse water pricing as a management options under water scarcity and salinisation problems. Water pricing is mainly applied in developed countries. In developing countries or in countries facing water scarcity water pricing is controversially discussed as an economic tool to prevent water overexploitation. The FAO (2000) points out that the effectiveness of water pricing needs to be regarded behind the background of a comprehensive study that includes different exemptions. The Middle Drâa valley is a good example of a system where water pricing needs to be regarded carefully in the light of surface and groundwater interactions as well as the already existing high salinity rates in irrigation water and therefore, the economic effectiveness of irrigation water pricing. Therefore, we want to adress two questions in this paper.

Firstly, how does a groundwater pricing scheme affect agricultural income? This is a question that has already been analysed by Heidecke et al. (2008) for the Middle Drâa valley, but with a model version that did not incorporate water quality issues. They analysed in detail the difference of surface and groundwater pricing with respect to water use and agricultural income. However, water quality might influence the results. This shall be analysed in this paper.

Secondly, how does a water charge affect groundwater use in the different oases? For this we analyse a range of water charges in different settings and evaluate the effects in each oases separately. As water use is highly interactive in the Middle Drâa valley, water pricing needs to be regarded in the specific regional setting.

The paper is set up as follows. We first describe the data and the optimization model used with references to previous publications and model descriptions. We also describe groundwater pricing as a management options analysed in this paper. Then, we present some results of economic and hydrologic relevance. We end this paper with conclusions for water management in the Middle Drâa valley and elsewhere and point out the limitations of this modelling exercise.

Methodology

The model set up and applied for the Middle Drâa valley is described in detail by Heidecke et al. 2008. The use of climatic data within the model and the estimation of inflow distributions have been conducted by Heidecke and Heckelei (2010). In this section we briefly refer to the main characteristics of the modelling approach and then point out the adjustments for management options that have been added in this paper.

The optimization model is a comparative static optimization model that maximises total agricultural income calculated as the product of exogenous crop prices which could be received on local markets and production quantities, minus the production costs including costs for groundwater use. Surface water use is free of charge to the farmers. The model maximizes agricultural income over all six oases and for all major crops cultivated which are wheat, barley, maize, alfalfa, a vegetable aggregate, and henna and date palms as perennial crops. The model is solved for monthly periods and for one year simultaneously over all oases. The model is calibrated using the positive mathematical programming technique (PMP) (Howitt, 1995), but introducing supply elasticities as prior information in the specification step (Heckelei, 2002, Heckelei and Wolff, 2003). The elasticities for the perennial crops, date palms and henna, are more inelastic compared to the other crops as farmers give priority to these for financial reasons and try to preserve them in times of water shortage.

Water supply is coming from two sources: surface water and groundwater. Surface water is determined by the inflows into the reservoir where it can be stored and released to the oases each month. From there it is directed to the six oases. Groundwater is locally available in each oasis and determined by lateral inflows, irrigation and river water infiltration. Aquifers are also connected with each other according to specific flow gradients. Thus groundwater use in an oasis upstream affects groundwater availability in the oases downstream the river.

The stochastic nature of water availability is considered by available regional projections of precipitation under climate change scenarios A1B of the Intergovernmental Panel of Climate Change (IPCC, 2007) derived within the IMPETUS project (Speth et al. 2010) by Born et al. (2008) and Paeth et al. (2008) for southern Morocco. Heidecke and Heckelei (2010) extended the model to include reservoir inflows as a random variable. They estimate gamma distribution parameters of water inflows and conduct Monte Carlo experiments with random draws from the estimated inflow distributions. In this paper we compare the historical inflow distribution estimated from climate data from 1960 to 2000 with the A1B scenario of the IPCC based on REMO model data from 2001 to 2050. The first moment of the historical gamma distribution is 567, for scenario A1B 206, respectively. As this presents the average of inflows, it gets obvious that water is very scarce in the climate change scenario A1B compared to the current distribution of water inflows.

Water requirements per month and salt tolerances are crop specific. The salinity of irrigation water is determined endogenously in the model by the initial salt content in surface and groundwater, the average salinity rates of the mix of groundwater and surface water applied on the fields and the amount of water and salt leached due to irrigation (see also Heidecke and Kuhn, 2007). In general, groundwater quality in the Middle Drâa valley is more deteriorated due to the geological characteristics in the Drâa valley (Klose et al. 2008).

The simulations in this paper are made by respecting for water quality affects, in contrast to simulations which leave out water quality aspects to be able to compare ceteris paribus solely the affect of water quality regarding management options.

Water pricing is one option to manage water more sustainable. The current costs of groundwater use in the Drâa valley consist of costs for fuel and gas, and maintenance of the motor pumps. These costs have been estimated by Heidecke et al. (2008) at 58 cents of Moroccan Dirham (MAD) per cubic meter. In this paper we analyse different groundwater pricing options for the historical inflow distribution as well as for climate change scenario A1B. We first assume that an additional water charge of 1 MAD is imposed on the farmer on top of the water costs for pumping. We later wary the groundwater charge up to 3 MAD to analyse the effect of the scope of a water charge. We also derive groundwater demand functions for all oases.

Results

We compare the historical inflow distribution that was calculated on the basis of precipitation data from 1960 to 2000 with climate change scenario A1B of the IPCC from REMO model precipitation data for the years 2001 to 2050. Furthermore we compare the effects of a water pricing scheme for groundwater for different pricing options, by adding a water charge to the current costs of 58 cents MAD per cubic meter.

To address the first question, of how a water pricing scheme affects agricultural income, four scenarios are compared in Table 1. The total basin income refers to the agricultural income plus the revenues received from water pricing assuming that the charges of groundwater can be redistributed or invested in the river basin. The charge for groundwater (on top of the pumping costs of 58 cent per cubic meter) are set at 1 MAD per cubic meter (around 10 US$ cent). It is obvious that on average, agricultural income and total basin income are higher under the historical inflow distribution than under the climate change scenario A1B as overall more water is available in the river basin during the year and agricultural production is thus more efficient and productive. With a water charge of 1 MAD per cubic meter income for farmers from agricultural production is lower in both scenarios as farmers have to pay the water charge for each cubic meter of groundwater used. The total basin income, which reflects

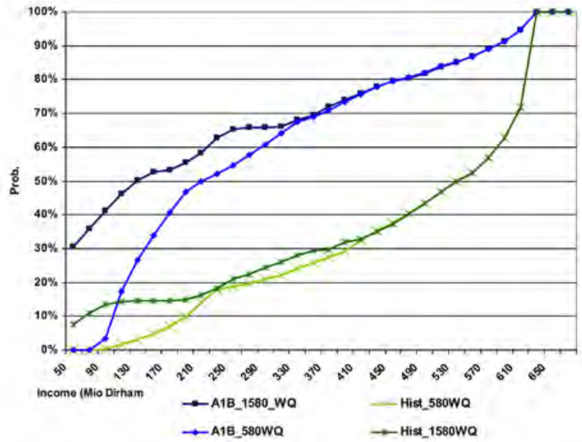
Table 1. Average values for selected indicator (and standard deviations in brackets) for the historical distribution and for one climate change scenario of the IPCC, both for the reference scenario and for the water pricing scenario

	Historical inflow distribution		A1B inflow distribution	
	No additional water charge	Water charge of 1 MAD	No additional water charge	Water charge of 1 MAD
Agricultural income	464 (166)	441(203)	277(175)	269(173)
Total income for the river basin	464(166)	466(166)	277(175)	365(125)
Surface water use	407(220)	410(218)	202 (170)	197(173)
Groundwater use	37(57)	24(40)	71(44)	86(54)

the agricultural income plus the water charge, is slightly higher in the historical scenario, and nearly 100 Million Dirham more in scenario A1B, as a lot of groundwater is used in the later and costs could be redistributed back to the farmers. Groundwater use is more expensive but therefore more efficiently distributed between the oases. In the northern oases the higher costs for groundwater use make groundwater use less profitable and more water can infiltrate to the oases downstream.

This leads to the conclusion that a water pricing scheme might even lead to higher total incomes and more effective use of groundwater in the Middle Drâa valley if water is scarce. However, a water pricing scheme that aims at water saving and at income security, the effects of a groundwater charge needs to be further investigated. Therefore,

Figure 1. Cumulative income distribution for four scenarios



we derive the cumulative income distribution function of the total basin income for the four scenarios on the basis of 1000 models runs of the inflow distribution functions in Figure 1.

The cumulative distribution of the total basin income for the four scenarios in Figure 1 reveals that with a water pricing of one Dirham per cubic meter, the distribution of income is shifted slightly to the left, which means that the probability to get lower incomes is more likely with a water price, especially in times of water scarcity as groundwater use arouses additional costs. So in case the water charge is not redirected to the farmers in monetary terms, in cases of extreme scarcity a water charge increases the probability of farmers to receive revenues of less than 200 Million Dirham.

The second question that we want to address is how water prices affect the demand for groundwater in the different oases. Therefore, several simulations with different water prices were made for the different scenarios (Figure 2). It is obvious that high salinity rates in irrigation water change the groundwater demand functions. Salinity rates are higher for groundwater than for surface water and higher

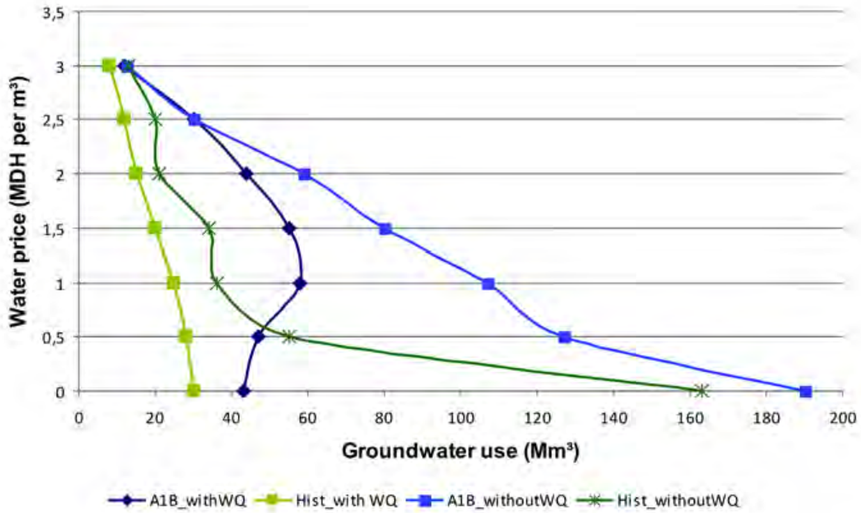


Figure 2. Groundwater demand under different scenarios

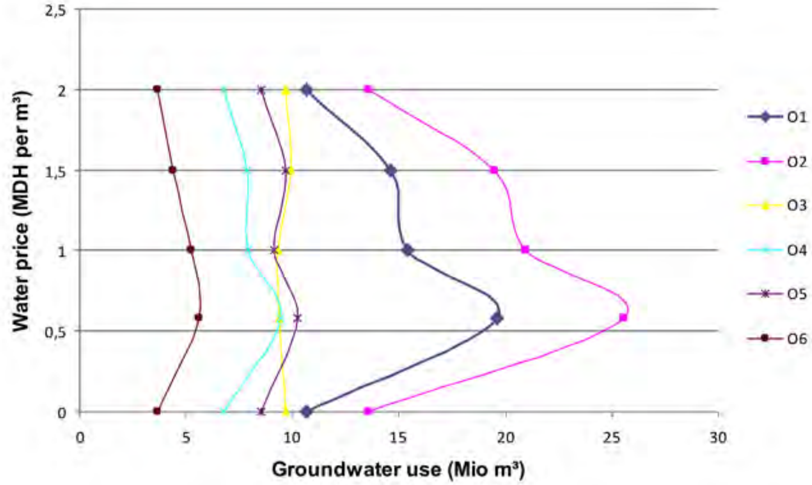


Figure 3. Groundwater demand in scenario A1B in each oases of the Middle Drâa valley

in southern oases compared to oases north upstream the Drâa river. Therefore, even with no water charge the demand of groundwater is much lower as salinity rates lead to less effective irrigation of crops.

To analyse the effect on the different oases, Figure 3 displays the different groundwater demand curves for scenario A1B´from the most northern oasis O1 to the most southern oasis O6. The northern oases closest to the reservoir have more surface water available from the river. Here, the groundwater demand curves (O1 and O2) are more elastic. However, in the more southern oases where water, especially groundwater, is scarce, the groundwater demand curves are more inelastic. This leads to the conclusion that a water pricing scheme needs to be carefully discussed taking into account the regional interactions and the demand curves of different sites. Under inelastic water demand a water pricing scheme will not lead to water conservation and will only have a negative impact on agricultural incomes.

Conclusion

Climate change impacts on water use were discussed in this paper by focusing on one case study of an arid river basin in Southern Morocco and by discussing water pricing as a management option under increasing water scarcity. We presented an optimization model which is able to consider the conjunctive use of ground- and surface water in a specific oases setting, providing the challenge that not only surface and groundwater interact, but also different groundwater bodies are connected with each other. From a methodological and an economic point of view it is of interest to see how water use in one oasis affects water use in the other oases downstream and how water pricing could be a management option for sustainable future water use, regarding the different characteristics and locations of the oases, as well as current water supply and future climate change projections.

Similar to other studies of climatic change impacts and economic valuation of water use we find that water pricing can be an option to stabilize groundwater tables and might also lead to more income given appropriate redistribution schemes of water revenues. Water pricing is less effective if water is already very scarce, either due to less water available from the reservoir, to shortages in specific oases, or water quality deterioration affecting irrigation productivity.

The limitations of this study are the following:

1. We use a comparative static setting for one year although we introduce climatic effects as a stochastic variable. Consequently, the effects between years and the availability of water depending on previous year's water use cannot be analysed.

2. A recursive dynamic simulation exercises such as Heidecke et al. (2008) allows for the analysis of groundwater tables over years. This would be interesting for future research including dynamic inter-annual salinity effects.

3. An appropriate use of the reservoir in the Middle Drâa valley is already a management option to stabilize water supply over the years. However, the reservoir is not large enough to store water over several years, so that the reservoir is more a water channel to the Middle Drâa valley from the upstream catchment area.

4. Climate change is discussed controversially and meteorologists always point out the high uncertainties related to, especially downscaled, regional data. Therefore, results related to climate change projections in this study have to be treated with caution.

References

» Born, K., Fink A. H., Paeth, H. (2008) Dry and wet periods in the Northwestern Maghreb for present day and future climate conditions. Meteorologische Zeitschrift 17, 553-551.

» Buras, N. (1963) Conjunctive operations of dams and aquifers. Journal of Hydraulics 89, 107-29.

» Burt, O.R. (1964). The economics of conjunctive use of ground and surface water. Hilgardia 36, 31-111.

» Feinerman, E., Knapp, K.C. (1983) Benefits from groundwater management: magnitude, sensitivity, and distribution. American Journal of Agricultural Economics 65, 703-710.

» FAO (2000) Pricing irrigation water – a literature survey.

» Gemma, M., Tsur, Y. (2007) The stabilization value of groundwater and conjunctive water management under uncertainty. European Review of Agricultural Economics 29(3), 540-8.

» Heckelei, T., (2002) Calibration and estimation of programming models for agricultural supply analysis. Habilitation thesis. University of Bonn. Germany.

» Heckelei, T., Wolff, H. (2003) Estimation of constrained optimisation models for agricultural supply analysis based on generalised maximum entropy. European Review of Agricultural Economics 30(1), 27–50.

» Heidecke, C., Heckelei, T. (2010) Impacts of changing water inflow distributions on irrigation and farm income along the Drâa River in Morocco. Agricultural Economics 41: 135-146.Heidecke, C., Kuhn, A. (2007) Considering salinity effects on crops yields in hydro-economic modelling. Brebbia, C.A. Kungolos, A.G., eds., Water Resources Management, Volume 4 , 63-72. WIT Press.

» Heidecke, C., Kuhn, A., Klose, S. (2008) Water pricing options for the Middle Drâa river basin in Morocco. African Journal of Agricultural and Resources Economics 2(2), 170-187.

» Howitt, R.E. (1995) Positive Mathematical Programming. American Journal of Agricultural Economics 77, 329-342.

» IPCC (2007) Climate change 2007- synthesis report. Fourth assessment report of the Interngovernmental Panel of Climate Change. Rome.

» Klose, S., Reichert, B., Lahmouri, A. (2008) Management options for a sustainable groundwater use in the Middle Drâa Oases under the pressure of climatic changes. Zereini, F., Hötzl, H., eds, Climatic Changes and Water Resources in the Middle East and in North Africa. Springer.

» Paeth, H., Born, K., Girmes, R., Podzun, R., Jacob D. (2008) Regional climate change in tropical and northern Africa due to greenhouse gas forcing and land-use changes. J. Climate, accepted.

» Provencher, B., Burt, O. (1994) Approximating the optimal groundwater policy in a multiaquifer stochastic conjuctive use setting. Water Resources Research 30, 833-843.

» Roseta-Palma, C. (2006) Conjunctive use of surface water and groundwater with quality considerations. Goetz, R., Berga, D., eds., Frontiers in water resource economics. Springer US. 225-240.

» Schulz, O., Busche, H., Benbouziane, A. (2008) Decadal precipitation variances and reservoir inflows in the semi-arid Upper Drâa basin (south-eastern Morocco). In: Zereini, F., Hötzl, H., eds., Climatic Changes and Water Resources in the Middle East and in North Africa. Springer.

» Speth, P., Christoph, M., Diekkrüger, B. (2010) Impacts of global change on the hydrological cycle in West and Northwest Africa. Springer Verlag Heidelberg, Berlin, 675 p.

» Tsur, Y. (1990) The Stabilization role of groundwater when surface water supplies are uncertain: The implications for groundwater development. Water resources research 26(5), 811-818.

Assessing the use of hydrologic drought indicators in characterizing the extent and severity of the 1999-2005 drought on the Canadian prairies

Richard Lawford[1] & Phillip Harder[2]

[1] University of Manitoba,
E-mail: lawford@umbc.edu

[2] University of Saskatchewan

Introduction

Hydrologic droughts are important because of their impacts on water availability and the resultant social and environmental hardships. Information on hydrologic droughts is important for planning restrictions of water use and for timing the access to alternate water supplies. Reduced flows and lowered lake levels are also very visible evidences that dry conditions are prevailing. Some Canadian provinces such as Ontario deal with dry periods by using the occurrence of flows lower than a prescribed threshold as their criteria for water rationing. Within the broader framework of drought, hydrological drought tends to be more difficult to characterize than other types of drought because measurements at a hydrometric station reflect meteorological and hydrological processes that have been taking place over the area upstream of the station for a period of time.

Given that agricultural droughts are primarily the result of a lack of water in the soil and that soil moisture affects runoff generation, one would expect that a relationship between agricultural and hydrologic droughts should exist although it could be complex especially during the winter and spring months. Agricultural droughts are of great concern during the growing season but hydrologic droughts are of concern during every month and season. In this article we review a hydrologic drought on the Canadian Prairies in terms of a number of hydrologic drought indicators.

These drought indicators or methodologies include:

» Comparative analysis of actual and naturalized (apportionment) flow hydrographs,

» Threshold Exceedance Analysis,

» Effective Basin and Synthetic (or incremental) Effective Basin Runoff Coefficients.

The purpose of this review is to assess drought indices in terms of their ability to capture the characteristics of a drought, their sensitivity to changes in the intensity of a drought and their ease of use when used to characterize a recent multiyear (1999-2005) drought on the Canadian Prairies.

Data used to compute the drought indices

The indices used in this drought indices analysis relied on streamflow data and, in the case of runoff coefficients, precipitation data.

Actual and naturalized (apportionment) streamflow data

Two types of flow information are used to assess drought. The first type is the actual streamflow data which are reported on a daily basis for a number of hydrometric stations on the Canadian Prairies. These data were obtained from Environment Canada and used in all of the analyses presented in this report.

The second set of "data" consisted of naturalized flow estimates (also known as apportionment flow amounts). They were obtained from the Prairie Provinces Water Board (PPWB) and covered the 1999-2005 period as well as 15 to 23 years preceding the drought (depending on the station). These natural flow values compensate for the effects of wetlands, reservoirs, evaporation, irrigation demands, other water uses, and drainage patterns on the flow. These computed flows are the PPWB's best estimate of the flow that would be present if there had been no interventions such as withdrawals, dams or reservoirs. In some ways these estimates should be considered as a management tool rather than a rigorous data set for scientific research. In order to ensure equity in water transfers between the three Prairie Provinces, the PPWB coordinates data and agreements related to the transfer of water across provincial boundaries as well as using the naturalized flows at inter-provincial border stations to monitor the implementation of these agreements.

On the Canadian prairies, naturalized (apportionment) flows are computed differently for different rivers and may have changed over time which adds to the complexity of using them as a drought index (Pomeroy, 2010). For example, the South Saskatchewan River basin naturalized flows are calculated using the Project Depletion Method (PDM), while the Qu'Appelle River flows are computed with the Annual Water Balance Method (AWBM) and the Cold Lake River flows are estimated using the Rational Method (PPWB, 2005). With the PDM method the naturalized flow at the apportionment point is calculated by summing the recorded flow plus any changes in reservoir storage plus diversions minus return flows. This method requires information on other factors such as reservoir evaporation, evapotranspiration, conveyance losses, ungauged flows, and unmeasured consumptive losses. Some of these factors are not measured and commonly indices are developed and applied to the entire upstream contributing areas (Halliday and Faveri, 2007). The AWBM uses an accounting of the masses of water moving through various portions of the hydrologic cycle over the basin annually. To obtain the true naturalized stream flow it would be necessary to determine all of the other water balance components, precipitation, evaporation, groundwater and storage and their fluctuations (Dingman 2002). Although less rigorous, the rational method which establishes an empirical relation between rainfall intensity and peak flow using coefficients fitted to the basin of interest is applied to estimate naturalized flow at some stations (see ASCE, 1996 for more details).

Precipitation data:

Precipitation estimates for each of the basins were computed from the Environment Canada CANGRID 2007 data for each of the basins as defined by the National Land Water Information System (NLWIS) effective area drainage basins. These precipitation estimates were

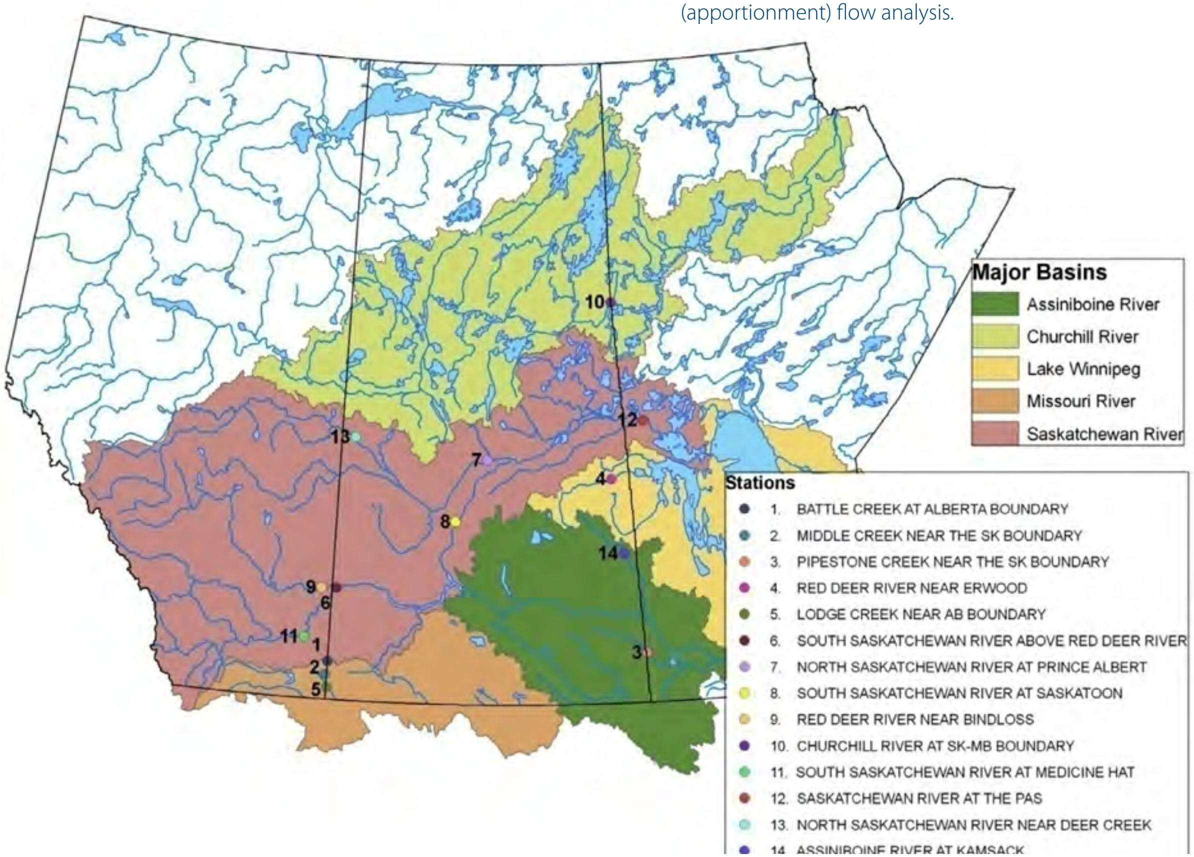


Figure 1. Map showing stations used in the naturalized (apportionment) flow analysis.

computed by overlaying the basin boundaries on the CANGRID grid cells; determining the area of each CANGRID grid cell contributing to each basin and multiplying the fraction by the CANGRID grid square precipitation estimate and summing these amounts to obtain monthly precipitation estimates for each basin. The CANGRID data set was developed for Canada by Environment Canada based on 111 years (1896-2006) of station data interpolated with an approximately 50km grid spacing. The representation of precipitation fields in this study was complicated by the lack of US coverage in the CANGRID precipitation data set. In US areas where precipitation data were missing estimates were developed by extrapolating the Canadian data,

Hydrologic drought indicators:

The drought of 1999 – 2005 brought record dryness to some parts of the Canadian Prairies seriously impacting agricultural production, water availability and the economic well-being of people and communities on the Canadian Prairies. As described by Hanesiak et al. (2011) the drought began with below average precipitation in the northern parts of the Canadian prairies in 1999. These deficits spread southward and by 2001 they covered the Prairie Provinces. In 2002, these deficits continued over the prairies with the exception of southeastern Alberta and southwestern Saskatchewan. This was followed by another below average precipitation year in 2003 and higher than average precipitation amounts in 2004 in southern Saskatchewan and over the entire southern prairies in 2005. One consistent feature of the anomalies in precipitation was the below average precipitation in the foothills of the Rocky Mountains for 1999 to 2004.

Comparative analysis of actual and apportionment flow hydrographs

The descriptions and analyses of monthly naturalized stream flows were presented as anomalies (departures from average) at the hydrometric stations and used to characterize the drought conditions at stations along the Alberta-Saskatchewan (A-S) and the Saskatchewan- Manitoba (S-M) borders. As noted earlier, these stations were chosen because of their relevance to the apportionment of water between provinces which is particularly critical during periods of drought. Figure 1 shows the location of these stations.

Figure 2. Monthly naturalized flows for the North Saskatchewan River near Blindloss.
Station #9: North Saskatchewan River near Deer Creek

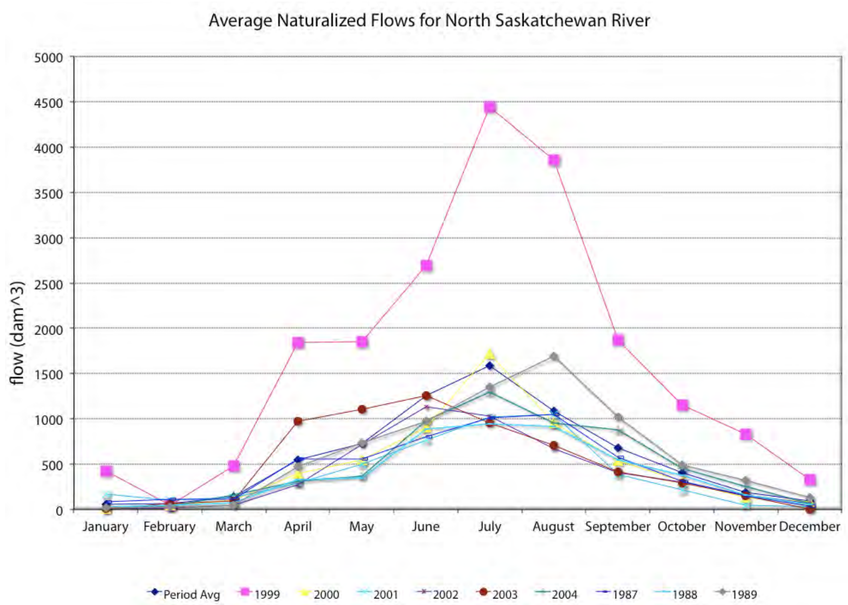
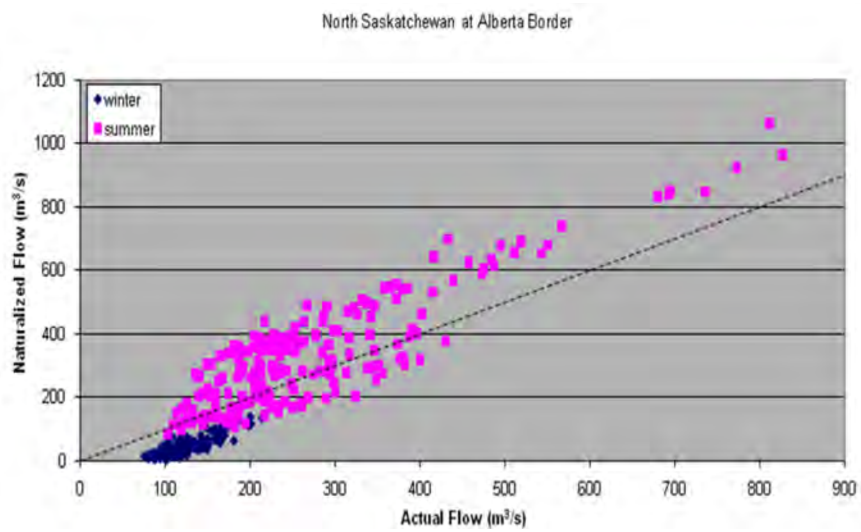


Figure 3. The relationship between the actual flows and the naturalized flows for the North Saskatchewan River at the A-S border. The straight line represents the points where actual streamflow equals naturalized streamflow.



The naturalized flow values are used by provincial and federal water managers when assessing whether commitments to transfer 50% of the annual water available in the upstream province across the border to the downstream province have been achieved. This analysis was completed for 8 stations (Assiniboine River at Kamsack, Churchill River at Saskatchewan-Manitoba border, North Saskatchewan at Prince Albert, North Saskatchewan near Deer Creek, Red River near Blindloss, Saskatchewan River at the Pas, South Saskatchewan River above Red Deer River, and South Saskatchewan River at Medicine Hat) for the period of 1977-2006 (30 years) and supplemented by 5 more stations (Middle Creek near the Saskatchewan Boundary, Lodge Creek near the Alberta Boundary, Battle Creek at the Alberta Boundary, Red Deer River near Erwood, Pipestone Creek near the Saskatchewan Boundary) for the 1985-2006 period (22 years).

The descriptions and analyses of monthly actual streamflows were also presented as anomalies (departures from average) at the same hydrometric stations and used to characterize the drought conditions. The results from this analysis were also compared to the findings of Hanesiak et al. (2011) who analyzed the drought from a number of perspectives, including considerations of meteorological and land surface conditions.

Analysis of naturalized (apportionment) flows and comparisons to actual flows

Single station analysis:

Figure 2 shows the normalized flows on the North Saskatchewan near Deer Creek. Peak flows in the North Saskatchewan occur in the summer (June to August). This reflects the distance that water travels from the source regions in the Rocky Mountains along the river to reach the A-S border. In addition, the snowmelt and glacier melt in the Rocky Mountains continues well into the summer in the case of snow and into the fall in the case of glaciers contributing to peak flows in the June to July period. From these results it is clear that 1999 was not a hydrologic drought year along the Saskatchewan River at the A-S border. However drier conditions occurred in 2000 with most months below average. Other very dry seasons included the summers of 2001 and 2002 and the fall of 2003.

During the period from 2001 to 2004 the naturalized flows in the North Saskatchewan were below average on a number of occasions. The spring flows in 2001 and 2002 were lower than average with the

Figure 4. Monthly naturalized flows for the Red Deer River at Blindloss.

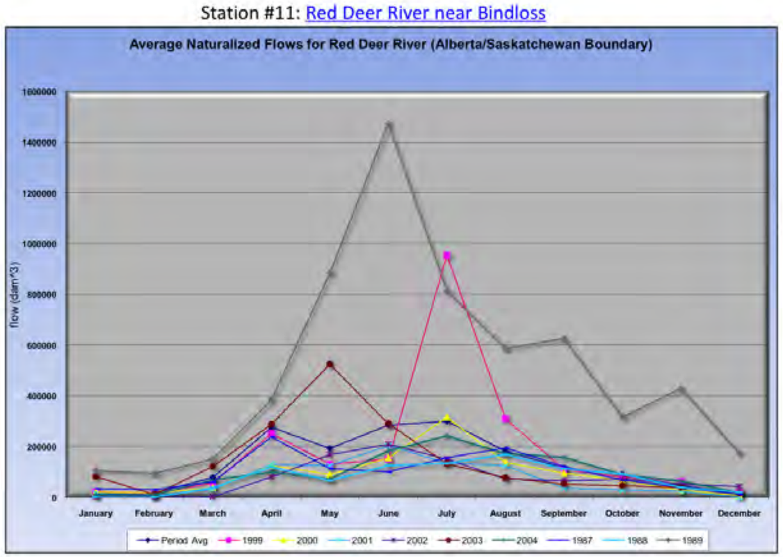
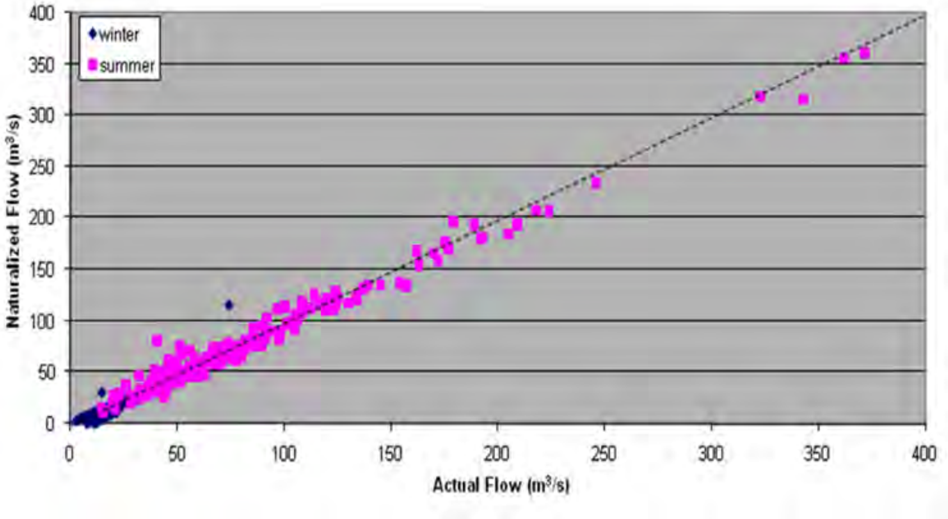


Figure 5. The relationship between the actual flows and the naturalized flows for the Red Deer River at Bindloss (on Alberta-Saskatchewan border). The straight line shows the one-to-one match between actual flow and naturalized flow.



lowest relative flows tending to come in September. The departures from average for the naturalized flow were significantly larger that the departures from average in the actual flows. At this station both actual and naturalized flows began to recover in the last half of 2004 and returned to near normal in 2005.

One issue affecting the interpretation of naturalized flows involves their relation to actual flows. Scatter plots were developed for border stations to assess the relationships at different stations between the naturalized flows and the measured flows during the summer and winter months. Figure 3 shows the distribution of naturalized flows versus actual flows for the North Saskatchewan River near the A-S border. The results of this analysis indicate that these monthly average flows are relatively well correlated especially when the actual flow exceeds 400 m^3/s although the naturalized flows are systematically higher than the actual flows. During periods when monthly average flows are less than 400 m^3/s they vary widely. Since drought is a low-flow event, naturalized flows during droughts are likely less than actual flows especially when the actual flow is less than 135 m^3/s.

The naturalized flows and actual flows for the Red Deer River, which drains a large area in central and eastern Alberta, are more consistent than they are at some of the other border stations. At Blindloss, the natural flows and actual flows on the Red Deer River (see Figure 4 for naturalized streamflow and the scatterplot for naturalized versus actual flows in Figure 5) are very similar indicating that human interventions on the river are less likely to have an impact on the measurements and that naturalized flows are a more reliable indicator of the severity of a hydrologic drought.

At Blindloss where the river enters Saskatchewan from Alberta, flows tend to have a relatively small annual cycle because the spring freshet is supplied by snowmelt on the prairies in central and eastern Alberta rather than the foothills. Beginning in the summer of 2000 the flows were below normal and continued to be below normal until April 2003 when they rose above average for two months only to decrease to below average values by June. According to the actual streamflow values the most significant period of streamflow drought occurred in August 2003. Figure 5 shows that there is good agreement between the naturalized and the actual flows at Bindloss.

Drought history derived from naturalized flows:

Based on the normalized flows an analysis of the drought was carried out that was in good agreement with the much broader drought analsyis carried out by Hanesiak et. al. (2011). Single station graphs were used to assess the progress of the drought along the A-S border and the S-M border. Similar results were obtained between naturalized and actual flows although a few shifts were noted a specific stations. The text below describes the signature of the drought found in naturalized and actual flows along the borders.

1999:

During this year the naturalized flow along the southern parts of the A-S border was below average in the latitudes south of 50°N. However, these are relatively small tributaries and which are nearly dry during many summers. Further north flows appeared to be average or even above average (North Saskatchewan River). Naturalized flows at stations on the southern part of the S-M border tended to be at or above average except for a below average flows on the Saskatchewan River in the April to July time frame. Farther north, the Churchill River was below average for the entire year reflecting the effects of the below average precipitation in the northern prairies. It appeared that the drought did not have a significant hydrologic signal in 1999.

2000:

Along the A-S border the hydrologic drought effects appeared at stations in the south. Naturalized flows in the central part of the A-S border were below average with both the Lodge and Middle Creeks going dry. The Red Deer River showed a large decrease beginning in August. The use of upstream irrigation to compensate for the lack of precipitation may have affected the drawdown rates in this basin. Naturalized flows along the southern part of the S-M border were below average with virtually no spring melt peak although secondary peaks in June and July appeared in both the Qu'Appelle and Assiniboine Rivers. The Saskatchewan River flow was also below normal from May on-ward. Further north, the Churchill River flow was above average for most of the summer.

2001:

During 2001 both actual and naturalized flows were very low at stations along the A-S border. These low flows indicated a much smaller snowmelt contribution than most other years. Flows in the larger basins decreased in 2001 with very low values beginning in the South Saskatchewan River in May 2001, the Red Deer River in June 2001 and the North Saskatchewan in September 2001. The Red Deer River was above average in May and then decreased rapidly to the point where June and July flows were well below average. The flows at stations further north were also lower than average for the entire year. Along the S-M border, the naturalized flows were average to slightly above average for the southern stations in the spring of 2001 but decreased to below average after June in the Qu'Appelle River. Further north, the Saskatchewan River was below average for the entire year while the Churchill River was below average with very low flows in the May to September period. These decreases were more dramatic in the naturalized flows than in the actual flows.

2002:

For the southern rivers on the A-S borders, the naturalized flows were below average but increased rapidly in May in the Red Deer River Basin and in June in the South Saskatchewan River. Flows for the other basins were below average with the exception of a peak in June in the Battle Creek and Lodge Basins. These increases may have been associated with a storm event that affected southern Alberta (Stewart et al. 2011), The drought effects also were clearly evident in the southern stations along the S-M border with naturalized flows well below average on the Qu'Appelle River and the spring peak was absent for the Assiniboine River. The Saskatchewan River naturalized flow was also below normal except for above average flows in the months of June and July, possibly associated with convective storms

Table 1. Characteristics of streamflow droughts observed in 1999-2004. *A=Actual N= Naturalized*

River	Total Months below Q10 (1999-2004) (A/N)	Max. consecutive months below Q10 (A/N)	Start date for longest consec period below Q10 (A/N)	Max. Deficit in the Actual Flow (m3)	Max. Deficit in the Naturalized Flow (m3)
North Sask. at AS border	10/1	3/4	Sep 1, 01/Sep 1, 01	4,819,392	6,432,903
Red Deer River at Bindloss	11/1	8/3	Aug 1, 03/Sep 1, 01	2,931,552	3,400,940
South Sask. below Red Deer River	12/11	5/8	May 1, 01/Aug 1, 01	8,825,376	15,332,151
Assiniboine River at Kamsack	11/13	7/8	Aug 1, 03/Sep 1, 03	73,815	35,606
Saskatchewan River at MS Border	16/15	4/8	Sep 1, 01/Sep 1, 01	57,049,920	23,378,889 (1/3/03 32,552,424)
Churchill River	7/2	6/1	Sep 1, 99/Mar 1, 02	900,000	2,615,903
Battle Creek	12/11	8/8	Mar 1, 01/Mar 1, 01	15,652	19,496
Lodge Creek	10/10	5/5	Mar 1, 01/Mar 1, 01	673	2,642
Middle Creek	11/13	3/7	Mar 1, 01/Mar 1, 01	2028	2,123
Pipestone Creek	3/5	1/2	Aug 1, 03/Mar 1, 04	603 (01/11/04 5090)	5,545
Red Deer River (near Elwood)	14/14	8/8	Jun 1, 01/Jun 1, 01	309,121 (01/03/02 740,863)	275,813 (01/03/02, 661,128)

in the South Saskatchewan River Basin. The Churchill River, where flows appeared to be decoupled from the southern basins in many years, remained below average until October.

2003:

The spring flows in the South Saskatchewan and Red Deer Rivers on the A-S border were above average until May and then dropped off rapidly in the summer as the drought conditions intensified. There were no significant decreases in any other stations in 2003 so it appeared that the hydrologic drought had ended along the A-S border at the end of 2003. On the M-S border the Assiniboine River had a significant spring peak but a strong recession quickly reduced the flows to below average flows. However, the Qu'Appelle was above average in the spring and remained above average for most of the year. The Saskatchewan River naturalized flow was below average until July while the Churchill River was slightly below average.

2004:

Naturalized flows along the southern A-S border were generally near average for the Red Deer River and the South Saskatchewan Rivers while flows in the Lodge and Middle Creeks were below average. Other stations along the border varied from above average to below average but only the North Saskatchewan River, which started the year below average but recovered by September, showed a significant streamflow deficit. Along the S-M border naturalized flows on the Qu'Appelle River and Saskatchewan Rivers were below average until the summer. The Assiniboine River was average with the exception of an above average spring runoff while further north the Churchill was slightly above average during the latter half of the year. Based on these results it appeared that the hydrologic drought had ended on most of the rivers by the close of 2004.

Assessment

While the use of hydrographs from actual and naturalized flows may appear to be very basic it is a useful step in understanding the behavior of drought at each hydrometric station. Furthermore, it does not appear that the use of naturalized flows rather than actual flows would influence conclusions from this approach except where large uncertainties exist in the data being used in the naturalized flows. In some cases the naturalized flows departed significantly from the actual flows making interpretation of the results more complex since the factors accounting for these differences were not monitored. However, in nearly all cases the direction of the anomalies (positive or negative) that were present in the actual streamflow also existed in the normalized streamflow estimates. A major limitation in using the naturalized flows for scientific applications arises from the reservation of both the data providers and experts about the unquantified uncertainties in the naturalized flows. In order for naturalized flows to be most useful in water management, the authors believe that it is important to document the uncertainties and variabilities that are used in calculating these flows. Ultimately these values would be most useful if these flows were calculated with the same methodologies for each station and the values of each input to the naturalized flow calculation was made available.

Threshold exceedance analysis:

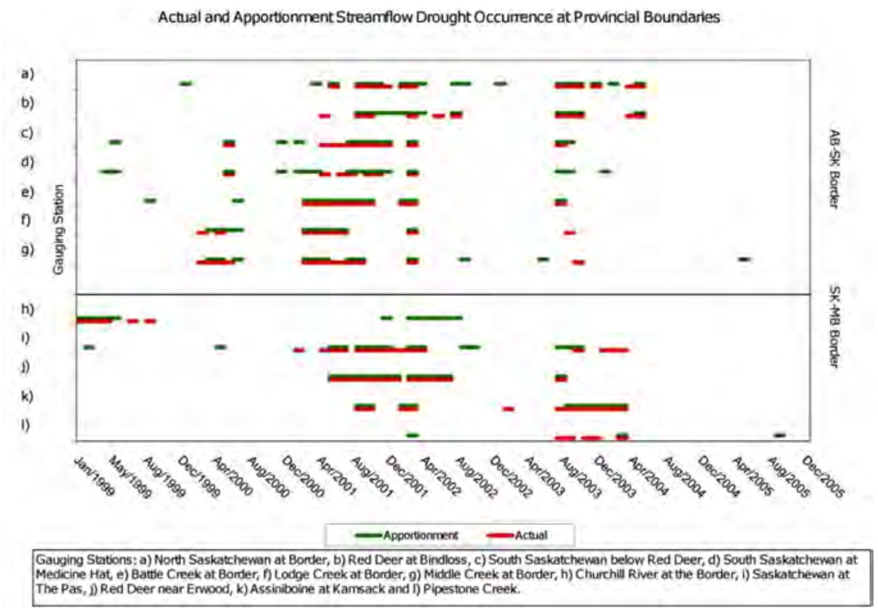
Although the comparative analysis provided qualitative information about the areas where drought effects on streamflow were most noticeable, it was evident that these analyses would be more meaningful if the results could be compared against a threshold or long-term average that indicated the severity of the drought conditions. An analysis was carried out for both the naturalized and actual monthly flows at each location using a threshold exceedance analysis for locations along the A-S and S-M borders.

The threshold exceedance analysis is a commonly applied quantitative streamflow drought estimation method. Initially this method was called 'method of crossing theory' and early hydrologic application was carried out by Yevjevich (1967). Conceptually, the threshold level method is used to define and study periods in a time series which occur above or below a certain level or threshold. Central to any application of the threshold level method is selection of a threshold value. Threshold levels can be fixed, time variant and based upon previous observations of the river or other rivers, or even arbitrarily selected. In this analysis the monthly threshold used was the 10th percentile flow designated as Q_{10}. This threshold, calculated for monthly flows, varies considerably over the course of the water year and can be thought of as the low flow that occurs only 10 percent of the time or less, or alternatively, the value for which monthly streamflow is greater 90 percent of the time. Once defined, the difference between the streamflow and the monthly threshold provides an indication of the intensity of a hydrologic drought for a particular gauging station.

For an individual station the difference between the actual or naturalized streamflow is subtracted from the threshold level [actual (or naturalized) streamflow – threshold level]. If the value of this difference is negative the station is considered to indicate deficit periods or hydrologic drought conditions. A pooling procedure was used to combine multiple hydrologic drought events if the intervening period between the events was no greater than 1 month. The length of the deficit period was calculated following the pooling procedure. The volume of flow that represents the difference between the threshold flow and the actual flow for the defined period was calculated by summing the deficits over each consecutive month when a deficit existed using the relationship:

Deficit volume (m3) = ∑ (Deficit) i

Figure 6. The distribution of very low streamflows (<Q_{10}) during the 1999 to 2005 drought on the Canadian prairies.



In addition, the cumulative value of the deficit was calculated by accumulating the deficits from month to month. This cumulative value was also used as a hydrological drought severity index.

Table 1 summarizes the results from this analysis. The table shows that the total number of months with deficits and the maximum number of continuous months with deficits based on both the actual and naturalized streamflows below Q_{10}. It also shows the month when these deficits started and the magnitude of the maximum deficit. In most cases the deficits for the actual flows are greater than the values for the naturalized flows except for the smaller rivers where the deficits in the actual flows tend to be larger. One exception is the South Saskatchewan River below the Red Deer River where the flows are large but the naturalized deficit is almost twice as large as the deficit in the actual flows. In 2001, there was a drought deficit of more than 16 million m^3 in the South Saskatchewan River naturalized flow along the A-S border accumulated over 5 consecutive months of hydrologic drought. These net anomalies were transmitted to the Saskatchewan-Manitoba through the Saskatchewan River where even larger deficits occurred at the border. Also in 2001, the small rivers along the more northern part of the Alberta-Saskatchewan border were dry.

Similar numbers of months with hydrologic droughts occurred on the Assiniboine and Middle Creek Rivers. The Saskatchewan River (Actual 16 months, Naturalized 15 months) at the S-M border experienced more months of hydrologic drought than any other station. On the other hand, the Churchill River just to the north of the Saskatchewan River experienced only two months of hydrological drought based on actual flows (7 months based on naturalized flows). Furthermore, the timing of hydrologic drought on the Churchill River suggests that it is out of phase with the more southern rivers. The longest periods of continuous hydrologic drought based on naturalized flows occurred along the A-S border at the South Saskatchewan River below the Red Deer River, the Red Deer near Elwood and Battle Creek (8 months), and the Assiniboine (8 months) and Saskatchewan River (8 months) on the S-M border. With the exception of the Battle Creek and Red Deer River where the consecutive number of months of normalized flows equaled the number of months of consecutive actual flows, the period of consecutive months of normalized flows were shorter than the sequences of months with deficit actual flows.

Figure 6 summarizes the results of the analysis for deficits for all of the stations included in the along-border analysis. This analysis shows that although the smaller tributaries were dry in southern Alberta during the drought these small streams are frequently dry in summer. However, in 2001 and 2002 in particular, the flows in the North and South Saskatchewan Rivers were below the Q10 value and these anomalies appeared to propagate downstream to the S-M border. With the exception of short-term relief associated with local storm systems, this hydrologic drought became significant again in 2003 and in early 2004 on both the A-S and S-M borders. This analysis shows that individual storms can impact a hydrologic drought event by increasing streamflow for one to two months in the basins where they occur.

The results of this analysis for individual stations provide additional insights to the station by station comparative analysis reported in section 3.1. During the period from 2001 to 2004 the actual flows in the North Saskatchewan on the A-S border decreased below the Q_{10} value for 13 months although none of these hydrologic droughts lasted for longer than 4 months. The spring flows in 2001 and 2002 were lower than average and were followed by the lowest relative flows which tended to come in the late summer. The naturalized flows had six short excursions below the Q_{10} values. Two of these excursions lasted for three months: one began in September 1, 2001 and the second began in February 2002. Flows began to recover in the last half of 2004 and returned to near normal in 2005. The streamflow deficit associated with the actual flow was significantly larger than the deficit in the naturalized flows. These variations may reflect the uncertainties in the naturalized flows on the North Saskatchewan under low flow conditions that were evident in Figure 3.

Assessment

The use of threshold exceedance analysis as a drought indicator demonstrated the value of having a threshold to indicate that drought conditions were occurring. The very large annual cycle in runoff led to the use of thresholds based on monthly averages instead of threshold based on an annual average. Although there may be some debate about the threshold value itself (Q_{10}) it is unclear that the choice of a larger threshold (e.g., Q_{20}) would have led to substantially different results although the frequency of drought would have been larger and the length of periods of continuous hydrological drought would have been longer (or shorter if a Q_5 threshold was used). The need to use a mix of stations with 30 years and 23 years of data in order to sample the maximum number of rivers possible also complicated this analysis. Although this was inconvenient, based on this analysis the authors do not think the results would have changed although the magnitudes of the cumulative deficits may have been reduced somewhat. The threshold also allows for more confident comparisons between basins. This approach is more labour intensive in terms of preparing and analyzing the data than analysis than the comparative analysis approach since it requires the development of a probability distribution and the specification of Q_{10} values for each station and for each month before the analysis can proceed.

Runoff indicators

Runoff indicators were used to explore the effect of prairie droughts on the generation of streamflow, including the average effect of rainfall over a basin on the discharge from that basin. Prairie runoff is usually snowmelt generated although there are a number of years such as the spring and summer of 2011 when rainfall has had a similar or even larger control on streamflow. During most years in the 1999-2005 drought, below average precipitation occurred in the source areas for much of the spring streamflow in the prairie rivers. The base flow in these rivers during late summer and autumn is generally produced by groundwater discharge. Rainfall that generates streamflow generally only occurs once the soil moisture and vegetation demands are met. The soil moisture demands are increased by evapotranspiration demands that dry out the soil and increase the infiltration. In the case where rain falls on very dry soil, the water generally will infiltrate the soil until the upper layers are saturated. The exception occurs in periods of heavy rain when the rain rate exceeds the infiltration rate and the excess moisture runs off. On the prairies during snowmelt most of the meltwater moves over the surface because the soil is partially frozen, which limits infiltration, and vegetation is inactive so there is no local drawdown or drying of the vadose zone moisture by evapotranspiration. In drought situations, the runoff would be further reduced because any rain that fell would be quickly absorbed by the parched soil. On many parts of the Canadian prairies the topography is so flat that the water does run off but not to a river where it merges with the streamflow but to a wetland or slough where it is held until it can infiltrate the soil or evaporated into the atmosphere. The compounding effects of contributing areas that are dependent on the degree of soil saturation, or on the extent of water usage, or on regulation of river flow make the interpretation of these results difficult. This difficulty is compounded by the lack of gauging stations with adequate record lengths and data quality.

The two runoff indicators described in this section examined effective basin and incremental basin runoff coefficients, utilizing similar datasets and methodologies. The difference between these two indicators is that the effective basin analysis is representative of the effective basin area upstream of a gauge and the incremental basin is area of the total effective basin area upstream of a gauge minus the effective basin area whose discharge is measured by the next upstream gauge.

In order to take into account the effects of cold region hydrology in terms of water storage in the snow pack and its effects on runoff precipitation, estimates were computed for the water year for each of the basins (October to September). The annual water year streamflow water volume for each station was computed from the actual streamflow values obtained from Environment Canada. The basins and corresponding stream gauge ID's and names are detailed in Appendix 1.

	05KJ001	05OJ010	05HD039	11AA005	05AJ001	05DA009	05DF001	05BB001	05CB001	05CE001	07CD001	05CK004	05BN012
1999	-0.61	1.23	0.97	-0.06	1.04	0.28	-0.34	-0.72	0.92	0.78	0.61	-1.21	-0.33
2000	-0.96	0.87	-0.13	-1.44	-0.53	-0.80	-0.57	-1.40	-0.75	0.39	0.38	-0.10	-0.60
2001	-1.28	-0.27	0.83	-1.60	-0.53	-0.40	-0.93	0.69	-0.46	-0.20	-0.59	-0.99	0.04
2002	0.27	-1.02	-1.14	-0.58	-1.48	-1.59	-1.33	-0.80	-1.62	-0.74	-0.67	-0.19	-0.96
2003	0.04	1.90	0.17	0.02	-0.33	0.11	0.29	0.90	0.05	-0.05	-0.06	-1.21	0.45
2004	-1.49	-0.39	-0.51	-0.22	-1.01	-1.38	-0.88	-0.12	-1.74	-0.24	-1.34	-0.44	0.26
2005	0.33	0.20	-2.29	1.84	1.72	1.19	0.51	-1.52	0.75	2.06	-0.33	0.27	-0.24
	07DA001	05FA001	05EF001	05GG001	05OC004	05ME001	05JM001	05NG001	05MH013	05OC001	05KH007	05AD007	Average
1999	1.19	-0.95	-0.30	-0.07	0.13	1.87	1.42	0.26	-1.19	-1.62	-1.40	0.07	0.08
2000	-0.44	-0.62	0.15	-0.60	0.04	-0.35	0.06	-0.92	0.78	-1.56	-1.63	0.66	-0.40
2001	1.01	-1.39	0.10	0.36	2.75	0.86	1.52	0.53	1.77	-0.44	-1.34	-0.69	-0.03
2002	-1.00	-1.71	-1.99	-1.25	-0.59	-0.79	0.87	-0.69	1.53	-0.95	-2.01	-1.13	-0.86
2003	0.63	-0.83	0.06	0.61	0.03	-0.51			0.01	-0.27	-1.32	1.35	0.09
2004	-0.77	-0.66	-0.50	-0.47	-0.53	-0.53			1.13	0.63	-1.05	-0.61	-0.56
2005	0.45	0.64	0.18	0.00	2.50	1.09	1.25	1.85	0.33	1.84	-0.01	-1.46	0.53

Table 2. Standardized Basin Runoff Coefficients

Figure 7. Runoff Coefficient Values

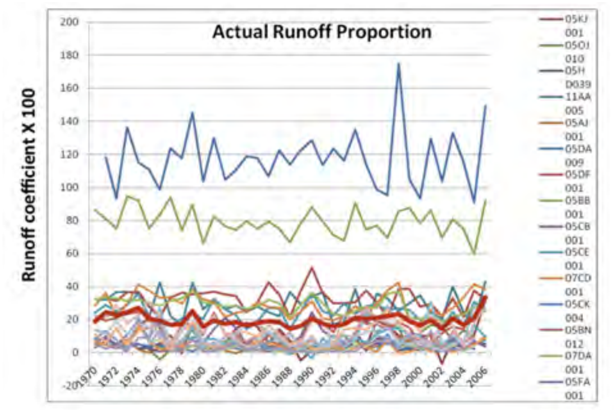
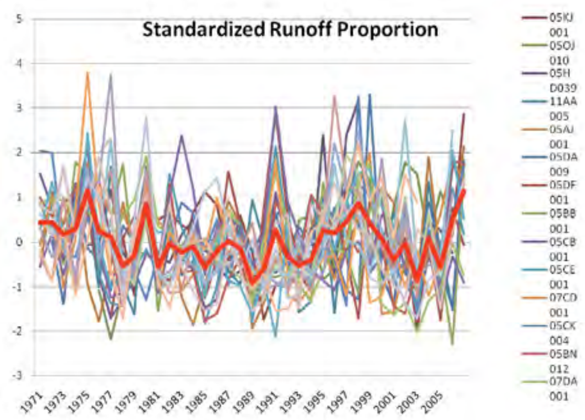


Figure 8. Standardized Runoff Coefficients



Basin	05KJ001	05OJ010	05HD039	11AA005	05AJ001	05DA009	05DF001	05BB001	05CB001	05CE001	07CD001	05CK004	05BN012
Mean	9.2	7.4	2.9	29.4	4.3	117.5	32.6	79.2	3.4	24.2	29.0	3.8	15.6
1999	6.8	1.1	2.2	29.9	7.4	104.9	38.5	87.5	4.9	25.7	17.8	3.0	15.2
2000	10.4	11.6	1.6	34.5	6.5	93.2	27.7	78.1	2.6	19.8	18.2	2.5	6.0
2001	10.0	16.9	3.0	24.0	3.6	129.5	29.6	86.3	2.6	22.0	25.9	1.7	4.9
2002	-6.7	15.6	0.8	20.6	1.7	103.6	22.1	69.5	1.2	15.5	22.4	0.8	11.7
2003	9.7	7.5	3.9	39.9	9.1	133.0	32.9	80.7	2.9	24.8	27.1	4.4	15.7
2004	5.2	13.5	3.5	24.6	3.3	115.3	21.3	74.9	1.9	16.6	33.3	1.8	14.1
2005	10.6	9.2	2.4	18.0	4.8	91.1	37.4	59.7	5.9	30.7	41.7	4.9	27.8

Basin	07DA001	05FA001	05EF001	05GG001	05OC004	05ME001	05JM001	05NG001	05MH013	05OC001	05KH007	05AD007	Average
Mean	28.4	8.5	6.8	4.1	9.1	9.4	2.8	3.7	9.8	12.1	10.1	16.0	18.7
1999	21.5	11.7	10.6	0.2	11.1	9.0	5.4	11.1	10.8	21.2	5.2	11.1	18.9
2000	20.4	10.5	8.7	3.8	1.9	6.0	1.9	2.3	10.1	12.5	6.9	8.3	16.2
2001	21.8	5.4	5.9	0.9	13.2	11.4	5.0	7.1	30.8	21.8	2.9	5.7	19.7
2002	18.5	5.0	3.3	3.5	3.7	2.3	0.7	0.6	5.3	17.7	1.2	18.1	14.4
2003	21.9	8.2	6.6	0.2		12.8	4.2	1.7	10.0		5.8	16.3	20.8
2004	23.2	1.5	5.7	2.7		6.7	1.2	1.6	5.7		6.7	4.0	16.9
2005	28.3	6.8	16.7	5.0	23.5	9.4	3.8	8.0	28.9	20.1	13.5	18.6	21.1

Table 3. Incremental Effective Basin Runoff Coefficients (expressed as a percentage)

The precipitation estimates and streamflow where combined to produce an annual runoff coefficient which was calculated for each basin using the equation:

Runoff Coefficient = (Streamflow/Basin Precipitation)

Effective basin runoff coefficient as an indicator of drought

Based upon the annual water year runoff analysis, the spatial distribution of the coefficient the variation of runoff generation across a selection of Western Canada's basins over time was documented. This coefficient varies spatially due to natural and possibly anthropogenic factors (e.g., land drainage, climate change, etc) which this paper does not address. Within the region a wide range of hydrologic regimes exist adding to the complexity of interpreting the results of the analysis. According to this analysis high values occur in the western basins. For example, the runoff coefficient varies from 0.8 to 1.2 for the head water basins of the Rockies (Bow River at Banff and North Saskatchewan River at Whirlpool). These values are the result of the strategic location of the gauges relatively close to glaciers and large winter snowpack's with very efficient drainage due to low permeability of the surface. Observational networks in these areas are also unable to document other factors such as the high spatial variability in precipitation amounts and the effects of warmer temperatures in accelerating glacier melt. Further to the east at the prairie stations (such as the Battle River or Swift Current) the runoff coefficients are .03 to .08 with relatively large variations and near-zero values in dry years. Values tend to be larger during the months with snowmelt when water is often released to the streams and rivers and then remain lower for the remainder of the water year.

Figure 7 shows the variations in the runoff coefficient. The graph shows the large variation of the runoff coefficient for the North Saskatchewan River at Whirlpool as well as significant variations for other stations. A significant number of prairie hydrologic stations had values that ranged from 0.0 to 0.15. In order to deal with this variability and to produce products that would be easier to analyze, standardized plots of variability were produced by applying the algorithm:

Standardized Runoff Coefficient = (Runoff Coefficient – Mean Runoff Coefficient for Basin)/STDEV of Runoff Coefficient for Basin)

By definition, the standardized runoff coefficients for the basin consequently have a means of 0 and standard deviations of 1. The resultant graph of standardized runoff coefficient for 1971 to 2006 is shown in Figure 8. The figure shows that the standard deviations of the deficits (drought) do not exceed 2 standard deviations while the standard deviations for a number of stations were larger than 3 standard deviations for wet years. Regardless of spatial variability and different regions supplying moisture the averages of both the average actual and standardized runoff coefficient values reflect the major influence of drought on runoff generation in the years of 1988 and 2002 (both exceptionally dry years).

Table 2 shows the variability in this standardized runoff index for the 6 years, 1999 to 2004, which capture the major features of the 1999-2005 prairie drought. Based on the runoff coefficient values for 2002 and 2004 the drought effects on streamflows were most significant for those years. This reflects the potential of these semiarid environments to yield a relatively high runoff from a given amount of rain in some years when the conditions are right. Table 2 shows the values of the standardized runoff coefficients for the drought years. The results indicate that the hydrological drought was most intense in 2002 with values of the standardized runoff coefficient at 12 of the 26 gauging stations was more than one standard deviation lower than the average value. Again in 2004 the hydrologic drought was very intense with 6 stations having values below one standard deviation. The only station hydrograph where a deficit greater than one standard deviation occurred in 2004 without a deficit of similar or greater magnitude in 2002 was the Saskatchewan River at the Pas suggesting that the flow at the Pas may be influenced by storage (e.g. reservoirs) in the upstream river network as much as it is influenced by precipitation.

In order to examine these possible effects in more detail, further analysis (not shown here) was undertaken to examine the runoff coefficients for sub-basin areas within these larger basins. Using the drainage areas immediately upstream of the gauging stations allowed the Canadian prairies to be discretized into an array of synthetic basins. By subtracting the streamflow from an upstream gauge from the gauge of interest it is assumed that the resulting streamflow value is representative of the runoff generated in the drainage area between the two gauging stations. On occasion the runoff coefficients for these synthetic basins are negative due to the storage in the subbasins.

Table 3 shows the runoff coefficients for the flow at specific stations from the synthesized or incremental basins for the drought years. Although one would expect that the runoff coefficient should always be positive this was not the case for the Saskatchewan River at the Pas in 2002. In the drainage area for this station there is significant storage capacity upstream that is greater than the basin precipitation or annual inflow. It is noteworthy that the mean runoff coefficient is less than 0.05 (or 5%) at 7 of these stations indicating that the semiarid climate and the flat topography of the prairie landscape is not very effective in producing runoff for the main rivers. Furthermore, during the 1999-2004 hydrologic drought the runoff coefficients never exceeded 0.1 at six stations and never exceeded 0.05 at four stations (Swift Current, Little Red Deer River near the mouth. Red Deer River near Bindloss, and North Saskatchewan River at Prince Albert).

Assessment:

The use of runoff coefficients as hydrologic drought indicators is labour intensive and requires the availability of reliable precipitation and streamflow data. It is a useful indicator because it represents physical processes that are occurring in the basin. They demonstrated the effects of the drought because there runoff coefficients were very low when the soils are dry and able to uptake any precipitation which falls on them. For this reason it provides more insight into conditions than do runoff values themselves. However, the values are influenced by water storage which can shift the flows generated by upstream precipitation from the year with precipitation to the following year and could even lead to a negative runoff coefficient for the synthetic basin. The analysis also shows that drought conditions are not as large a departure from average conditions as are wet events for the semi-arid Canadian prairies. The use of synthetic effective areas enhances the ability of the hydrologic drought index to resolve the areas most affected by drought but they can also be influenced by other processes in the basin. On the other hand, where representative precipitation values are not available (See Station 05DA009 in Table 3) it is possible for runoff coefficients to exceed 1.0 (or 100%).

Discussion and summary

Based on the analysis of these flows the following conclusions can be reached:

- Small basins respond more quickly and may be more susceptible to drought than large basins. In some cases the rivers in small basins go completely dry during the drought conditions.
- Naturalized flows reflected the progress of the drought along the Alberta/Saskatchewan and Saskatchewan/Manitoba borders. However, based on our knowledge of these flows, it is clear that the temporal trends in factors such as water use and land drainage that influence the computation of the naturalized flows must be considered when comparisons of droughts from different periods are being made.
- While small rain events do not have a measurable impact on the flows in larger basins, larger-scale, heavy rain events can produce significant increases in flows that can last for one to two months.
- the climate and runoff from northern prairie basins appears to be somewhat decoupled from the southern prairies basins. This is seen in the Churchill River Basin that had below average flows before the hydrologic drought in the south and above average flows as the drought intensified in the southern basins between 2000 and 2003.
- Runoff generation is reduced when basins are affected by drought.

The picture that emerges from this analysis regarding the drought itself is that although some hydrometric stations in southern Alberta registered no flow for a number of consecutive summer months these stations were on small tributaries that are frequently dry in summer. In 2000 and particularly in 2001 the flows in the North and South Saskatchewan were below the Q_{10} value and these anomalies propagated downstream without major interferences to the Manitoba-Saskatchewan border. With the exception of short-term high flow events associated with local storm systems, this hydrologic drought generally continued until early 2004 on both the Alberta-Saskatchewan and Saskatchewan Manitoba border.

Although their general features are same, hydrologic droughts at some stations defined in terms of naturalized flows can be significantly different than hydrologic droughts described by actual flows, especially for hydrologic droughts on larger rivers having larger cumulative deficits for their actual flows than for their naturalized flows. This may be explained by the effects of the drought on many of the intervening processes, upstream water use and regulation, that are used in the computation of naturalized flows. It is important for those who make decisions based on naturalized flows to be aware of these differences particularly when providing interpretations of these flows in support of inter-provincial water allocation and transfer agreements.

In conclusion, this study has found that several indices are available to increase our ability to characterize hydrologic droughts. To increase our quantitative understanding of the severity of the drought, it is important to establish a threshold against which to compare flows during the drought and to account for the strong relationship between precipitation over a basin and the runoff produced within that basin. However, the use of indices such as flow deficits and runoff coefficients still requires a proper understanding of the physical processes taking place to account for what was observed through the indices.

References

- American Society of Civil Engineers (ASCE). 1996. Hydrology Handbook 2nd Edition. ASCE Manuals and Reports on Engineering Practice no.28. pp 784.
- Dingman, S. L. 2002. Physical Hydrology 2nd Edition. Prentice Hall, New Jersey, pp 646.
- Halliday, R. and G. Faveri. 2007 The St. Mary and Milk Rivers: The 1921 Order Revisited. Canadian Water Resources Journal, Vol. 32(1): 75 –92
- Hanesiak, J., B. Amiro, E. Atallah, A. Barr, A. Black, B. Bonsal, P. Bullock, J. Brimelow,
- R. Brown, H. Carmichael, C. Derksen, L. Flanagan, H. Greene, J. Gyakum, P. Harder,
- W. Henson, T. Hogg, B. Kochtubajda, R. Lawford, H. Leighton, C. Lin, Y. Luo, H. McCaughey, A. Meinert, R. Stewart, A. Shabbar, K. Snelgrove, K. Szeto, A. Trishchenko, G. van der Kamp, S. Wang, L. Wen, E. Wheaton, C. Wielki, Y. Yang, S. Yirdaw, and T. Zha, 2011. Physical characterization of the 1999-2005 Canadian Prairie drought, (In The 1999-2005 Canadian Prairie Drought: Science, Impacts, and Lessons. Edited by Ronald Stewart and Richard Lawford), DRI, Winnipeg, MB, p. 13-22.
- Pomeroy, J.. 2010. Personal communication
- Prairie Provinces Water Board (PPWB), 2005. 2005 Annual Report of the Prairie Provinces Water Board. http://www.mb.ec.gc.ca/water/fb01/fb00s13.en.html

» Stewart, R., W. Henson, H. Carmichael, J. Hanesiak, and K. Szeto, 2011. Precipitation events during the recent drought, (In The 1999-2005 Canadian Prairie Drought: Science, Impacts, and Lessons. Edited by Ronald Stewart and Richard Lawford), DRI, Winnipeg, MB, p. 43 – 46.

» Yevjevich, V. 1967. An objective approach to definition and investigations of continental hydrologic droughts. Hydrology Papers 23, Colorado State University, Fort Collins, USA.

Acknowledgements

The authors would like to express their appreciation for Dr. John Hanesiak who made the services of his students, Shannon Moodie and Justin Hobson, available to help conduct this analysis.

Streamgauge ID's and names

ID	Name
05AD007	OLDMAN RIVER NEAR LETHBRIDGE
05AJ001	SOUTH SASKATCHEWAN RIVER AT MEDICINE HAT
05BB001	BOW RIVER AT BANFF
05BN012	BOW RIVER NEAR THE MOUTH
05CB001	LITTLE RED DEER RIVER NEAR THE MOUTH
05CE001	RED DEER RIVER AT DRUMHELLER
05CK004	RED DEER RIVER NEAR BINDLOSS
05DA009	NORTH SASKATCHEWAN RIVER AT WHIRLPOOL POINT
05DF001	NORTH SASKATCHEWAN RIVER AT EDMONTON
05EF001	NORTH SASKATCHEWAN RIVER NEAR DEER CREEK
05FA001	BATTLE RIVER NEAR PONOKA
05GG001	NORTH SASKATCHEWAN RIVER AT PRINCE ALBERT
05HD039	SWIFT CURRENT CREEK NEAR LEINAN
05JM001	QU'APPELLE RIVER NEAR WELBY
05KH007	CARROT RIVER NEAR TURNBERRY
05KJ001	SASKATCHEWAN RIVER AT THE PAS
05ME001	ASSINIBOINE RIVER NEAR RUSSELL
05MH013	ASSINIBOINE RIVER NEAR BRANDON
05NG001	SOURIS RIVER AT WAWANESA
05OC001	RED RIVER AT EMERSON
05OC004	PEMBINA RIVER AT NECHE
05OJ010	RED RIVER NEAR LOCKPORT
07CD001	CLEARWATER RIVER AT DRAPER
07DA001	ATHABASCA RIVER BELOW MCMURRAY
11AA005	MILK RIVER AT MILK RIVER

Lake Winnipeg basin – confronting cultural eutrophication with bioeconomy opportunities

Richard Lawford[1], Dean Medeiros[1], Henry David Venema[1], Greg McCullough[2] & Matt McCandless[1]

[1] *International Institute of Sustainable Development, Winnipeg, Manitoba*

E-mail: lawford@umbc.edu

[2] *University of Manitoba, Winnipeg, Manitoba*

Background

Agricultural prosperity during the past 150 years in the Lake Winnipeg River Basin (see Figure 1 for boundaries) has been achieved by the conversion of natural landscapes to arable lands. Producers in the basin have become very efficient in converting inputs such as water, energy and soil nutrients into grain and other food crops to satisfy local needs and to export elsewhere. In 2008, Manitoba exported CDN$ 4.7 billion of agrifood products to 178 countries (Manitoba Agriculture, Food and Rural Initiatives (MAFRI), 2009).

However, these successes have carried environmental costs in terms of their consumption of chemical fertilizers and water. For example, when the concept of virtual water is used to characterize the amount of water used to produce the crops exported from this area it sheds light on water use in the basin. Using the estimates of virtual water for growing different crops (see Appendix A) and the standard methods for calculating virtual water (Mekonnen and Hoekstra, 2010) and MAFRI crop exports for 2010 (personal communication, Bob Ward, MAFRI) it is estimated that the volume of water represented by the crops exported from Manitoba's croplands (which are essentially all in the Lake Winnipeg drainage basin) is equivalent to 12.16 km^3 of virtual water. During the past four decades, productivity and exports have been enhanced by the widespread application of fertilizers. While the climate of the basin allows for this purposeful use of water, as this paper shows, there have been significant environmental issues and costs associated with the intensification of agricultural production. These costs are now affecting other parts of the Manitoba economy to the point where the government is considering steps to address these issues.

One critical environmental consequence of the intensive agriculture has been the growing eutrophication problem in Lake Winnipeg. The water quality of Lake Winnipeg has deteriorated significantly over the past three decades, primarily as a result of excessive nutrient enrichment (Lake Winnipeg Stewardship Board (LWSB), 2006) which occurs, in part, when nitrogen and phosphorous from the farming operations that have accumulated on farmlands are washed away in runoff to nearby rivers that carry them to the lake.

In the past, Lake Winnipeg has played an important role in transportation and fisheries. Although the lake still supports active commercial fisheries with annual catches of more than 6.3 million kg of fish, worth almost $21 million, the lacustrine transportation services have been overtaken by roads. Today, Lake Winnipeg is better known for its importance for recreation. Recreation and tourism along the lower Red River (fishing) and around the lake are estimated to generate over $110 million annually (LWSB, 2006). However, in the view of many, the recent environmental problems have made Lake Winnipeg a less desirable recreational location impacting tourism and the value of lakefront properties.

Limnological evidence indicates that large nutrient loading reductions will be required to reduce the lake's hyper-eutrophy. This requirement is occurring when there is evidence that nutrient surpluses are continuing to accumulate on Manitoba's agricultural landscape. Rather than remaining a victim of these circumstances, Manitoba is developing a plan to use surplus nutrients as a strategic resource and a source of economic activity over the coming decades. Anticipated new value streams include nutrient recycling, particularly phosphorus, which is also emerging as key strategic resource for world food security. This paper provides an overview of the problem and outlines a recovery strategy based on bioeconomy principles that combines traditional and non-traditional approaches that are now under consideration by the province of Manitoba.

Hydrological characteristics of the Lake Winnipeg basin

Lake Winnipeg is one of Canada's largest freshwater lakes, ranking 11th in area (Lake area is 24,514 km^2) in the world and sixth in area in Canada behind Lakes Huron-Michigan, Lake Superior, Great Bear and Great Slave Lakes and Lake Erie. The lake is 436 km long, but at its widest point its width is 111 km in the North Basin and 40 km across in the South Basin. On the other hand, because it is a shallow lake (mean depths are 9.7 and 13.4 m in the South and North Basins respectively), it is only 284 km^3 in volume, making it smaller and more sensitive to changes in nutrient loading than other North American great lakes.

Runoff from the heartland of agricultural productivity in Canada and northern U.S.A drains into Lake Winnipeg. As shown in Figure 1, Lake Winnipeg's basin boundaries stretch from the Rocky Mountains almost to Lake Superior, and south to northern South Dakota. Table 1 identifies the percentage of the measured flow in the different rivers flowing into Lake Winnipeg. These rivers drain 953,000 km^2, the second-largest basin area in Canada. The basin is home to 5.5 million Canadians and 1.1 million Americans (LWSB, 2006). The ratio of land drained to the area of the lake is approximately 40:1 (the highest such watershed:lake area ratio for any lake of its size in the world) indicating that the land must have a significant influence on water quality of the lake. Except in the eastern and most western parts of the Basin, the Lake Winnipeg Basin is relatively flat and has a continental climate (warm in summer and cold in winter) . While the runoff ratio (the ratio of annual runoff to annual precipitation) is estimated to be as high as 0.3 where annual precipitation exceeds 700 mm in the eastern Precambrian Shield portion of the basin, it averages 0.1 in most of the drier (400–500 mm precipitation annually) Saskatchewan River basin and is estimated to be as low as 0.02 in the Assiniboine River basin (the large western Canadian tributary of the Red River) (McCullough, personal communication). In the dry parts of the South Saskatchewan River Basin potential evapotranspiration can equal or exceed precipitation, and a large proportion of the landscape does not contribute to the river discharge. Rain that falls on these areas is retained in wetlands, drainage ditches and depressions until it evaporates or infiltrates the soil. Often the nutrient residues in these depressions only reach a river during the periods of snowmelt and high runoff. As much as 80% to 85% of the annual runoff and nutrient loading in the rivers occurs during snowmelt and spring rains (Glozier et al., 2006, Gray and Landine 1987) or during spring floods that submerge fields, as frequently occurs in the Red River basin. Freeze-thaw cycles increase the amount of dissolved phosphorous in spring runoff (Benchmann et al., 2005) and large areas of farmland are exposed to nutrient leaching by flood waters, so that dissolved nutrient concentrations tend to be higher during spring floods than in the lower flow conditions that prevail during the rest of the year.

Table 1. Range of measurements of the contributions of each of the major rivers flowing into Lake Winnipeg over different time periods.

**- estimate includes the contribution of the Assiniboine River*

River	% of inflow (1964-2005)	% of nitrogen load	% of phosphorus load	Turbidity
Red River of the North*	11%	30 – 41*%	54 – 75*%	Sediment load varies with season
Saskatchewan	26%	8 - 10%	4 - 5%	Little loading
Winnipeg	45%	18 - 25%	11 - 12%	Very little loading
Other rivers	18%			
Dauphin		3 - 4%	1%	
Assiniboine		4%	8%	
Others (West shore)		1-6%	1-6%	
Other (East shore)		- 11%	2-9%	
Atmosphere		10 -11%	6-7%	
Nitrogen fixation		10-11%		

The structure of river and lake networks in Manitoba also affects the fluxes of water and nutrients into Lake Winnipeg. A number of the rivers entering Lake Winnipeg flow through smaller lakes or major storage facilities that act as natural filters. In the Winnipeg and Saskatchewan River basins, and in the basin of the smaller Dauphin River which drains Lake Manitoba, major sources of nutrients (mainly farmland and population centres) are generally upstream of large lakes or reservoirs which help to trap sediments and nutrients, and maintain moderate nutrient concentrations in downstream reaches. The one exception is the Red River which flows directly into Lake Winnipeg. As indicated in Section 4, the Red River is the largest single source of nutrients to Lake Winnipeg. Seventy-four per cent of the Red River basin (excluding the Assiniboine) is farmed (65% cropland, 9% pasture). Carlyle (1984) reported that 40,000 km2 of drained lands in the watershed; a number that has substantially increased since his report. Most of the population and the intensely drained and cropped farmland are concentrated along a band of very low relief land (slopes as low as 0.25 m per km) underlain by nearly impermeable glaciolacustrine fine sediments – approximately 80 km wide and stretching southward 450 km from near the mouth of Lake Winnipeg.

Lake Winnipeg itself is ice-free from April–May to November, with the North Basin freezing over a few days earlier than the South Basin, and the ice leaving the south basin ten days to two weeks earlier than it leaves the North Basin. Over the past two decades the thaw dates have become earlier and freeze-up dates have become later; factors that are associated with warmer water temperatures during the summer months (McCullough, 2005). Lake water temperatures peak in early August with values as warm as 18–20°C in the North Basin, and 20–22°C in the South Basin. Flows into the lake typically peak during the ice breakup period although larger flows frequently continue into June. Table 1 shows the annual contributions of each of the major rivers flowing into the lake.

The nature and scope of the eutrophication problem (What's the problem?)

Over the past decade the people who benefit from the recreational aspects of Lake Winnipeg have been troubled with massive algal blooms during the summer months. At first, these blooms affected only the northern basin, but in recent years they have become ubiquitous in the lake. In 2003, the bloom had become severe enough that a warning was issued at a popular beach. In some recent summers these algal blooms have been so large that they have covered more than 15,000 km2 or almost 60% of the lake. The shallow nature of the lake (its average depth is 12 m) may affect the rate at which material are mixed through the vertical columns in the lake and could increase the concentration of phosphorus in the surface layers where the algae grow.

Figure 1. Google Earth Map depicting location of Lake Winnipeg and the Lake Winnipeg Watershed (MLI 2010)

The extent of algal blooms and their timing are being monitored using satellite data. In particular, images from the Moderate Resolution Imaging Spectroradiometer (MODIS) now orbiting aboard two of NASA's satellites, Terra and Aqua, have been processed by the Universities of Manitoba and Maryland to map the phytoplankton blooms. Algal blooms appear in these images as bright greens in the water. Fainter greens are also present because the lake varies from clear to high mineral sediment concentration. In general, algal blooms usually grow through the summer and reach peak areal extent and depth by late August or early September.

There are two important controls on the algal bloom in addition to the nutrients being carried by the incoming waters. These include:

1. The amount of light and heat received during the months without ice cover.

2. Turbidity (which limits penetration of light) from sediments either delivered by tributary rivers or resuspended by wind-driven disturbance of the bottom;

a) The amount of light and heat received during the months without ice cover:

As noted earlier, ice break-up generally begins in mid-April and continues until the end of the month. The break-up commences in areas with strong surface currents or where the rivers flow into the lake. The lake refreezes during November, with the ice appearing as early as October 27th and the freeze-up occurring as late as December

17th. During the spring and summer months the shallow waters of Lake Winnipeg warm quickly as the air temperatures rise. Analysis of satellite images has been used to show that, given sufficiently high nutrient concentrations, surface blooms of phytoplankton in the lake tend to be larger and more intense in warmer years (McCullough et al., 2006). If greater summer warming leads to more frequent stratification, then dissolved oxygen concentration in bottom waters may be reduced, possibly to the point of anoxia in the hypolimnion or bottom sediments, and internal nutrient loading may be increased. This in turn has implications for primary productivity in Lake Winnipeg. Any changes to water chemistry or primary production would have consequences at higher trophic levels. Moreover, increased temperature may affect fish directly. In a recent study of potential climate effects on the Lake Winnipeg fishery, Franzin et al. (2005) pointed to summer temperature as one determinant of the species composition in a lake and to the importance of the length of the period with water temperatures lower than 10°C to over-winter survival of young-of-the-year fish.

Another factor that has recently been observed in the northern basin is the development of a thermocline – a sharp thermal gradient that prevents oxygen resupply to near bottom waters. According to B. Hann (personal communication), hypoxic conditions have been observed on at least two occasions under such thermoclines. Although rarely observed, such hypoxic events may be common enough to cause changes to more hypoxia-tolerant groups among the bottom fauna in the North Basin. Anoxic conditions that typically develop in the sediments below such a deep thermocline facilitate release of phosphorous molecules from the sediments, increasing the concentration of phosphorous in the lake water. Primary productivity, and cyanobacterial productivity in particular, have been shown to be positively correlated with summer temperature in numerous multi-year studies (e.g., Hamilton et al., 2005). Consequently, the nature and extent of eutrophication and associated effects on Lake Winnipeg may be exacerbated by rising air temperatures.

b) The turbidity of rivers flowing into the lake:

The optical qualities of water at and below the surface of the lake also influence the extent of the algal bloom. Light penetrates more deeply in clearer water, providing a deeper layer through which algae can grow and reproduce. In much of the North Basin, that layer is typically several metres deep, and has been the location of the largest surface blooms of the last decade. In the more turbid South Basin, light often penetrates only a few decimetres. The clarity of the water is related to the sediment being transported by the inflowing rivers. Although this transport varies from year to year, the rivers flowing into the lake also have different sediment characteristics. For example, the eastern watershed, including the Winnipeg River, drains the soils, muskegs and boreal forests overlying the igneous bedrock of the Precambrian Shield (Brunskill et al., 1980). The southern, western and north-western portions of the drainage basin are within the Paleozoic and Mesozoic sedimentary terrains of the Prairie Provinces and north central U.S.A. (Burbidge et al., 2000). These areas were originally prairies to the south and mixed forests to the west and northwest; the southern areas now support extensive agriculture and several large cities (Brunskill et al., 1980). The individual characteristics of rivers flowing into Lake Winnipeg based on the assessment of satellite data are described below and are tabulated in Table 1.

The lake is often clear in the early spring immediately after break-up because sediments have settled to the bottom during the calm winter months when the lake is covered by ice and because dense surface blooms of cyanobacteria (which also limit light in deeper waters) have not yet developed. However, this situation changes rapidly in the South Basin at least, as the spring peaks of the Red River and several small western tributaries, with their high sediment concentrations reach the lake. The Winnipeg, Saskatchewan and Dauphin Rivers are generally clear and as a result appear black on satellite images because they absorb the light falling on them. In the case of the Saskatchewan River, Cedar Lake, which is just upstream of Lake Winnipeg, acts as a sediment filter because most sediment settles to the bottom there before the flow reaches Lake Winnipeg. Near the mouths of the Saskatchewan and Winnipeg Rivers suspended solids concentrations are almost always less than 50 g m^{-3}. Both rivers tend to create large areas of relatively clear water where they enter the lake.

In contrast the turbidity of the Red River (of the North) varies from year to year and season to season. Turbidity on the Red River is more variable as the suspended sediment concentration ranges from a few g m^{-3} to as much as 2000 g m^{-3} at peak flood flow. (The flow-weighted mean concentration is 280 g m^{-3} using daily data from 1962–1984.) The Red River tends to be clearer in the summer, possibly because of slower flows, or because spring floods scour and carry away a lot of the most easily erodible sediments along the channel. The optical characteristics of the Red River are often modified by the Assiniboine River at the Forks in Winnipeg, which tends to transport higher concentrations of sediment. However, turbidity is not solely contributed by the rivers, it is also generated in shallow (<12 m) regions far removed from the turbid Red River as soon as the first strong winds begin to resuspend bottom sediments (McCullough et al. 2001).

The Fisher River, which enters Lake Winnipeg at the south end of the large bay along the west side, in the Narrows region, tends to be red-brown during some periods due to dissolved organic matter from wetlands in its watershed. On satellite imagery the Netley Marshes tend to appear as a lighter brown because they contain fine sediment that has been mixed up from below.

The major algal bloom on Lake Winnipeg in 2006 arose from a confluence of events that promoted growth of the blue-green algae. High runoff continued after the usual spring peak into the summer and carried extra nutrients dissolved from soils and vegetation that were inundated through most of July. The early break-up was followed by warm spring and early summer temperatures that fostered algal growth. During the rest of the summer and fall the Red River carried less than the usual load of silt and clay, bringing low turbidity to the waters in the South Basin. With deep light penetration and warm water temperatures, this led to the most widespread bloom in the South Basin in over two decades of satellite records. Stronger calls for action to reduce the algal blooms arose in September 2006 after surface blooms seen by satellite spread over the North and South Basin.

Background to the eutrophication problem (How did we get here?)

The nitrogen and phosphorous used in agricultural fertilizers to enhance agricultural production are believed to be a major cause of the algal blooms in Lake Winnipeg. Residuals of these nutrients left on the land, either bound in biomass or unattached in the soil, are carried to river channels by runoff either over the surface of in shallow subsurface layers and then are moved by streams and rivers to Lake Winnipeg, where they provide the nutrients that support algal blooms.

Although nitrogen and phosphorous from factory-produced fertilizers are a principal source of nutrients, livestock operations and urban sewage also contribute. Bourne et al. (2002) assessed the ambient nutrient loading in flows into Lake Winnipeg based on available (albeit limited) water quality data. These numbers suggest that the levels of nutrients transported in the Lake Winnipeg basin are much lower than those transported in other basins in Canada or in other parts of the world. Average phosphorus concentrations are 13 and 18 times higher in the Red River than the Saskatchewan and Winnipeg Rivers respectively. Nitrogen is 5 times higher both cases. Overall the Red River contributes 70% and 35% of total phosphorus and nitrogen loading respectively to the lake (Armstrong and McCullough 2011). Furthermore, Winnipeg, with its 630 000 residents, is only 60 km upstream of the mouth of the Red River. More recent work by Armstrong and McCullough (2011) indicates that phosphorus export per unit area from many sub-basins of the lower Red River is in the same range as phosphorus exports from intensely farmed lands in the Mississippi River basins, although certainly lower than exports from western European watersheds. Further water quality measurements, particularly during peak flows, are necessary to better improve our understanding of nutrient fluxes to Lake Winnipeg.

During the period from 1965 to the mid-1990s phosphate fertilizer applications increased from approximately 20,000 tons of P2O5 per year (or 8,600 tons of P) to 120,000 tons per year of P2O5 (or 51,600 tons of P) (Johnston and Roberts, 2001). Since the mid-1990s, the annual application has fluctuated around this level (LWSB, 2006). Phosphate associated with animal husbandry has also increased over the same period. The number of cattle on Manitoba farms increased throughout the 20th century to reach 1.2 million by 1965, and peaked at 1.6 million in 2005 (Honey, 2011a). The number of pigs increased more dramatically in the recent period, from 600,000 in the mid-1970s to peak at over 2.9 million in 2006 (Honey 2011b). Pig and cattle manure tend to be important sources of fertilizer in regions where they are produced which generally are regions critical for nutrient supply to Lake Winnipeg. In particular, cattle have increased in the small tributary watersheds on the west side of the lake, and pigs have increased in the lower Red River basin. Two watersheds, the Seine and Rat River basins, are among the 10 highest in concentrations of manure phosphorus application in Canada with approximately 7–8 kg P/ha applied annually (Statistics Canada, 2004).

Computations by Medeiros et al. (2011, in progress) based on the fertilizer application rates and the uptake and removal rates by crops (Canadian Fertilizer Institute, 2001) indicate that the mass balance loadings for nitrogen and phosphorous are much higher than implied by the in-stream measurements. Mass balance estimates are very sensitive to the initial assumptions. By using phosphorus crop removal estimates reported by Heard and Hay (2006), Medeiros et al.(2011, in progress) obtained estimates of residual phosphorous that are nearly double the mass balance estimates calculated using Canadian Fertilizer Institute (CFI) (2001) parameters (See Table 2). According to these estimates, 73-85% of the phosphorous applied to crops as fertilizer in Manitoba is removed in the harvested portion of the grain and 58-64% of applied nitrogen fertilizers are removed in the harvested portion of the crop. These differences may arise from variability in climate conditions, natural variability in plant uptake rates or the proportion of nutrients carried in sediments. Although the rates of removal for crops in Manitoba need more study, it is known that plants grown under different environmental conditions sequester different amounts of nutrients. It is felt that the CFI estimates are accurate because farmers have incentive to follow guidelines since uptake and removal rates help them reduce their input costs without adversely affecting their outputs.

Table 2. Nutrient balance loading estimates for the Manitoba portion of the Lake Winnipeg watershed (See Medeiros et al. 2011 for more details.)

	Nutrients (metric tonnes)	
	Phosphorous	Nitrogen
Fertilizer Mass-Balance Estimate in Manitoba		
Canadian Fertilizer Institute (2001)	7,200	138,000
Heard and Hay (2006)	13,200	120,000
Total Nutrient Estimate Based on Available Water Quality Data Bourne et. al (2002)	3,700	47,100

As shown in Table 2, when compared to estimates based on available water nutrient data obtained from in-stream measurements (Bourne et al., 2002), the mass-balance nutrient loading estimates are nearly triple for nitrogen and 2 to 3.5 times as much for phosphorous.

These differences between the computed mass balance and the extrapolation of the ambient concentrations are surprising since the ambient values include urban sewage releases and other emission sources, while the mass balance computation considers only synthetic fertilizer applications. The differences could be the result of the sampling frequencies and period of water quality samples in

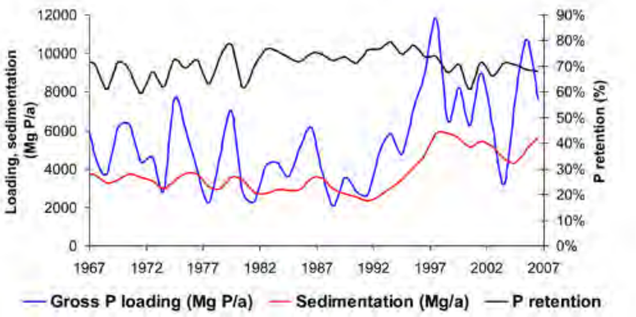


Figure 2. Modeled annual Phosphorous loading to Lake Winnipeg, Phosphorous sedimentation rate in Lake Winnipeg, and annual retention of Phosphorous in the Lake. This graph was developed using a model and parameters described in McCullough et al.(2011).

the Bourne et al. (2002) data. If the data do not adequately capture key nutrient loading events, especially during the snow melt floods, then they will not reflect the true cumulative transport of nutrients (Glozier et al., 2006). The lower phosphorous concentrations in the water measured by Bourne et al. (2002) may also reflect the tendency of phosphorous molecules to attach themselves to sediment particles, so that much of the phosphorus leaves the landscape as sediment rather than being dissolved in the water itself.

The efficient application of fertilizers and nutrient management mitigates the amount of nutrients that will be transported into surface waters. The eutrophication of surface waters is of growing global concern (Carpenter et al., 1998). Crops and livestock in Manitoba were estimated to contribute 32% of the phosphorous (1,200 tonnes of P) and 11% of the nitrogen (5,100 tonnes of N) ending up in Lake Winnipeg from Manitoba sources (Manitoba Water Stewardship, 2006). Clearly, improved nutrient management could help reduce eutrophication of Lake Winnipeg. Management of Lake Winnipeg may also be an issue. Between 1990 and 2006, the difference between the inflow of phosphates and the transport of phosphates out of the lake increased dramatically, meaning that more phosphates are being retained in the lake and potentially building up in the sediments (LWSB, 2006). This observation is supported by modeling studies that indicate that sedimentation of phosphorus has increased since the mid-1990s as have phosphorous concentrations. Similar trends have been found in sediment cores taken from Lake Winnipeg (Kling et al., 2011). This also suggests that more phosphate is being retained by the algal bloom, although it is unclear if it is formation of the bloom that is retaining the phosphate or if the phosphate is not being flushed through the lake quickly enough so that it is captured in the bloom.

Phosphorous:

The phosphorous cycle tends to be slower than the nitrogen cycle and has little interaction with the atmosphere. In the natural cycle, phosphorous enters water bodies as it is slowly released from rock and mineral deposits through weathering. However, phosphorous is also an essential plant nutrient and is applied as fertilizer. It cycles through food chains but leaves residuals, which make their way into watersheds and load-receiving water bodies where excess phosphorus leads to eutrophication (Smil. 2004). As Figure 3 shows, agriculture is responsible for approximately one-third of the annual phosphorus loading of Lake Winnipeg.

In general, farmers are applying phosphorous efficiently because the harvested portion of the crop represents approximately 80% of the phosphorous that is applied to fields. An additional 8% of the applied fertilizer is taken up in non-harvested plant tissue (straw, roots), which is frequently left on the field (McCandless et al., 2011 in progress). Although the percentage of phosphorous that is not absorbed by cultivated crops is relatively small, when aggregated over the vast cultivated landscape of the Lake Winnipeg basin, it has a cumulative impact, resulting in significant nutrient loads for Lake Winnipeg. Similar findings were reported by Glozier et al. (2006), who concluded that significant ecological impacts occur when aggre-

Figure 3. Sources of Phosphorus loading to Lake Winnipeg from Manitoba (McCandless et al, 2011).

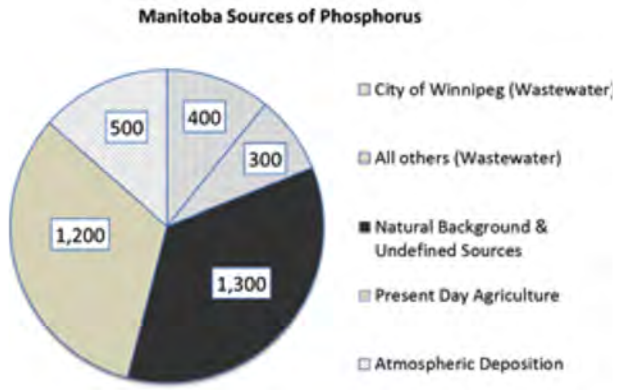
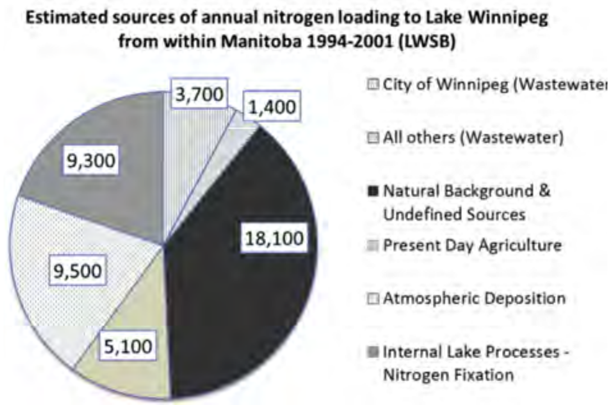


Figure 4. Sources of Nitrogen loading to Lake Winnipeg from Manitoba (McCandless et al., 2011).



gated over the entire watershed area even though fertilizer nutrient losses to the streams were 2% or less.

Nitrogen:

During the early days of agriculture on the Prairies, nitrogen fertilizers were hard to obtain. However, the development of the Haber Bosch process in 1913 made nitrogen fertilizers more popular and accessible, with the result that much more nitrogen is cycled through the environment. Between 1960 and 2010, flows of nitrogen have tripled in terrestrial systems (Millennium Ecosystem Assessment, 2005a; Smil, 2004), which has profoundly altered the nitrogen cycle. As Figure 4 shows, agriculture is responsible for approximately eleven percent of the annual nitrogen loading from Manitoba to Lake Winnipeg. When a crop is harvested and exported to another country, nitrogen is also exported and subsequently moves through the food chain in other regions of the world. If not removed or neutralized, the residual can reach water bodies and be carried to lakes and rivers. In addition, some nitrogen remains on the land as either crop residual or unused nitrogen. However, nitrogen movements are very uncertain due to various factors affecting the transport and fate of nitrogen. For example, nitrogen is subject to numerous transformation processes such as volatilization, immobilization, mineralization, denitrification and biological fixation (Swink et al., 2011). Diverse atmospheric interactions that affect its transport and an improved understanding of these interactions could also be used to improve nitrogen management.

Nitrogen and phosphorous cannot be managed in isolation. If either nutrient is over-applied relative to the other, the nutrient applied in excess will increase progressively in the soil and will more likely be present in excess in surface water runoff. Since manure is relatively rich in phosphorous compared to the nitrogen requirements of crops, soil phosphorous will progressively accumulate in regions fertilized primarily with manure (Swink et al., 2011).

Options for addressing the problem: Traditional approaches (What are we doing about it?)

Although the application of fertilizers has generally followed industry standards, large fluxes of nutrients to Lake Winnipeg still persist. Small residuals of nitrogen and phosphorous that accumulate on the landscape in the soils and plant residues during the year are released to the surface and shallow subsurface flows during the spring melt and in many cases find their way into the main river channels. As the spring and summer progress, the warm temperatures and long summer days lead to extensive blooms on the lake. This problem has been acknowledged by governments for some time and has been a consideration in Best Management Practice (BMP) approaches.

Numerous agricultural BMPs such as conservation tillage, vegetated buffer strips and wetland restoration (Dinnes, 2004; Carpenter and Bennet, 2011) can reduce total nutrient runoff into waterways and water bodies. However, current BMPs should be chosen carefully and on occasion modified to accommodate the wide range of ecosystems in the Lake Winnipeg basin. For example, Sheppard et al. (2006) reported that vegetated buffer strips may not be effective in reducing phosphorous loading in Manitoba because runoff tends to flow off the field in narrow outlets through relatively small portions of the buffer strip due to the flat landscapes of the Lake Winnipeg basin. On the other hand, precision fertilizer applications would minimize the need for new fertilizer inputs and reduce the losses to runoff.

Patience is required in looking for results from even the most effective suite of BMP applications. When nutrient residuals build up in a watershed, as they have in the Lake Winnipeg Basin (McDowell and Sharpley, 2001; McDowell et al., 2004), the soils and sediments of lakes, wetlands and waterways (i.e., ditches) hold large concentrations of nutrients. These nutrients can be remobilized in response to favourable hydrological and environmental conditions (Carpenter et. al., 1999). Considering the annual loads reported in mass balance assessments of nutrients from fertilizers (Medeiros et al. 2011, in progress), the decadal timeframe that fertilizers have been applied at such rates, and the current difference between the fluxes entering the lake and leaving the lake (LWSB, 2006). the sediments in Lake Winnipeg have likely been a sink for significant quantities of nutrients (especially phosphorous). The sediments could continue to be a source of algae bloom-promoting nutrients, even if nutrient loads to Lake Winnipeg were effectively reduced. Consequently, improvement of Lake Winnipeg water quality will require a multi-pronged approach involving upstream management options and direct nutrient removal from Lake Winnipeg, such as harvesting phosphorous from cattails from Lake Winnipeg's coastal marshes such as Netley-Libau Marsh (Cicek et al., 2006)

Improvements of the ecological integrity of lakes may have a lag of 10 to 15 years (Jeppesen et al., 2005) after nutrient inputs are first reduced. This lag could be reduced if upstream nutrient management can be coupled with initiatives to remove nutrients directly from the eutrophic lake. However, as a general principle, eutrophication problems that have taken decades to develop will require solutions with similar decadal timelines and will require long-term commitments to nutrient reduction and recycling along with careful management of stakeholder expectations.

Non-traditional approaches – Enhancing ecosystem services through the bioeconomy and biorefineries (What else could we do about it?)

Another approach to the problem of Lake Winnipeg eutrophication involves considering the nutrients being transported by waterways as a resource that can be harvested. To assess the feasibility of this opportunity, we need to evaluate options within the framework of ecosystem services and, more generally, the bioeconomy. Ecosystem services characterize the benefits people obtain from healthy functioning ecosystems articulated in a way that allows them to be compared with purely economic factors. Costanza and Daly (1997) reported that the value humans receive globally from healthy functioning ecosystems totals between $16 and $54 trillion per year.

Agricultural production can be considered as an ecosystem service. Today, agriculture accounts for 24% of GDP in low-income developing countries (Millennium Ecosystem Assessment, 2005b). The total economic wealth derived from the exploitation of ecosystem services, including the food production industry, is worth over $980 billion per year. In the past 40 years, humans have benefited from more efficient and intensive farming practices (Smil, 2001; Foley et al., 2005). An important component of these services is associated with the cycling of elements such as carbon, nitrogen and water through the geosphere, biosphere and atmosphere. As has been shown earlier, human activities intensify these flows, threatening the health of the receiving waters. For example, changes in the nutrient cycling in the Lake Winnipeg basin over the past five decades have affected ecosystem services including commercial fisheries through changes in the ecology of the lake. Recreational services have also decreased as a result of beach closures and reduced beach usability arising from the presence of high concentrations of blue-green algae.

Although regulation by government and voluntary BMPs will remain central options for dealing with excess nutrients, the flows also provide opportunities to recover and reuse the surpluses that are cycling in these systems.

The bioeconomy paradigm includes an economic framework and the concept of natural capital for assessing the net gain or loss associated with different actions. In countries that are rich in natural resources, such as Canada, economic success and wealth-generation are often dependent on the efficiency with which natural resources are converted into commodities and brought to market. This framework can be used to assess the sustainability of an activity by looking at its impacts on the natural capital, and benefits for the conventional economy, and exploring shifts in benefits and costs between the private and public sectors or between countries where the wastes of agricultural activities are transported into other countries by international rivers.

Evaluating investments and activities in terms of the bioeconomy has the potential to provide a stronger economic basis for a wide range of ecosystem services such as food security, improved surface water quality and more sustainable land use management (Langeveld et al., 2009; OECD, 2009). Another significant component of the bioeconomy are biorefineries, which take low-value inputs such as recyclables and waste organic material and turn them into high-value end products (Johnson and Virgin, 2010; OECD, 2009, Cai et al, 2011).

Biorefineries can produce biofuels and bioproducts such as gases, plastics, chemicals, pharmaceuticals and nutraceuticals (Langeveld et al., 2009; OECD, 2009; Cortez et al. 2010; Levin et al., 2007) by using appropriate technologies that can use lignocellulosic biomass as feedstocks, essentially generating value from agricultural waste products (Diaz-Chavez,2010; Johnson and Virgin 2010). A side benefit of biorefineries is that nitrogen and phosphorous can be captured for reuse before they are lost to waterways and the atmosphere (OECD, 2009; Sendich and Dale, 2009).

A recent analysis of the benefits of a biorefining industry in Manitoba (McCandless et al.,2011) estimated that the harvest of lignocellulosic biorefinery feedstocks could also yield large amounts of nitrogen and phosphorous. It estimates that the potential harvest of agricultural wastes, riparian biomass and restored wetlands in Manitoba ranges from 15 million tons per year under aggressive soil conservation strategies to around 9 million tons per year under moderate soil conservation strategies.

The production of bioproducts from lignocellulosic feedstocks is an active research area, and the first commercial-scale applications of this emerging technology are now being tested. The development of a lignocellulosic biorefining industry has many benefits. For example, it could provide local employment, improve local environmental quality and contribute to ecosystem services by reducing net anthropocentric greenhouse gas emissions (by displacing fossil fuels as a refinery feedstock) and by lowering the requirements for other environmental feedstocks. In addition, harvesting and processing lignocellulosic feedstocks have the potential to lower residual nitrogen and phosphorous on fields, preventing their leaching into surface waters.

The development of a biorefining industry has the potential to deliver significant ecosystem service benefits in the Lake Winnipeg basin, although it may shift some benefits from the private sector to the public sector. For example, certain feedstocks may have greater ecosystem service benefits than others but may not provide the same returns to farmers as traditional crops. In addition, a detailed analysis of biorefineries in terms of energy, water and investments should be undertaken to understand their potential and near-term feasibility. The benefits of biorefineries and their implementation should be more broadly discussed to ensure all aspects are adequately considered.

Summary and conclusion

This review has shown the role of nutrient cycling in Lake Winnipeg and its linkage to the eutrophication problem. In spite of uncertainties about removal rates, mass balance calculations indicate that approximately 130,000 tons of nitrogen and 10,000 tons of phosphorous are being added annually to the southern Lake Winnipeg basin from commercial agricultural fertilizers alone with livestock and urban waste adding to this total. As pressures mount to resolve the Lake Winnipeg eutrophication problems, the factors leading to these high nutrient levels will need to be better understood so that a monitoring and assessment framework can be developed.

Further research is required to better refine crop uptake and removal rates in Manitoba (and throughout the entire Lake Winnipeg Basin) so that fertilization applications may be better optimized to reduce costs for farmers and further reduce nutrient loads to Lake Winnipeg. Research is also needed to find the convergence between the various estimates of phosphorous removal rates. Producers should be encouraged to experiment with the amount of fertilization actually needed for their crop so that they can assess for themselves the ideal fertilization rates for their specific conditions. Examples of innovative support programs exist, such as the America Farmland Trust's BMP Challenge for Nutrient Management, which compensates producers for any losses arising from their experimentation.

The development of long-term nutrient management plans for the Lake Winnipeg basin will require an understanding of Lake Winnipeg nutrient loading dynamics. The lack of water quality monitoring stations and the limited frequency of water quality measurements present key challenges in understanding total nutrient loads across the basin. In addition, a regional program involving soil testing and subsequent precision fertilization could identify deficits that need to be addressed to restore the nitrogen-to-phosphorous balance and minimize nutrient runoff.

Controlling the quantity of nutrients released to waterways is a critical factor in regulating the nutrient problem. In some cases this could mean making more effective use of the tools already available such as upstream BMPs. However, a complete portfolio of upstream BMPs will be critical to reduce the flow of nutrients to Lake Winnipeg. Furthermore, multi-decadal support for the implementation of BMPs will be necessary to achieve significant results given the time lags inherent in the flow of nitrogen and phosphorous through watersheds. BMPs also will need to be adapted to Manitoba-specific conditions. Areas requiring development include BMPs that can reduce snow-melt-driven nutrient loss, particularly dissolved nutrients, over the flat prairie region of southern Manitoba (Salvano et al., 2009), including BMPs that reduce the accumulation of nutrients in crop residues and soils (Tiessen et al., 2011).

There is also a need to enhance research on these issues. Some research questions about nutrient cycling in the Lake Winnipeg Basins that need to be resolved are:

- How much phosphorous is stored in the sediments of Lake Winnipeg and how will it be released over time?
- Does climate change play a significant role in the uncertainties related to extreme events flushing landscape residuals into waterways and in the extent and duration of the algal blooms on the lake?
- How will population growth, urbanization, and increasing demands for food and bioenergy feedstocks affect the nutrient loadings of rivers in the Lake Winnipeg Basin?
- In the longer term, how will the potential limits for rock phosphate resources affect agricultural practices and options for new approaches to farming practices?

In terms of the bioeconomy, the loss of ecosystems due to the steady advance of industrialization has led to a steady erosion of ecosystem services. In the Lake Winnipeg basin, the trade-off in the loss of these services has generally benefited food production. Biorefineries should be assessed in the bioeconomy framework as an element in addressing the Lake Winnipeg nutrient problem. Efforts to promote the use of lignocellulosic feedstocks to replace fossil fuel inputs not only enhances environmental services, but provides ways to recycle nutrients before they reach Lake Winnipeg.

References

- Armstrong, N. and G.K. McCullough, 2011. Nutrient loading to Lake Winnipeg. Section 7.0 in L. Lévesque and E. Page (Ed.) State of Lake Winnipeg: 1999 to 2007. Environment Canada and Manitoba Water Stewardship Report
- Benchmann, M.E., P.J.A. Kleinman, A.N. Sharpley, and L.S. Saporito, 2005: Freeze-thaw effects of phosphorous loss in runoff from manured and catch-cropped soils. J. Environ. Qual.,34, 2301-2309.
- Bourne, A., N. Armstrong, and G. Jones, 2002: A preliminary estimate of total nitrogen and total phosphorous loading to streams in Manitoba Canada. Manitoba Conservation Report No. 2002-04. 49 pp.
- Brunskill, G.J., Elliott, S.E.M., and Campbell, P. 1980. Morphometry, hydrology, and watershed data pertinent to the limnology of Lake Winnipeg. Department of Fisheries and Oceans, Winnipeg, Manitoba. Canadian Manuscript Report of Fisheries & Aquatic Science No. 1556.
- Burbidge, S.M., Blenkinsop, J., and Cousens, B., 2000. Sources of lead in Holocene Lake Winnipeg sediments: evidence from stable lead isotopic abundances. Natural Resources Canada, Ottawa, Ontario. Geological Survey of Canada: Open File 3470, p. 199-216.
- Cai, X., X. Zhang, and D. Wang, 2011: Land availability for biofuel production.Environ. Sci. Technol., 45, 334-339.
- Canadian Fertilizer Institute, 2001: Nutrient uptake and removal by field crops: Western Canada 2001. Canadian Fertilizer Institute, 2pp. www.cfi.ca/_documents/uploads/elibrary/d160_NU_E_01%5B1%5D.pdf.

» Carlyle, W.J. 1984. Water in the Red River Valley of the North. Geographical Review. 74(3): 331–358.

» Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith, 1998: Nonpoint pollution of surface waters with phosphorous and nitrogen. Ecol. Appl.,8, 559-568.

» Carpenter, S.R., D. Ludwig, and A.W. Brock, 1999: Management of eutrophication for lake subject to potentially irreversible change. Ecol. Appl.,9, 751-771.

» Carpenter, S.R., and E.M. Bennett, 2011: Reconsideration of the planetary boundary for phosphorous. Environ. Res. Lett.,6, 12 pp.

» Cicek, N., S. Lambert, H.D. Venema, K.R. Snelgrove, E.L. Bibeau, and R. Grosshans, 2006: Nutrient removal and bio-energ production from Netley-Libau Marsh at Lake Winnipeg through annual biomass harvesting. BiomassBioenerg.,30, 529-536.

» Cortez,L., M. Regis, L.V. Leal, and T. Sinkala, 2010: Why biofuels are important. Food versus Fuel: An Informed Introduction to Biofuels, F. Rosillo-Calle, and F.X. Johnson, Eds., Zed Books, 58-85.

» Costanza, R., and H.E. Daly, 1997: The value of the world's ecosystem services and natural capital. Nature, 387, 253-260.

» Diaz-Chavez, R., 2010: The role of biofuels in promoting rural development. Food versus Fuel: An Informed Introduction to Biofuels, F. Rosillo-Calle, and F.X. Johnson, Eds., Zed Books, 116-1137.

» Dinnes, D.L., 2004: Practices to reduce nitrogen and phosphorus nonpoint source pollution of Iowa's surface waters. USDA-ARS National Soil Tilth Laboratory, Iowa Department of Natural Resources, 380pp.

» Foley,J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, and P.K. Snyder, 2005: Global consequences of land use. Science, 309, 570-574.

» Franzin, W.G., D.A. Watkinson, and S. Backhouse. 2005. Fishes of the Lake Winnipeg Basin, their temperature tolerances and potential effects of climate warming on populations. Final report to the Canadian Climate Action Fund Project A499. Winnipeg, Manitoba.

» Glozier, N.E., J.A. Elliot, B. Holliday, J. Yarotski, and B. Harker, 2006: Water quality characteristics and trends in small agricultural watershed: South Tobacco Creek, Manitoba, 1992-2001. Environment Canada, 86 pp.

» Gray, D.M., and P.G. Landine, 1987. An energy-budget snowmelt model for the Canadian Prairies. Can. J. Earth Sci., 25, 1292-1303.

» Hamilton et al., 2005: The human dimensions: demographic impacts of fisheries decline. International Council for the Exploration of the Sea. Theme Session on cod in a changing climate. Copenhagen, the Council. 1p.

» Heard, J., and D. Hay, 2006: Nutrient content, uptake pattern and carbon: Nitrogen ratios of prairie crops. Manitoba Agriculture, Food and Rural Initiatives, 10pp. http://www.umanitoba.ca/afs/agronomists_conf/proceedings/2006/heard_hay_nutrient_uptake.pdf

» Honey, J., 2011a: Manitoba Cattle and Beef Industry 2010. Prepared for the Department of Agribusiness and Agricultural Economics, University of Manitoba

» Honey, J., 2011b: Manitoba Pig and Pork Industry 2009. Prepared for the Department of Agribusiness and Agricultural Economics, University of Manitoba

» Jeppesen, E., M. Sondergaard, J.P. Jensen, K.E. Havens, O. Anneville, L. Carvalho, M.F. Coveney, R. Deneke, M.T. Dokulil, B. Foy, D. Gerdeaux, S.S.E. Hampton, S. Hilt, K. Kangur, J. Köhler, H. Eddy, H.R. Lammens, T.L. Lauridsen, M. Manca, M.R. Miracle, B. Moss, P. Nöges, G. Persson, G. Phillips, R. Portielje, S. Romo, C.L. Schelske, D. Straile, I. Tatrai, E. Willén, and M. Winder,2005: Lake responses to reduced nutrient loading - an analysis of contemporary long-term data from 35 case studies. Freshwater Biol.,50, 1747-1771.

» Johnston, A.M., and Roberts, T.L., 2001. High soil phosphorus – is it a problem in Manitoba? Second annual Manitoba Agronomists Conference, 2001, pp. 74-82.

» Johnson, F.X., and I. Virgin, 2010: Future trends in biomass resources for food and fuel. Food versus Fuel: An Informed Introduction to Biofuels, F. Rosillo-Calle, and F.X. Johnson, Eds., Zed Books, 164-190.

» Kling, H.J., S.B. Watson, G.K. McCullough and M.P. Stainton. 2011. Bloom development and phytoplankton succession in Lake Winnipeg: a comparison of historical records with recent data. J. Aquatic Ecosystem Health and Management. In Press.

» Lake Winnipeg Stewardship Board, 2006: Reducing nutrient loading to Lake Winnipeg and its watershed: Our collective responsibility and commitment to action. Report to the Minister of Water Stewardship, 78 pp.

» Langeveld, H., J. Sanders, and M. Meeusen, Eds., 2009:The Biobased Economy. Earthscan, 389 pp.

» Levin, D.B., H. Zhu, M. Beland, N. Cicek, and B.E. Holbein, 2007: Potential for hydrogen and methane production from biomass redidues in Canada. Bioresource Technol., 98, 654-660.

» McCandless, M., D. Medeiros, and H.D. Venema, 2011: Biorefinery Feedstock Harvesting and Water Quality Improvements. International Institute for Sustainable Development, in progress.

» McCullough, G.K., K. Hochheim and P.M. Cooley. 2001: Retrospective Study of Suspended Sediment Patterns on Lake Winnipeg using NOAA AVHRR Satellite Imagery. Report to the Department of Fisheries and Oceans, Winnipeg, Canada. v+72 pp.+4 appendices.

» McCullough, G., 2005: Surface water temperature and break-up and freeze-up of the ice cover on Lake Winnipeg. Report prepared for Fisheries and Oceans Canada for submission to Natural Resources Canada Climate Change Action Fund.

» McCullough, G.K., M. Stainton and H.J. Kling, 2006: Environmental controls on algal blooms in Lake Winnipeg. Canadian Water Resources Forum: Managing Nutrients in the Lake Winnipeg Watershed. Winnipeg, Canada. 18,19 October, 2006.

» McCullough, G.K., S.J. Page, R.H. Hesslein, M.P. Stainton, H.J. Kling, A. Salki, D.G. Barber. 2011. Hydrological forcing of a recent trophic surge in Lake Winnipeg. J. of Great Lakes Research. In press.

» McDowell, R.W., B.J.F. Biggs, A.N. Sharpley, and L. Nguyen, 2004: Connecting phosphorous loss from agricultural landscapes to surface and water quality. Chem. Ecol.,20, 1-40.

» McDowell, R.W., and A.N. Sharpley, 2001: Approximating phosphorous release from soils to surface runoff and subsurface drainage. J. Environ. Qual.,30, 508-520.

» Manitoba Food, Agriculture and Rural Initiatives, 2009:Manitoba Agriculture Yearbook, 2008. Knowledge Management Knowledge Centre,http://www.gov.mb.ca/agriculture/statistics/yearbook/mb_%20agriculture_yearbook.pdf

» Manitoba Land Initiative, 2010: Manitoba Land Initiative. Government of Manitoba. http://mli2.gov.mb.ca/

» Manitoba Water Stewardship, 2006: Literature review related to setting nutrient objectives for Lake Winnipeg. Report prepared by North-South consultants, 186 p.

» Medeiros, D, M. McCandless and H. D. Venema, 2011: Nitrogen and Phosphorus Balance from synthetis fertilizer application in southern Manitoba, International Institute for Sustainable Development (In preparation).

» Mekonnen, M.M. and A.Y. Hoekstra, 2010: The green, blue and grey water footprint of crops and derived crop products. Value of Water Research Report Series, No. 47, UNESCO-IHE, Delft, the Netherlands.

» Millennium Ecosystem Assessment, 2005a:Ecosystems and Human Well-being: General Synthesis. Island Press, 155 pp.

» Millennium Ecosystem Assessment, 2005b: Ecosystems and Human Well-being. Volume 1: Current State& Trends Assessment. Findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment. R. Hassan, R. Scholes, and N. Ash, Island Press.

» Organisation for Economic Co-operation and Development, 2009: The Bioeconomy to 2030: Designing a Policy Agenda. OECD Publishing, 2009, 332 pp.

» Salvano, E., D.N. Flaten, A.N. Rousseau, and R. Quilbe, 2009: Are current phosphorous risk indicators useful to predict the quality of surface waters in southern Manitoba, Canada? J. Environ Qual.,38, 2096-2105.

» Sendich, E.D., and B.E. Dale, 2009: Environmental and economic analysis of the fully integrated biorefinery. GCB Bioenergy, 1, 331-345.

» Sheppard, S.C., M.I. Sheppard, J. Long, B. Sanipelli, and J. Tait, 2006: Runoff phosphorous retention in vegetated field margins on flat landscapes. Can. J. Soil Sci.,86, 871-884.

» Smil, V., 2001:Feeding the World: A Challenge for the 21st Century. MIT Press, 392 pp.

» Smil,V., 2004:Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. MIT Press, 338 pp.

» Statistics Canada, 2004. http://www.statcan.gc.ca/pub/16f0025x/phosph/4148090-eng.htm

» Swink, S.N., Q.M. Ketterings, L.E. Chase, K.J. Czymmek, and M.E. van Amburgh, 2011: Nitrogen balances for New York State: Implications for manure and fertilizer management. J. Soil Water Conserv.,66, 1-17.

» Tiessen, K.H.D., J.A. Elliott, M. Stainton, J. Yarotski, D.N. Flaten, and D.A. Lobb, 2011: The effectiveness of small-scale headwater storage dams and reservoirs on stream water quality and quantity in the Canadian Prairies. J. Soil Water Conserv., 66, 158-171.

Appendix A

Calculation of the virtual water represented by crop exports from Manitoba in 2010 based on techniques and parameter values from Mekonnen and Hoekstra (2010).

Crop Category	Export Volume (tones)	Water Footprint (m^3/tone)	Total Volume of Virtual Water (km^3)
Fodder Crops	9,307	253	0.002
Vegetables	71,000	322	0.023
Cereals	4,241,570	1644	6.973
Oil Crops	1,795,682	2364	4.244
Pulses	191,353	4055	0.776
Spices	19,507	7048	0.137
Total			12.16

Effect of changing anthropogenic and climate conditions on BOD loading and in-stream water quality in Europe

Anja Voß[1], Ilona Bärlund[2], Manuel Punzet[3], Richard Williams[4], Ellen Kynast[1], Olli Malve[5] & Frank Voß[1]

[1] Center for Environmental Systems Research (CESR), Kurt-Wolters-Straße 3, 34109 Kassel, Germany
E-mail: avoss@usf.uni-kassel.de

[2] Helmholtz Centre for Environmental Research (UFZ), Brückstrasse 3a, 39114 Magdeburg, Germany

[3] University of Göttingen, Department Silviculture and Forest Ecology of the Temperate Zones, Büsgenweg 1, 37077 Göttingen, Germany

[4] Natural Environment Research Council - Centre for Ecology and Hydrology (NERC-CEH), OX10 8BB, Wallingford, United Kingdom

[5] Finnish Environment Institute (SYKE), P.O. Box 140, 00251 Helsinki, Finland

Abstract

Catchment scale modelling of water and solute transport and transformations is a widely used technique to study pollution pathways and effects of natural changes, policies and mitigation measures. There are, however, only a few examples of global water quality modelling. This paper provides a description of the new continental-scale water quality model WorldQual and the analysis of model simulations under changed climate and anthropogenic conditions with respect to changes in diffuse and point loading as well as surface water quality. Biological Oxygen Demand (BOD) is used as an indicator of the level of organic pollution and its oxygen-depleting potential, and for the overall health of aquatic ecosystems. The first application of WorldQual is to river systems of Europe. The model itself is being developed as part of the EU-funded SCENES Project which has the principal goal of developing new scenarios of the future of freshwater resources in Europe. Using WorldQual the influence of climate and anthropogenic changes on European water resources can be compared. The results indicate that changes in loading and in-stream concentrations following socio-economic changes and seem to override the effect of climate change.

Keywords

water quality modelling, gridded continental-scale model, pollution loadings, biological oxygen demand, point sources, diffuse sources, scenarios, climate change, socio-economic change

Introduction

Estimates of future water quality are needed for two major reasons: to assess the future state of aquatic ecosystems and to determine the suitability of surface water supply for different water users such as industries and the domestic sector. For this, pan-European scenarios on water quantity and quality have been developed in a participatory process within the SCENES project (Water Scenarios for Europe and Neighbouring States (Kämäri et al. 2008). The project aims to address the complex questions about the future of Europe's water resources up to 2050s. Biological Oxygen Demand (BOD) is used as a representative substance but the framework is generic and thus applicable to any other substance e.g. for salts or total nutrients.

The presence of trends in water chemistry provides an indication of environmental changes and gives insight into contributing factors such as climatic variation or anthropogenic changes. Although basin scale modelling of water and solute transport and transformations is a widely used technique to study pollution pathways and effects of policies and mitigation measures (e.g. Schob et al. 2006, Bärlund et al. 2007, Hesse et al. 2008, Krause et al. 2008, Volk et al. 2008) there are only a few examples of global water quality models (Seitzinger et al. 2002, Green et al. 2004, Grizzetti and Bouraoui 2006).

The aim of the WorldQual model is to determine chemical fluxes in different pathways combining analysis of water quantity with water quality. Simple equations, consistent with the availability of data on the continental scale, are used to simulate the response of in-stream BOD concentrations to diffuse and anthropogenic point loadings as well as flow dilution. The calculations on water availability and water use required for this large-scale water quality modelling are performed by the WaterGAP (Water Global Assessment and Prognosis, Alcamo et al. 2003, Döll et al. 2003, Flörke and Alcamo 2004) model. Here the WaterGAP3 version with a 5 by 5 arc minutes grid (longitude and latitude; ca. 6 x 9 km for Europe) is used (Verzano 2009).

Material and methods

Model description

The WorldQual model is used to calculate the in-stream water quality on continental scale. Its aim is to determine chemical fluxes in different pathways which will allow a combination of water quantity with water quality analyses. In the model, it is generally distinguished between point sources and diffuse sources. Point sources are divided into manufacturing, domestic, urban and loadings from scattered settlements, whereas diffuse loadings origins from agricultural input (for instance livestock farming), and also from natural background sources.

Solute transport in open water channels is an important topic in water quality studies. In addition to any biological and biochemical reactions that may occur in river streams, polluting solutes that enter water courses are transported and dispersed downstream. Due to application on a large (continental) scale only simple approaches can be considered. Such an approach was first introduced by Chapra in 1997. Based on this work, a nonlinear formulation assuming a temperature dependent decay rate as proposed by e.g. Bowie et al. (1985) and Benham et al. (2006) for non-conservative substances like BOD was derived. It is assumed that input from direct upstream and from other tributaries enters the grid cell right at the beginning of each cell and defines the upstream concentration C0 (Figure 1). All the input from diffuse and point sources reaching the river network within a cell is distributed uniformly all over the river length within this cell. For conservative substances, loadings entering the channel are dissolved in distributed inflow qd, whereas for non-conservative

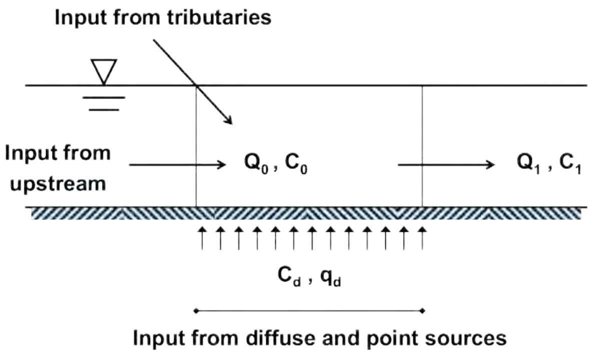


Figure 1. Basic model concept for solute transport in open channel flow.

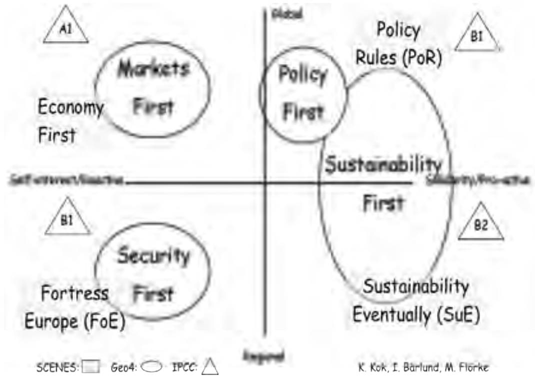


Figure 2. Scenario overview.

determinants only the substance itself is distributed longitudinally. In total, additional loadings from within a cell define the concentration Cd. Concentration in downstream flow is defined as C1. Downstream routing is predefined as order from upstream to downstream.

Scenario description

The analysis within this work is based on a combination of two climate and four socio-economic scenarios. The latter were developed within the SCENES project. The time frame of the climate scenarios used in the model calculations are the 2050s (2040 – 2069). The socio-economic storylines describe the future up to 2050.

The aim of the climate scenario selection was to choose global circulation model - IPCC SRES A2 emission scenario combinations, that produce, not the most extreme, but high temperature increase combined with a high increase in precipitation or with a low increase or decrease in precipitation to show the range of change. Two GCM-scenario combinations emerged:

- IPCM-A2: IPSL-CM4, Institute Pierre Simon Laplace, France + IPCC SRES A2 scenario: high temperature increase with low precipitation increase or decrease
- MIMR-A2: MICRO3.2, Center for Climate System Research, University of Tokyo, Japan + IPCC SRES A2 scenario: high temperature increase, high precipitation increase or low decrease.

The choice of an A2 emission scenario for all SCENES socio-economic scenarios underlines the view of the storylines developed within the project which stress climate change as one of the strongest triggers of actions during the scenario period.

The four socio-economic scenarios – Economy First (EcF), Fortress Europe (FoE), Policy Rules (PoR) and Sustainability Eventually (SuE) – that were developed within SCENES are based on the Global Environment Outlook (GEO-4) scenarios which were used as a starting point in the first scenario development phase, the so-called Fast-Track period (Figure 2, Kok et al. 2009).

Results and discussion

BOD loadings – current conditions

The total BOD loading of the baseline 2005 shows a pattern in which lowest loadings are in Scandinavia and highest loadings in a North-West to South-East band reaching from Ireland to Western Turkey and the Eastern Mediterranean. There are also high loadings on the west coast of Portugal (Figure 3 a).

The main current pollution load in Europe comes from the diffuse sector accounting for 53%, followed by sectors depending on population development, namely domestic (31%) and scattered settlements (13%) (Table 1). Manufacturing and urban runoff are insignificant small. There can, however, be some variation in these values between individual basins. For example, Thames has a 67% loading contribution from domestic and only 29% from diffuse sources, whereas Ebro and Vistula have much more diffuse loading with 89 resp. 69%. As would be expected, the high diffuse loadings like in Ebro and Vistula reflect a high density of animal production. In contrast hereto, the Thames River is dominated by high population density.

Table 1. Total BOD loading 2005 and its sectoral distribution for Europe and selected basins.

	total [t/a]	manu-facturing [%]	domestic [%]	scattered settlements [%]	urban runoff [%]	diffus [%]
Europe	9 636 182	3	31	13	0	53
Vistula	229 293	2	18	11	0	69
Thames	40 560	2	67	0	1	29
Ebro	99 806	1	10	0	0	89

BOD loadings - climate and socio economic change

In order to analyse the impact of climate and socio-economic change on pollution loadings scenario calculations have first been performed separately and then together.

The percentage change of BOD loadings under climate only and socio-economic only change show that the difference between baseline loadings and changes for the climate scenario is small for the total as well as for the sectoral loadings (Table 2). Here only the IPCM4-A2 climate scenario is presented because the MIMR-A2 scenario shows the same results. The impact of the socio-economic change is much bigger and differs between Europe and the selected basins and sectors. For Europe the result is as expected: under EcF and FoE conditions the loadings will increase and in SuE as well as in PoR the loadings will decrease. The biggest impact is calculated for SuE by -31% - here the main sources of reduction are the point loadings and scattered settlements by 61%. Diffuse loadings decrease by 4 %. Between the individual basins there is a clear variation in these values. Vistula as part of Eastern Europe shows a decrease of total, point and diffuse loadings for all four scenarios. For the Western European Thames only the SuE scenario leads to a small decrease

Table 2 Percentage change of BOD loading under different scenario conditions for Europe and selected basin**S.**

	Baseline [t/a]	Climate Only [%]	EcF Only [%]	FoE Only [%]	SuE Only [%]	PoR Only [%]
Total loadings						
Europe	9 636 182	-0.011	4	2	-31	-3
Vistula	229 293	-0.001	-14	-20	-26	-22
Thames	40 560	-0.072	22	10	-3	20
Ebro	99 806	-0.002	15	-5	2	16
Point loadings and scattered settlements						
Europe	4 558 528	-0.021	-3	2	-61	-15
Vistula	70 181	0.000	-12	-18	-33	-25
Thames	28 621	-0.102	25	13	-4	23
Ebro	11 396	-0.001	65	-4	-17	49
Diffuse loadings						
Europe	5 077 654	-0.003	11	1	-4	8
Vistula	159 111	-0.001	-15	-21	-24	-21
Thames	11 939	-0.002	16	3	1	14
Ebro	88 411	-0.002	8	-5	5	12

of loadings. The relationship between point and diffuse sources is equal. The Ebro in Southern Europe shows a small decrease in total loadings only for FoE. Noticeable is the huge increase in point loadings within the Ebro basin for the scenarios EcF and PoR.

To analyse the impact of climate and socio-economic change together two scenario combinations were selected: IPCM4-A2-EcF as example for a globalising, market-oriented Europe and IPCM4-A2-SuE with focus of environmental sustainability. The results are shown as maps in Figs 3 b and c (Figure 3 a shows the baseline 2005 loading distribution).

Both scenarios have regions with decreasing and increasing BOD loadings, but in SuE the area of decreasing pollution load is much bigger. For EcF it is expected that the loadings in Eastern Europe will decrease. In Northern and partly in Western and Southern Europe small increases of loadings can be found. For the Atlantic coast, Ireland, British Isles as well as for Western Asia the increase of BOD pollution is the highest. Within the SuE scenario a decrease of loadings can be found not only for Eastern Europe, but also for Western and parts of Northern and Southern Europe and for Western Asia. For all other parts of Europe a small to medium increase is expected. The reasons for these changes are mainly developments in the domestic, scattered settlements and diffuse loading sectors, like sewage treatment and livestock numbers.

BOD in-stream concentrations

BOD loading is only one component that can influence the in-stream concentration. Aside exist also river availability, water temperature and flow velocity that go into the scenario calculations. The in-stream concentration in Europe for the baseline 2005 shows that no influence of loading on water quality is detected for Northern Europe (Figure 4a). In contrast, the highest concentrations can be found for the Iberian Peninsula, Western Asia and Eastern Mediterranean. All other rivers of Europe have low to medium BOD concentrations. The BOD concentration in rivers can be coupled with water quality classes. Thereby <1 mg/l means very good and >50 mg/l

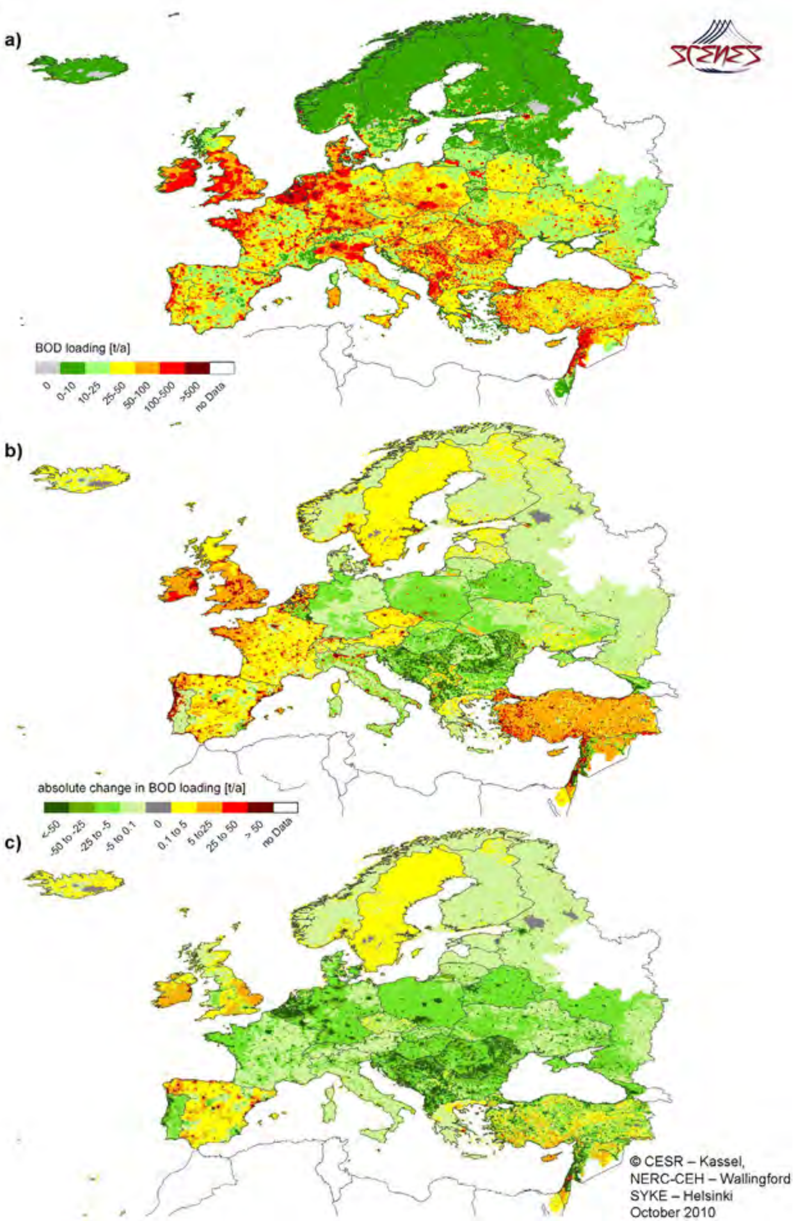


Figure 3. a) Total BOD loading 2005 b, c) Absolute change in total BOD loading 2005 vs. 2050 climate IPCM4-A2 b) Economy First and c) Sustainability Eventually.

means highly polluted river streams. For the baseline as well as for the three different scenarios all cells within a river basin belong to one of nine classes.

In order to investigate the in-stream BOD concentrations in more detail, the differences between the classes (scenario minus baseline) were calculated for the IPCM4-A2-EcF and IPCM4-A2-SuE scenarios (Figs. 4b and c). Thereby positive values (degradation), negative values (improvement) and no changes (zero) occur. In EcF the water quality will stagnate for Scandinavia and most parts of Eastern Europe. For the Iberian Peninsula, big parts of Western Europe and Western Asia the in-stream concentration will get worse by up to 2 classes compared to the baseline 2005. Different patterns can be found in the SuE scenario in which big parts of Europe show an improving water quality by up to 2 classes. For Scandinavia the same result as for the EcF scenario can be seen with a stable BOD in-stream concentration. Only small regions of the Iberian Peninsula and Western Asia show a degrading water quality. The reason for these results is mainly a combination of changes in river availability due the different water uses and in BOD loading. As an example, Eastern Europe shows a decreasing BOD loading for both scenarios EcF and SuE, but only in SuE a clear improvement in water quality results. Here the water availabilities differ because of different water uses. In EcF the water use is higher than in SuE and therefore the river availability is lower and effects again higher in-stream concentrations. Climate change itself has not an important impact on water quality. Only small changes could be identified as effect on river availability, BOD decay and flow velocity.

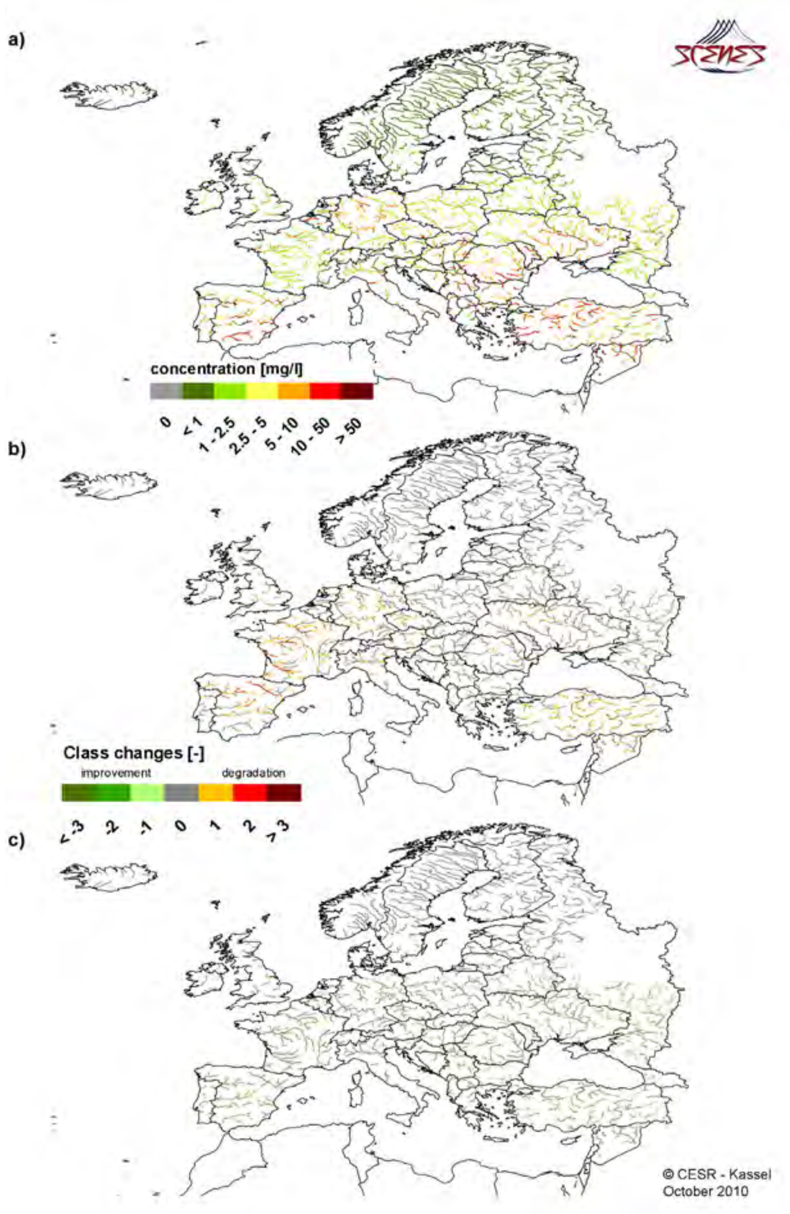


Figure 4.
a) BOD in-stream concentration in July 2005 b, c) Changes in water quality classes 2005 vs. 2050 climate IPCM4-A2
b) Economy First and
c) Sustainability Eventually.

Conclusions and outlook

The WorldQual model provides a framework for water quality modelling at the continental scale. Such a framework can be used to analyse long-term future European water quality. These results for Europe show that future changes in loading and in-stream concentrations following socio-economic changes seem to override the effect of climate change.

Modelling on continental scale raises the question what is required for such methods to be used in e.g. decision making – can confidence be increased by defining uncertainty estimates and what would be the mechanism for putting the framework into practice. Global scale modelling of water quality points out potential hotspots. In order to assess the implications of water quality for river basin management solutions river basin modelling is necessary. Here a synthesis on national or regional scale is required to link these scales and to get the benefits of both.

Acknowledgement

This research has been supported by the European Union project SCENES (EC-funded FP6, Contract number 036822).

References

» Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B. Rösch, T., Siebert, S., 2003. Development and testing of the WaterGAP2 global model of water use and availability. Hydrol. Sci. J. 48: 317-337.

» Bärlund, I., Kirkkala, T., Malve, O., Kämäri, J., 2007. Assessing SWAT model performance in the evaluation of management actions for the implementation of the Water Framework Directive in a Finnish catchment. Environmental Modelling & Software 22(5): 719-724.

» Benham, B.L., Baffaut, C., Zeckoski, R.W., Mankin, K.R., Pachepsky, Y.A., Sadeghi, A.M., Brannan, K.M., Soupir, M.L., Habersack, M.J., 2006. Modeling bacteria fate and transport in watersheds to support TMDLs. American Society of Agricultural and Biological Engineers 49(4): 987-1002.

» Bowie, G., Mills W., Porcella, D., Campbell, C., Pagenkopf, J., Rupp, G., Chamberlin, C., Johnson, K., Gherini, S., 1985. Rates, Constants, and Kinetics Formations in Surface Water Quality Modeling. Athens, GA, U.S. Environmental Protection Agency.

» Döll, P., Kaspar, F., Lehner, B., 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology 270: 105-134

» Chapra, S.C., 1997. Surface water-quality modeling. Boston, Burr Ridge, Dubque, Madison, New York, San Francisco, St. Louis, McGraw-Hill.Malve

» Flörke, M. & Alcamo, J., 2004. European Outlook on Water Use. Center for Environmental Systems Research, University of Kassel, Final Report, EEA/RNC/03/007, 83 pp.

» Green, P., Vörösmarty, C.J., Meybeck, M., Galloway, J., Peterson, P., Boyer, C., 2004. Preindustrial and contemporary fluxes of nitrogen through rivers: a global assessment based on typology. Biogeochemistry 68: 71105.

» Grizzetti, B. & Bouraoui, F., 2006. Assessment of Nitrogen and Phosphourus Environmental Pressure at the European Scale. Institute for Environment and Sustainability, Joint Research Centre, Italy. ISBN 92-79-03739.

» Hesse, C., Krysanova, V., Päzold, J., Hattermann, F.F., 2008. Eco-hydrological modelling in a highly regulated lowland catchment to find measures for improving water quality. Ecological Modelling 218(1-2): 135-148.

» Kämäri, J, Alcamo, J., Bärlund, I., Duel, H., Farquharson, F., Flörke, M., Fry, M., Houghton-Carr, H., Kabat, P., Kaljonen, M., Kok, K., Meijer, K.S., Rekolainen, S., Sendzimir, J., Varjopuro, R. and Villars, N., 2008. "Envisioning the future of water in Europe - the SCENES project", E-Water [online] European Water Association.

» Kok, K., van Vliet, M., Bärlund, I., Sendzimir, J., Dubel, A. 2009. First ("first-order") draft of pan-European storylines – results from the second pan-European stakeholder workshop. SCENES Deliverable 2.6. Wageningen University, Wageningen. Available online at www.environment.fi/syke/scenes.

» Krause, S., Jacobs, J., Voss, A., Bronstert, A., Zehe, E., 2008. Assessing the impact of changes in landuse and management practices on the diffuse pollution and retention of nitrate in a riparian floodplain. Science of the Total Environment 389(1): 149-164.

» Schob, A., Schmidt, J., Tenholtern, R., 2006. Derivation of site-related measures to minimise soil erosion on the watershed scale in the Saxonian loess belt using the model EROSION 3D. Catena 68: 153-160.

» Seitzinger, S.P., Kroeze, C., Bouwman, A.F., Caraco, N., Dentener, F., Styles, R.V., 2002. Global patterns of dissolved inorganic and particulate nitrogen inputs in coastal ecosystems: recent conditions and future projections. Estuaries 25: 640-655.

» Verzano, K., 2009. Climate change impacts on flood related hydrological processes: Further development and application of a global scale hydrological model. Reports on Earth System Science. 71-2009. Max Planck Institute for Meteorology, Hamburg, Germany.

» Volk, M., Liersch, S., Schmidt, G., 2008. Towards the implementation of the European Water Framework Directive? Lessons learned from water quality simulations in an agricultural watershed. Land Use Policy.

Virtual water flows - Methods of water accounting and examples

Hong Yang[1] & Zhouying Zhang[2,3]

[1] Swiss Federal Institute of Aquatic Science and Technology, 8600, Dübendorf, Switzerland

E-mail: hong.yang@eawag.ch

[2] Graduate University of Chinese Academy of Sciences, 100049, Beijing, China

[3] Research Centre on Fictitious Economy & Data Science, Chinese Academy of Sciences, 100190, Beijing, China

Abstract

Issues relating to virtual water trade and water footprint have drawn increasing attention in the scientific community and the political sphere since their advent. This paper provides an overview of the research on the relevant issues with a focus on methods applied and implications of results. Examples from different geographical regions and economic sectors are provided for illustration. The paper highlights that the international trade of goods and services imposes significant impacts on water resources and uses on water scarce countries and regions. The concepts of virtual water and water footprint are useful for supporting water policies at different geographical levels and across economic sectors and regions. But they alone cannot determine the optimal water allocations and trade patterns of a country or region.

Introduction

Virtual water is defined as the water required in the production process of goods and services (Allan, 1993; Yang et al., 2006). Water footprint refers to the volume of water used to produce the goods and services consumed by people (Hoekstra and Chapagain, 2006). For a product, its water footprint is the volume of freshwater used to produce the product, measured over the full supply chain (Hoekstra et al., 2011). The major difference of the two concepts lies in their perspectives in viewing water use. By and large, virtual water views the water requirement from the production perspective, whereas water footprint views water use from the consumption perspective. In the framework of virtual water, water footprint can also be defined as the volume of virtual water embodied in the final products. The concepts of virtual water and water footprint have received much attention since their advent because they provide new perspectives in addressing water scarcity and insights into water resources management on different geographical scales and interconnections among different sectors and regions.

This paper provides an overview of the virtual water research with a focus on methods applied and implications of the results. The topics covered include: 1) Methods of virtual water accounting and interpretations of water saving; 2) Relations between water scarcity and virtual water trade; 3) Application of the input-output model to trace virtual water flows among economic sectors and across river basins.

Virtual water accounting and water saving associated with virtual water trade

Virtual water accounting

The water that is required for the production of a unit of product is termed the 'virtual water content', expressed in m^3/kg. It is simply the inversion of water productivity measured in kg/m^3. Virtual water studies so far have focused on agricultural products because of their generally high water intensity in production. Virtual water content of a given crop is a function of climate conditions, agronomic practices and field management. The value differs largely across geographical locations. In quantifying virtual water flows, some aggregate ratios have often been used. For example, 1 m^3/kg was used as the virtual water content of cereal crops (Allan, 1997; Yang and Zehnder, 2001). Some other studies used virtual water contents measured in fields or experimental sites to take care of the spatial variations (Renault, 2003; Oki and Kanae, 2004). In recent years, process-based crop growth models supported by GIS techniques have been applied to estimate crop water consumptive use and virtual water content/water productivity (Hoekstra and Hung, 2005; Liu et al., 2007). The modeling approach has provided a systematic tool to account for spatial variations on virtual water content, and enabled analysis of impacts of changes in input factors on crop yield and water productivity.

Multiplying the virtual water content of a particular product with the quantity traded derives the volume of virtual water flow for that product. Allan (1997) estimated that the virtual water embodied in cereal import into the Middle Eastern and North African countries exceeded the total annual water use for food production in Egypt. Hoekstra and Hung (2005) estimated the virtual water flows between nations at about 1000 km^3/year at the turn of the last century (from the perspective of exporting countries). Of which, about 70% was attributed to crop related trade. In recent years, some studies have attempted to quantify virtual water trade at the river basin level. For example, Zhao et al. (2010) estimated that net virtual water import of the Haihe River basin in China for the years 1997, 2000 and 2002. The results showed that the average net virtual water import to the region was about 5.1 billion m^3, accounting for approximately 11% of the region's total water footprint in the year.

Crops	Global gross virtual water import (km3 year-1)	Global gross virtual water export (km3 year-1)	Global water saving	
			Volume (km3 year-1)	Ratio of virtual water saving to total virtual water import
Wheat	318.8	188.4	130.3	40.9
Rice	53.5	63.2	-10.1	-18.8
Maize	97.3	39.5	57.4	59.0
Barley	55.1	31.7	20.1	36.4
Soybean	104.9	67.3	37.1	35.3
Others*	351.1	249.2	101.9	29.0
Total	980.7	644.0	336.8	34.3

Table 1. Global virtual water import and export and the scale of reduced water use, average over 1998-2002 (Yang et al., 2006)

Magnitude of the reduction of global water use associated with food trade

In the global food trade system, the volume of total food export is approximately equal to the volume of total food import. This is especially so when averaged over a period of time as the effect of yearly stock exchange is smoothed out. Concerning the global virtual water trade, however, this equilibrium does not apply. As crop water productivity differs across countries, the virtual water content also varies. The virtual water 'value' of a given amount of food may not be identical on the importing and exporting sides. Table 1 shows the gross virtual water import and export at the global level. The total volume of virtual water export associated with the food crops considered is about 644 km3/year. The corresponding volume for import is 981 km3/year. The difference is 337 km3/year. This volume is the reduced global water use resulted from the trade. In other words, this amount of additional water would otherwise be required if the imported amount of food were produced in the importing countries. The reduced global water use associated with the trade has often been referred to as 'global water saving' (Chapagain et al. 2006).

For individual crops, the scale of reduced water use varies. For wheat and maize, the trade resulted in a 41% and 59% reduction in the global water use in producing the traded amounts of the respective crops. The trading of these two crops contributes greatly to the reduction of global total water use. An exception, however, is rice where the volume of virtual water embodied in rice export is larger than that in rice import. This indicates that the rice production in the exporting countries requires more water than the production in the importing countries. This may partly be explained by the relatively high crop evapotranspiration in the major rice exporting countries, such as Vietnam and Thailand.

The reduced water use at the global level is the result of a relatively high crop water productivity in the major exporting countries in comparison to most importing countries. The estimation by Liu (2009) shows that crop water productivity of wheat is mostly over 1 kg/m3 in the major exporting countries in North America and Western Europe in comparison to below 0.6 kg/m3 in many countries in Africa and Central Asia. For maize, the water productivity is over 1.5 kg/m3 in the USA, Australia, and the EU countries. In contrast, the figure in most countries in Africa and Central Asia is below 0.9 kg/m3. The low crop water productivity is mainly seen in poor countries. This situation is expected because the level of crop water productivity is closely related to the material inputs, agronomic practices and water management at both regional and farm-level. Efforts to raise crop water productivity are often associated with greater material inputs and improved agronomic practices and water management, which are generally lacking in poor countries.

The scale of the global reduction in water use due to trade depends on the wideness of the water productivity gap between exporting and importing countries and the quantity of food trade. The narrower the gap, the smaller the volume of global water use reduction holding other factors constant. If the food importing countries can improve their water productivity, the gap will be narrowed and the volume of global water use reduction will decline. The improved water productivity may also enable importing countries to produce more food with a given amount of water. Food import requirement will be smaller and so will the volume of global water use reduction. For this reason, promoting virtual water trade for global water saving is misaligned.

It is also worth noting that from the perspective of the hydrological cycle on the Earth system, the term 'global water saving' may not be appropriate. This is because the global water cycle is quantitatively constant and water cannot be conserved globally. The main effect that may be globally relevant is the longer time elapsing before water is reused.

Relations between water scarcity and virtual water trade

While water scarcity has been at the center of virtual water discussion, not all virtual water trade is driven by water scarcity. Table 2 shows the shares of three importing country groups in total virtual water import associated with the global cereal trade. The division is based on annual per capita freshwater resources availability of the countries. The water scarcity threshold of 1700 m^3/capita defined by Falkenmark (1995) is used as a benchmark. A minimum of 2500 m^3/capita is set for non-water scarce countries. This is based on the observation that above this level, a country is very unlikely to endure a nationwide physical water resources scarcity, though some regions may experience water stress. The countries with water resources availability between 1700 m^3/capita and 2500 m^3/capita are at the margin, which may or may not endure a widespread water scarcity.

The total net virtual water import of all net cereal importing countries is around 715 km^3 annually. Of this volume, about 20.4% occurs in the countries with water resources below 1700 m^3/capita, 11.5% is in the countries with water resources between 1700m^3/capita and 2500m^3/capita. The remaining 68.1% is in the non-water scarce countries. Based on these figures, one can conclude that water scarcity has a relatively limited role in shaping the global virtual water trade flows. For developed countries, such as Japan, Switzerland, Italy, etc., lack of land resources would have been an important drive for food import (Oki and Kanae, 2004).

Nevertheless, for water scarce countries, virtual water import plays an important role in balancing the water budget and alleviating water stress. Yang et al. (2003) modeled the relationship between water

Table 2. Net virtual water import in cereals by country groups, average of 1997-2001 (viewed from the importing side)
Source: Yang et al. (2006)

	Total	Countries with water availability below 1700 m^3/capita	Countries with water availability between 1700 and 2500 m^3/capita	Countries with water availability larger than 2500 m^3/capita
Total net virtual water import (km^3/year)	715.5	145.8	82.1	487.1
Percentage of total net virtual water import (%)	100	20.4	11.5	68.1

Table 3. Net virtual water import (NVWI) in the MENA countries (million m^3) (Average of 1995-2000)
Source: Yang et al. (2006).

	NVWI	Water resources	Ratio of NVWI to WR
	m^3/cap/year	m^3/cap/year	%
Algeria	374	437	86
Cyprus	671	995	67
Egypt	202	859	24
Israel	574	276	208
Jordan	350	179	196
Lebanon	362	1261	29
Lybia	632	113	559
Morocco	212	971	22
Tunisia	512	482	106

Figure 1. Water resources and virtual water export of the Huang-Huai-Hai region in China

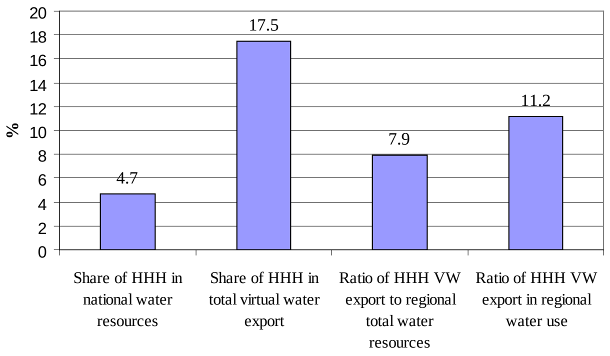
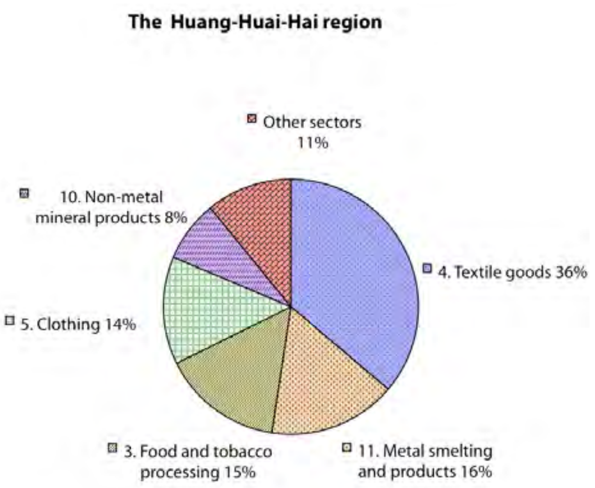


Figure 2. Shares of the major net virtual water export sectors in total net virtual water export in the HHH region (2002)



resources availability and cereal import for the countries in Asia and Africa. A water scarcity threshold of approximately 1500 m^3/capita/year was identified. Below the threshold, a country's demand for cereal import increases exponentially with decreasing water resources. Above the threshold, no systematic relationship exists between cereal import and water resources availability. This figure is very close to the 'rule of the thumb' threshold of 1700 m^3/capita/year defined by Falkenmark (1995).

To further illustrate the significance of virtual water trade in compensating for water scarcity in water scarce countries, Table 3 provides the net virtual water import in the Middle Eastern and North African region. It can be seen that many of them have extremely high ratio of virtual water import to their renewable water resources. In Libya, the volume of virtual water import is more than five times its own available water resources.

Application of the Input-Output model for tracing virtual water flows across system boundaries

Until very recently, studies on virtual water flows and water footprint have generally used the so called apparent consumption method, which first estimates the virtual water content of a unit of product and then multiplies the total quantity of the product with its virtual water content. For a chosen final product, e.g., a piece of bread, a cotton T-shirt, this method works well. But for accounting for water footprint and virtual water flows across all economic sectors in a regional/national economy, the method is cumbersome, time-consuming and subject to many approximations. To overcome this problem, the input-output (IO) method has been increasingly applied (Llop, M., 2008; Zhao et al., 2009; 2010; Dietzenbacher and Velazquez, 2007; Lenzen, 2009; Wang et al., 2009). The method can systematically evaluate water footprint and virtual water trade of final demand in the context of the whole economic circulation, instead of only crops or individual products as seen in most of the previous studies.

Figure 1 shows the virtual water flows of the Huang-Huai-Hai region (the HHH region) associated with its international trade of goods and services estimated using the input-output model. The HHH region is one of the most economically important regions, contributing to 27% of the GDP of China in 2009 (National Bureau of Statistics of China, 2010). The region is facing a severe water scarcity. The average per capita water resources availability is only about 500 m^3/capita/year (Zhang et al., 2011). Yet, the investigation found that the HHH region is a net virtual water exporter of 8.1 km^3/year, accounting for 17.5% of China's total net virtual water export. The net virtual water export of the HHH region accounts for 7.9% of the region's water resources and 11.2% of its water use.

It is noticed that some of the major net virtual water exporting sectors in the HHH region are those where agriculture provides raw materials in the initial process of the production chain (Figure 2). Typical sectors include textile goods, food and tobacco processing, and clothing. The net virtual water export of these sectors amounts to 5.3 km^3/year, 65% of the HHH region's total net virtual water export. These sectors are not only land and water intensive, but also pollution intensive. The results suggest that the international trade imposes a heavy pressure on the HHH region's water resources both in term of quantity and quality. The inconsistence of the trade patterns with the water endowments in the region may be partially explained by the market failure in internalizing the full cost of water into the prices of products. On the other hand, however, it is also related to the fact that trade patterns are influenced by many factors. Water endowment alone cannot determine the optimal trade patterns of a region or country. For a given region, a comprehensive analysis of all the influencing factors is needed to assess the rationality of its trade patterns amid the increasing water scarcity.

Concluding remarks

Over the years, both the research methods and the understanding of virtual water and water footprint have advanced considerably. In terms of research methods, more and more sophisticated tools have been applied to account for spatial and temporal variations of virtual water content and water footprint of a given product. This is particularly so with regard to the application of the GIS techniques and process-based crop models. The adoption of IO-models and other similar models has enabled the quantification of virtual water and water footprint of individual economic sectors as well as the investigation of inter-connections of water resources and water uses among economic sectors and across regions. Concerning the understanding of virtual water and water footprint, it has been recognized that although virtual water plays an important role in compensating water scarcity in water stressed regions, the current international trade of goods and services is mostly governed by other factors rather than differences in water endowments across countries. This is partly because the water endowment is only one of the factors influencing trade. It alone cannot determine the optimal trade patterns. Nevertheless, the international trade of goods and services does impose significant impacts on water resources and uses on the source and destination countries and regions of the trade. The information on virtual water and water footprint is useful for supporting water policies concerning water resources management at different geographical levels and across economic sectors and regions.

References

- Allan, J.A., 1993. Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible. In: Priorities for water resources allocation and management. London: ODA, 13-26.
- Allan, J.A., 1997. 'Virtual water': A long term solution for water short Middle Eastern economies? Occasional Paper. SOAS Water Issues Group, King's Collage. UK.
- Chapagain, A. K., Hoekstra, A., Savenije, H., 2006. Water saving through international trade of agricultural products, Hydrology and Earth System Sciences, 10, 455-468.
- Dietzenbacher, E., Velazquez, E., 2007. Analyzing Andalusian virtual water trade in an input-output framework. Regional Studies. 41, 185-196.
- Falkenmark, M., 1995. Coping with water scarcity under rapid population growth. Conference of SADC Ministers, Pretoria 23-24 November 1995.
- Guan, D.B., Hubacek, K., 2007. Assessment of regional trade and virtual water flows in China. Ecological Economics. 61, 159-170.
- Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: Water use by people as a function of their consumption pattern. Water Resources Management. 21, 35-48.
- Hoekstra, A.Y. and P.Q. Hung., 2005. Globalization of water resources. Global Environmental Change, 15, 45-56.
- Lenzen, M., 2009. Understanding virtual water flows: A multiregion input-output case study of Victoria. Water Resource Research. 45, Article number W09416.
- Leontief, W., 1941. The Structure of the American Economy. Oxford University Press.
- Liu, J.G., Zehnder, A.J.B., Yang, H., 2007. Historical trends in China's virtual water trade. Water International. 32, 78-90.
- Liu, J. G. Zehnder, A.J.B., Yang, H. 2009. 'Global crop water use and virtual water trade: the importance of green water'. Water Resources Research.
- Llop, M., 2008. Economic impact of alternative water policy scenarios in the Spanish production system: An input-output analysis. Ecological Economics. 68, 288-294.
- National Bureau of Statistics of China, 2010. China Statistical Yearbook 2010. China Statistical Press, Beijing, China.
- Oki, T., S. Kanae, 2004. Virtual water trade and world water resources. Water Science and Technology, 49 (7), 203-209.
- Renault, D., 2003.Value of virtual water in food: principles and virtues. Value of Water Research Report Series No. 12. UNESCO-IHE, Delft, Netherlands.
- Wang, H.R., Wang, Y., 2009. An input-output analysis of virtual water uses of the three economic sectors in Beijing. Water International. 34, 451-467.
- Yang, H., Wang, L., Abbaspour, K.C., Zehnder, A.J.B., 2006. Virtual water trade: an assessment of water use efficiency in the international food trade. Hydrology and Earth System Sciences. 10, 443-454.
- Yang, H., Zehnder, A.J.B. 2001. China's regional water scarcity and implications for grain supply and trade, Environ. Plann. A, 33, 79-95.

» Yang, H., Zehnder, A.J.B. 2007. 'Virtual water - an unfolding concept in integrated water resources management'. Water Resources Research.

» Zhao, X., Chen, B., Yang, Z.F., 2009. National water footprint in an input-output framework -A case study of China 2002. Ecological Modeling. 220, 245-253.

» Zhao, X., Yang, H., Yang, Z.F., Chen, B., Qin, Y., 2010. Applying the input-output method to account for water footprint and virtual water trade in the Haihe River basin in China. Environmental Science and Technology.

» Zhang, Z.Y., Yang, H., Shi, M.J., Zehnder, A.J.B., Abbaspour, K.C., 'Analyses of impacts of China's international trade on its water resources and uses'. Hydrology and Earth System Sciences. 15: 2871-2880.

Water pricing and tariffs

The UN International Conference on Water and the Environment in Dublin adopted in January 1992 four principles for water management. Principle No. 4 states that:

> *"Water has an economic value in all its competing uses and should be recognized as an economic good. Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources."*

In the EU Framework Directive on Water (2000) it is declared in the preamble that "It is necessary to undertake analyses of the characteristics of a river basin and the impacts of human activity as well as an economic analysis of water use" (36). Further it defines that: "'Water use' means water services together with any other activity […] having a significant impact on the status of water" (Art.2, 39), while "'Water services' means all services […] for households, public institutions or any economic activity" (Art.2, 38). On water pricing the Directive states, that: "The principle of recovery of the costs of water services, including environmental and resource costs associated with damage or negative impact on the aquatic environment should be taken into account in accordance with, in particular, the polluter-pays principle" (Preamble, 38).

Water pricing is mainly applied in developed countries but even there it is doubtful if all the costs related to water use are fully reflected in the tariffs. In developing countries or in countries facing water scarcity water pricing, especially for drinking and agriculture, is quite controversially discussed because water is such a vital social good. Thus, water pricing and tariffs have also to consider ethnic, cultural and religious principles. According to Rogers et al (2002) the costs of water use should consider full supply costs, plus opportunity costs and economic externalities plus environmental externalities. Especially the latter is mostly disregarded in the assessment procedure.

In the Islamic perception "humans are the stewards of water and other common resources that belong to the community" (Faruqui, 2001, 12). Kadouri et al. (2001) conclude that recovering costs for providing water is allowable in Islam. However, special consideration must be paid to low-income users who do not have the ability to pay and, for some users, water should be subsidized.

High subsidies in water supply are often linked to inefficient water management and utilization. High losses in water storage and distribution system are accompanied by high per capita consumption rates of end users. This holds for drinking water supply, industrial and agricultural water consumption. Market approaches to water management, such as increasing tariffs and privatizing utilities, raise the question: what is a fair tariff? A fair tariff will assist in increasing water use efficiency and it will lead to greater equity across society. Given the need to conserve water in the region water pricing may be one element of a strategy, and it should be accompanied by raising public awareness and the development of education strategies.

The tariff should promote efficient allocation of the resource by considering all the cost components related to water use across customer classes. The public should understand the rate-setting process which requires that economic assessment should be transparent.

Privatization of the service (but not the resource itself) can include positive aspects, though public control and partnering are essential. Tariffs are not bad if used properly. Someone has to pay anyhow but the question is: who benefits in the long term?

References:

» Rogers, P., de Silva, R. and R. Bhatia, 2002. Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. Water Policy 4, 1–17.

» Perard, E., 2008. Private Sector Participation and Regulatory Reform in Water Supply: The Southern Mediterranean Experience. OECD Development Centre Working Paper No. 265, OECD, Paris, France.

» Dublin Statement on Water and Sustainable Development, 1992. URL: http://www.un-documents.net/h2o-dub.htm

- Faruqui, N., 2001. Islam and Water Management: Overview and Principles. In: Naser I. Faruqui, Asit K. Biswas, and Murad J. Bino (eds.) "Water management in Islam". United Nations University.

- Kadouri M. T., Djebbar, Y. and M. Nehdi, 2001. Water rights and water trade. An Islamic perspective. In: Naser I. Faruqui, Asit K. Biswas, and Murad J. Bino (eds.) "Water management in Islam". United Nations University.

- Directive 2000/60/EC (2000) of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. Official Journal of the European Communities, L 327. URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:327:0001:0072:EN:PDF

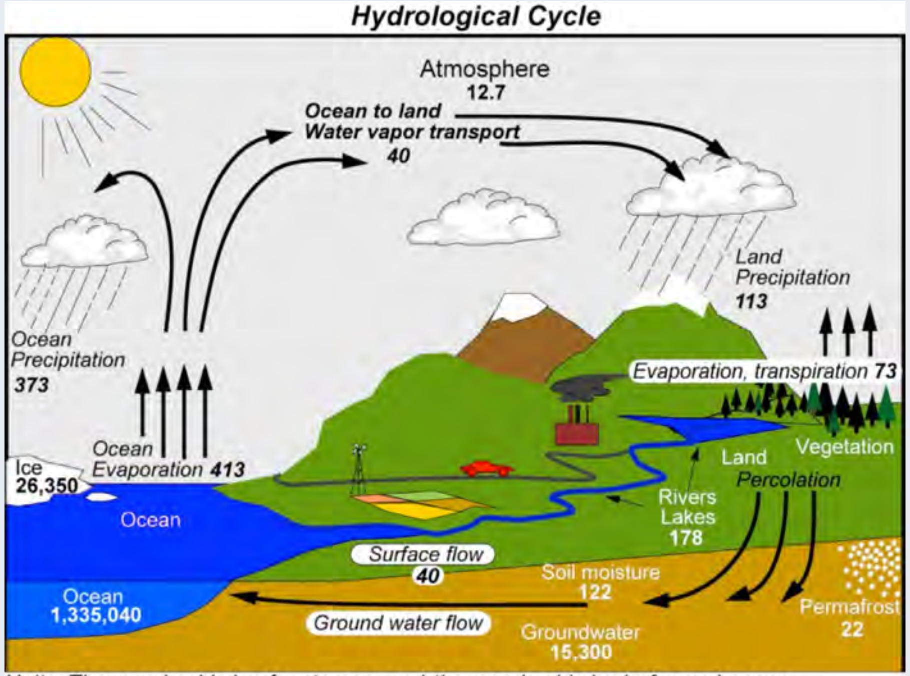
Accounting for both „blue water“ and „green water“ in water resources management

"Blue water" is defined in the present freshwater discourse as water available in surface and saturated ground water bodies (rivers, lakes, aquifers); "green water" is defined as water captured in the vadose zone (unsaturated soil profile) and in plants. Green water originates from precipitation and returns via evapotranspiration to the atmosphere without contributing to runoff or seepage towards ground water bodies. Traditionally water resources management was considered to deal with the so called "blue water" only, as "green water" was "inaccessible" by engineering and other usual water resources management interventions. Whether concerning technical interventions, or allocation of water rights, "green water" was indeed not considered explicitly. This said, it has to be acknowledged that rainfed agriculture, the oldest economic activity of humans has been and still is relying on what is called "green water". Even in irrigated agriculture the "blue water"-based irrigation deliveries usually only supplement and enhance "green water" fluxes which are essential for plant growth.

The assessment of the global hydrological cycle (see Figure 1) explicitly accounts for this so called "green water" flux. Its estimated annual volume (73.000 km^3) is about twice as much as the total "blue water" flux of approximately 40.000 km^3/year (the aggregate of surface runoff, stream flow and groundwater outflow to the oceans). The magnitude and role of the "green water" in the global water cycle is significant as this flux is approximately equal to the sum of the total annual "blue water" flow and the moisture flux from the oceans towards the continents.

It is necessary to consider "green water" explicitly in the water balance, especially in agricultural water use, compared to the hitherto "implicit reliance" on it. However it should be acknowledged that irrespective of its considerable volume the "manageable" component of the "green water" flux is only the difference between the "green water" evapotranspired by the agricultural vegetation versus that of the natural vegetation at the same location. This is an important issue and could significantly influence water balance and water footprint calculations and truncate the so-called "water footprint" of crops, depending on the natural vegetation they replace. This feature reflects the peculiarity of water resources management (the management and modifications

Figure 1. Estimated fluxes and storage components of the global hydrological cycle between 1979-2000. (after Trenberth et al., 2007)



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges of a natural cycle) versus that of the management (and consumption) of a limited and finite resource. In this context irrigation means using "blue water" to increase the availability of "green water" to be transpired through and stored in crops. Even if we speak about water consumption this means only a temporary deviation and retardation of water to participate in the global hydrological cycle. Ultimately all water, even if physically consumed and stored, in the tissues of living organisms, returns to this cycle, though frequently in deteriorated quality state and geographically at different locations.

While the terminology "green water" and "blue water" has found its way into the scientific discourse as proven also in this book, this "color coding" is not without certain potential of misunderstanding. Even in this book a paper mentions the "blue drop" and "green drop" initiatives describing monitoring of water supply and sanitation development in South Africa respectively. Furthermore the original meaning of "blue water" in the English language is deep waters, the open sea.

As a potential alternative for a scientific nomenclature for "blue water" and "green water" respectively the editors suggest to distinguish between waters in the terrestrial part of the hydrological cycle of which the movement is governed overwhelmingly by molecular forces ("green water") opposite to those governed principally by gravitational forces ("blue water").

References

» Trenberth K.E., L. Smith, T. Quian, A. Dai, J. Fasullo, 2007. Estimates of the global water budget and its annual cycle using observational and model data. J Hydrometeor 8, 758-769.

» Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The water footprint assessment manual: Setting the global standard, Earthscan, London, UK.

Indicators and their limitations

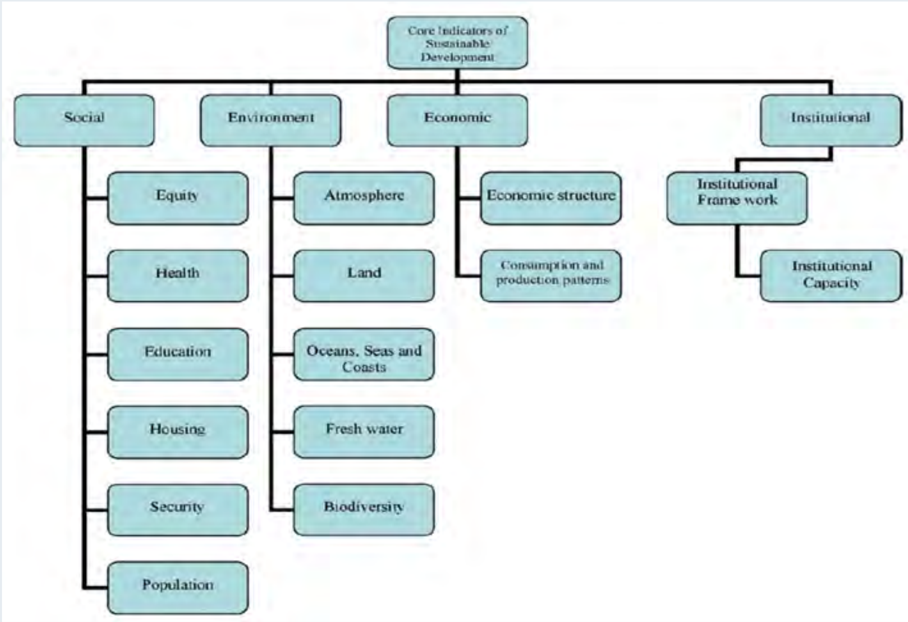
Whether the matter is water scarcity, flood risk, water availability or sustainable development, there is considerable need to support political decisions and resource management with easy-to-use information describing the state of the system, the efficiency and effectiveness of planned and implemented projects. This description would be very complicated unless we resort to indicators characterizing the complexities of reality with a few selected features and corresponding metrics. We need to know whether we are on the right track or whether the assessed status quo necessitates interventions. Measuring does not automatically mean 'numerical quantification' but common scales and a common terminology are needed to facilitate dialogue within the disciplines of the professional community and the communication with the public, the media and policy makers.

The problem is not only how to use simplified scales to measure, but also how to select those indicators which are facilitating communication. These problems are not unique for water resources management. Data scarcity and representativeness forms one group of problems. Simplification and selection of specific indicators without distorting the complex truth is another.

The basic dilemmas associated with indicators will be highlighted using the example of sustainability indicators. Singh, Murty, Gupta and Dikshit (2009) published for example an overview of sustainability assessment methodologies. In an excellent, however unavoidably eclectic study they introduce, and partially compare 70 sustainability indices classified into 12 categories. Indices are usually aggregates of scores of individual and composite indicators. Among those 41 summarized in a comparative table, indices like the 'Well being index' (WBI) with 87 or the 'Environmental Sustainability Index' (ESI) with 68 sub-indicators seem to be the most complex ones. While both appear to be quite complex and comprehensive, they differ considerably. ESI uses equal weights to calculate the arithmetic average of these subcomponents while WBI uses subjective weights to calculate the weighted average.

This type of 'super indices' which aggregate cores of simpler indicators depend excessively on factors like data availability and reliability on the global scale to measure and compare so many dimensions of what might be called sustainability. It is however clear that indices, through being chosen, could and usually do include value judgement. Using weights, as-

Figure 1. Framework of Measuring Sustainability used by UNCSD 2001



signed to individual indicators or even the selection which aspect should be considered are examples of this inherent value judgement.

There is nothing wrong with it but this subjective component has to be acknowledged. Beyond this feature which can only be overcome by broad-based consensus, it is obvious that an aggregate of 60 or 80 indicators hardly yields an easily understandable metric. But can the multidimensional assessment of sustainability be avoided? Compromise concepts tend to settle on a 4-dimensional assessment like recommended by United Nations Commission on Sustainable Development, UNCSD (2001) within the four "main dimensions" of sustainability.

Measuring the social, environmental, economic and institutional dimensions needs additional categories which could (and probably should) be considered. Figure 2 shows 15 possible and frequently used subcategories.

These subcategories are not exhaustive and each of them could be measured with many indicators. Consequently, such kind of frameworks may not ensure the required simplicity either.

Just to juxtapose this easily escalating trend, one of the indices also used and presented in the context of sustainability is the Human Development Index (HDI).

Measuring only 3 dimensions like

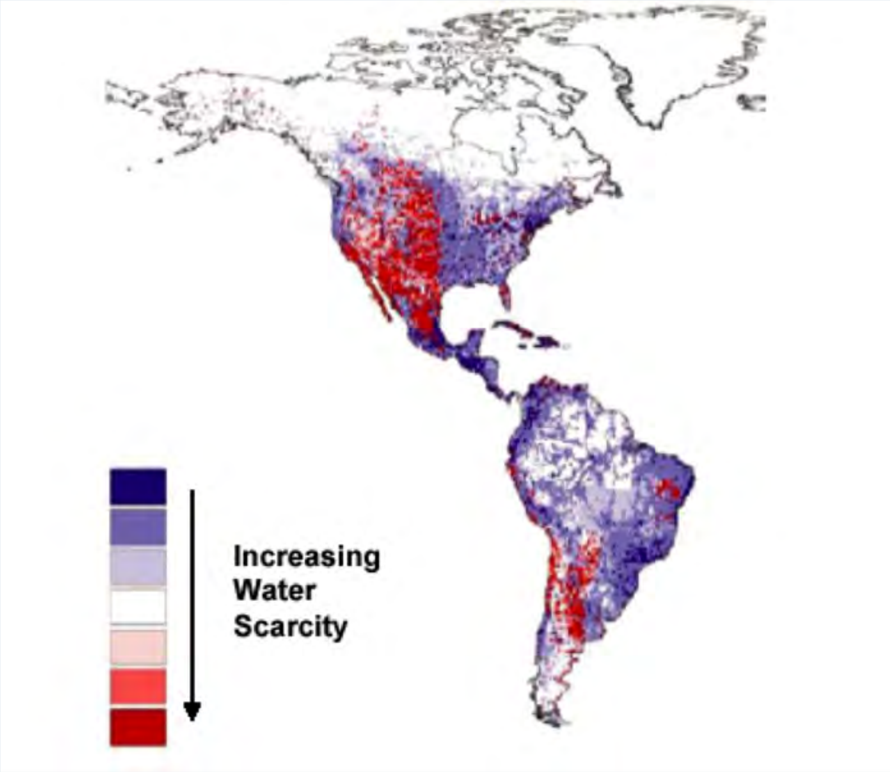
- the environmental dimension: with the indicator 'life expectancy at birth';
- the social dimension: with adult literacy rate (2/3 weight) and aggregated primary, secondary, tertiary school enrolment ratio (1/3 weight) and the
- economic dimension: GDP/head in purchasing power parity (PPP) US$ the HDI is hardly comprehensive enough to measure sustainability, yet being calculated and published annually at country level since several years it has assumed the role of an Olympics-like competition.

Admittedly, measuring sustainability is probably the most complex task. However developing water resources and/or water management and governance indicators is not an easy task either. While core physical characteristics like annual renewable water resources (over a reference area) may seem a robust indicator much depends on the choice of the resolution. Figure 2 displays the Americas. In a relative scale the water scarcity is shown for a fine pixel-based resolution. Worth to compare this detailed information with the global distribution of the renewable annual water resources per capita as published by the first World Water Development Report (WWDR I) in 2003 (Figure 3)..

The country-based resolution completely hides large discrepancies which may exist even within water rich countries like the US, Canada, Brazil etc.

Similar discrepancies can be shown in case of the water use within the so-called Falkenmark index (Falkenmark, 1995), assigning countries

Figure 2. Water scarcity in the Americas (Courtesy of C.J. Vörösmarty)



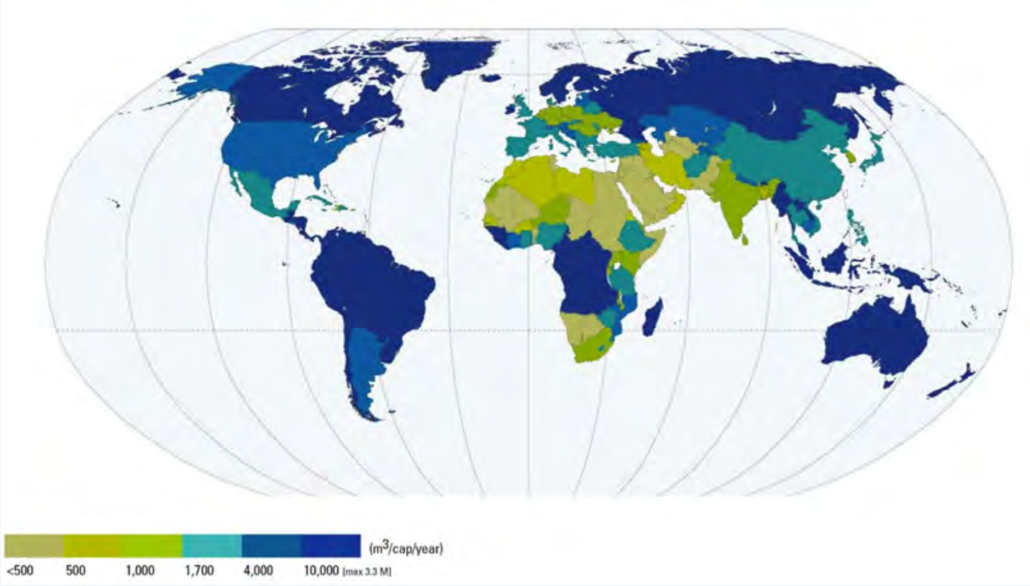


Figure 3. Annual renewable water resources per capita (country based) Source: WWDR I

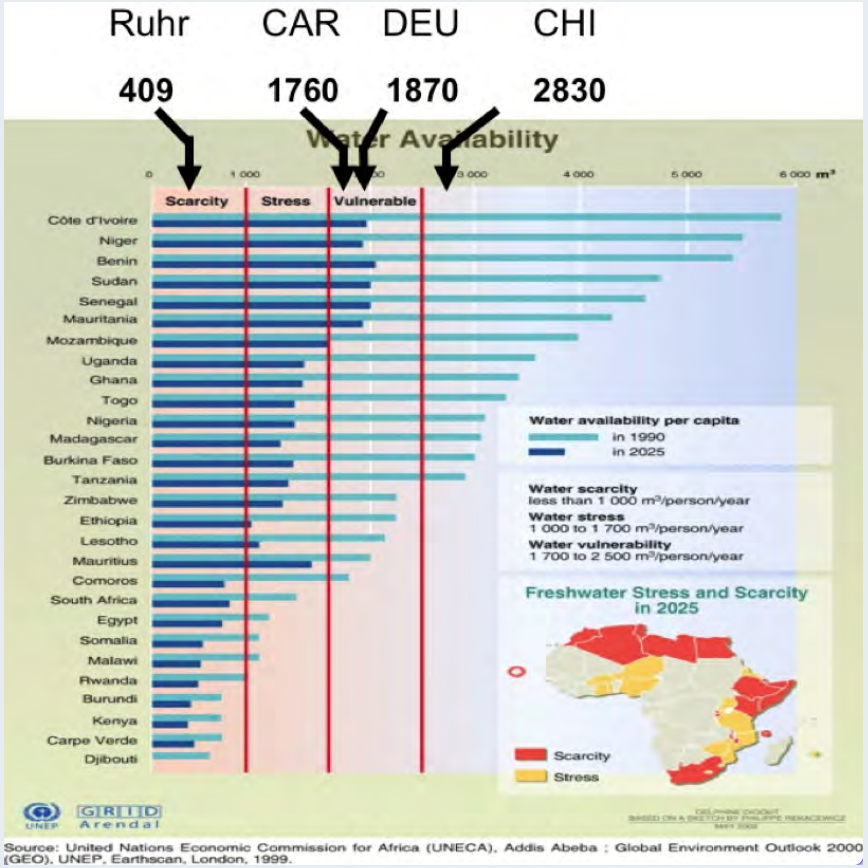
into scarcity, water stress, vulnerable or normal classes depending on their annual renewable water resource per capita. 1000; 1700; 2500 m^3/ capita and year are set as upper limits for the scarce, stress and vulnerable country classes respectively. Figure4 shows a number of African countries and the widely varying water availability in the continent. The two bars indicate the dramatic decrease of the value of the index between 1990 and 2025 due alone to increasing population. Climate change may induce additional lowering, but Figure 4 documents that the overwhelming component of (future) water stress is related to demographics. In addition, black arrows indicate the positions of China (CHI), Germany (DEU) and the Central Asian Republics (CAR), as well the Ruhr river basin, a highly industrialized river basin in Germany.

This index, which served and still serves as basis to make the world aware of water problems has the drawback that neither within year variability of seasonal differences, nor the available technical, infrastructure and other means of water resources management are considered. This explains why a densely populated basin in the moderate climate of Western Europe would be classified as a very water scarce area. Besides fairly uniform distribution of water resources within the year the Ruhr basin has several upstream reservoirs and multi stakeholder based water resources management services.

The dilemma of water resources indicators and developing indicators altogether has been highlighted by the preceding examples. The need for a "policy relevant compromise" is obvious. As far as integrated water resources management or the assessment of water resources for human use but also for ecosystem services are concerned a single dimension (like renewable water resources per year and head) is clearly dissatisfactory. The compromise solution was proposed by the Task Force on Indicators, Monitoring and Reporting of UN Water which suggested in 2009 a set of 15 indicators, classed into four categories: context, functioning, governance and performance.

A further major issue to be debated is, whether indicators are needed for hydrological units like river basins or for jurisdictional entities like countries. Actually both types of information are needed. Discrepancies can be huge as Figure 2 (country versus pixel scale resolution) and Figure 4 (Germany versus the embedded Ruhr basin) indicate. As most of the water resources management investments are public funding and the ultimate decision making is usually following the sovereignty lines, country-based indicators remain essential. The inherent uncertainties and potential pitfalls notwithstanding the need for indicators and aggregate indices is likely to increase. Thus indicator development and testing will remain an important research area.

Figure 4. Availability of annual renewable water per capita (country based)



References

» Falkenmark, M., 1995. Coping with water scarcity under rapid population growth. Conference of SADC Ministers, Pretoria, 23-24 November 1995

» Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An Overview of Sustainability Assessment Methodologies. Ecological Indicators 9, pp. 189-212, Elsevier.

» UNCSD, 2001. Indicators of Sustainable Development: Framework and Methodologies. Background Paper No. 3, Ninth Session 16 - 27 April 2001, New York. URL: http://www.un.org/esa/sustdev/csd/csd9_indi_bp3.pdf

» http://www.unwater.org/Indicators.html

Foto: Rhine River near Bonn, Meinhard/Bosse und Meinhard

Dialogue between scientists and river basin managers: Documentation of a panel discussion at the GWSP GCI Conference in Bonn

Moderator

Janos Bogardi
Executive Officer of the Global Water System Project (GWSP), Center for Development Research (ZEF), Bonn, Germany

Rapporteur

Mike Muller
Professor at the Graduate School of Public and Development Management, University of the Witwatersrand, and former Director General, Department of Water Affairs and Forestry, Johannesburg, RSA

Panelists

Charles Biney
Executive Director of the Volta Basin Authority (VBA), Ouagadougou, Burkina Faso

Joyeeta Gupta
Professor at the Institute for Environmental Studies, Vrije Universiteit, Amsterdam, the Netherlands

Hans Peter Nachtnebel
Head of the Institute for Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Life Sciences, Vienna, Austria

Benoit Rossignol
Director of Development and External Relations of the Loire River Basin Authority, Orléans, France

Thomas Stratenwerth
Head of Division for General, Fundamental, International and European Aspects of Water Management at the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Bonn, Germany

What can scientists offer river-basin managers?

Bogardi: What can scientists offer to river-basin managers and what do they need?

Stratenwerth: First of all, I think we need to differentiate between the type of science that river-basin managers need to support their work and on the other hand the type, which we could call a kind of 'free science'. In the latter case the scientific community itself defines the research questions. And I think today we are focusing more on the former, namely applied science.

Nachtnebel: So what I have learnt in many projects is that what the managers need are problem-driven answers. You have a problem and you ask science. And I think what we could deliver is not just highly sophisticated science, but rather useful, quantitative descriptions of flow paths of water, sediments, pollutants in the catchment, etc. Secondly, we could assist in understanding and describing complex processes and interactions between different sectors, let's say in terms of competition between the water, the economy, and the environmental sectors for example. And lastly, I think we could provide some general outlook on future developments (as we have done in this conference), on the uncertainties in the various climate models and so forth.

Stratenwerth: I think we need both, applied and 'free science'. As to some extent through applied research there is the danger that it is used for hidden agendas or framed in terms of specific political interests. So we need 'free research' in order to develop new concepts, new ideas, and a critical discourse. But in terms of making the applied research more useful, we should discuss here different mechanisms that allow us to improve the capacities of institutions - on the one hand to use research and on the other hand to define research questions, to finance research projects themselves and also to evaluate research results and bring these into management practice. I think these are the questions to be addressed in the applied science arena, where we can definitely do better.

Kienzle: I am from the University of Lethbridge in Canada. As an academic I can say it's a matter of 'publish or perish'. That's what we get paid for. But the problem is: Who reads my publications and therefore what impact do they have? I am happy when I have a citation number of 20 or more. But only other scientists read my papers, not the decision makers or water managers whose problems I often try to address. We have tried to explain the gap between science and decision makers, and how this can be bridged. The only idea we came across was that we basically have to publish everything twice; first in a the form of a scientific publication, so that we can fulfill the requirements set forth for academics and then we have to write a second paper in knock-down, non-scientific plain English for the decision makers. We would have to milk down our results in bullet form and publish a one-page summary. However, we still need some kind of forum in order to do this, i.e a recognized means through which scientists can communicate their key findings to decision makers. I can't just write that one pager and email it to a water manager. It would probably end up as 'junk mail'.

Gupta: We also have no other solution than to publish twice…once in the high- ranking Institute for Scientific Information (ISI) journals, and at the same time try and do something in policy journals in a condensed format.

Nachtnebel: I have personally solved the dilemma between science and applied science in terms of doing research at a university, the results of which not too many people can understand, but which can be published, and then at least once a year I also do consulting work… going mainly to the Middle East, Near East but also Africa… and here I try to do something that is needed. And doing this, being outside and working with river basin managers, has helped me a lot in understanding problems.

What do basin managers need from science?

Biney: To put it bluntly, science needs to come to us with knowledge that would enable us to make decisions, whether these are decisions concerning immediate problems or long-term progress doesn't matter. To do that, I think scientists must spend some time interacting with us. By 'us' I mean basin managers or other water managers. You can do your basic science, which has nothing to do with the management of a river basin or of natural resources, but if you want to do something to support this cause, I think you need to plan with whoever you think is going to use your output. To date, what science is largely doing, is trying to fit answers to our problems. So what I am saying is: science must take some time out and do some 'linking up' with us - after all science must be more than just doing science.

Bogardi: So scientists cannot just arrive for a 24 hour visit and then fly back, but rather need to 'live with basins'. If this were to improve, would basin managers implement science?

Rossignol: Many conferences are being held about how to transfer knowledge, the research results, the data, in a suitable way for managers. There are many many research results that are either not yet published, or they are published in a scientific way but not in an 'operational friendly way'. We (Loire River Basin Authority) have a financial instrument to circumvent this problem. We have the capacity to grant some research projects, but before accepting a project we check if the project research team has taken into account operational needs, has involved one or two, or three different water managers. Yet the transfer is still very irregular and we cannot find a simple framework with which to ensure this automatic transfer from research results to operational actions.

Gupta: Similarly, in the Netherlands, the National Science Foundation does not provide any research funds unless the stakeholders in the developing partner country agree with the research questions. So a particular research question is allowed to change from the moment you get the initial funding, to the moment you have had your concluding workshop. So in a sense, they are trying to deal with the problem in this manner.

Groenfeldt: I think one way of making the application stick is through institutions and organizations. So for example using the Rhine River case, I think the fact that a commission exists, which scientists can use as an audience makes it easier to bring science into the discussions. In my own case, the Santa Fe River which is a small river in New Mexico, we have a number of very good scientists from the United States Geological Service (USGS). They do the basic research. They don't apply anything. So we have wonderful studies but we don't have basin-level organizations to listen to those studies. So I think at the local level, basin organizations have the potential to provide a forum within which science can be applied, or at least be discussed.

Bogardi: Maybe UN-Water constitutes such an intermediate institution…

Adeel: Yes, regarding the 'interfacing' role of UN Water I can say that it is a unique mechanism in the international development community. Because we are not working directly as an organization, but rather as an inter-agency coordinating mechanism between all UN entities dealing with issues related to aspects of freshwater and sanitation, we are able to tap quite directly into scientific knowledge, to discuss it and reach some form of consensus on specific issues. One example is water security, which we are discussing right now. It is a broad policy concern, in both governmental and international circles, however no one has agreed on what 'water security' actually means. There is no common definition. Currently UN-Water is trying to define the term through the use of scientific literature on the topic, which we will then adopt as a working principle. So as a coordinating mechanism there are certain flexibilities that are introduced and these allow us to tap into science very directly. How good the uptake is on the other side, that's another story.

The position of science in global governance structures

Bogardi: How is science *impacting* on and at the same time *controlled by* political institutions? And how do we ensure that science 'trickles down'?

Stratenwerth: This is a really difficult question, because to a large extent, the political debate around water is controlled at a governmental level and so therefore scientific influence also goes through the government. But also the problem lies in how we (Stratenwerth is a representative of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) are organizing science. If I look for example to the European level and how science programs or research programs are organized there, then it is very difficult for scientists to follow this bottom-up approach in terms of really talking to the river managers on the ground, taking into consideration what their problems are, because they have to primarily address issues defined by the EU Commission or a group of advisors to the EU Commission. So there is a gap in terms of how we politically organize and finance research programs on the one hand and on the other hand in terms of our expectation that this science will be used and taken up at a local level, when the local managers to a large extent have no influence on the research questions.

Muller: We have asked an EU representative the same question: "Why do scientists not seem to be answering the right questions?" And he gave exactly the same answer! In South Africa we have a water research commission that generates funds from water users for research. The deal is that if the municipality or the farmers pay for the research, the municipality or the farmer has a say in what research gets done. It looks very sensible and yet it seems that we set up a model for science. It starts to solve the issue that so many complain about, i.e. "We want to do useful science, but the funders set criteria for us; we're not allowed to be practical; we are measured by publication, not whether we have an impact on useful things like helping farmers".

Schulze: I am from the University of KwaZulu-Natal and one of the beneficiaries of this model outlined by Muller, more specifically a beneficiary of the South African Water Resource Funding Scheme. I would like to share with you what has happened in the Umgeni Catchment in South Africa. It is a catchment of 4,000 square kilometers. It constitutes one-third of one percept of the country, but it produces 20% of the GDP. Now how does our university department of hydrology interact with the bulk water supplier, namely Umgeni Water? Number one, they come to us to get the latest expertise on three types of decisions: strategic decisions (such as climate change, where research is conducted by a group of PhD students), tactical decisions concerning week-by-week or month-by-month operations on the dams (including various yield models), and then short-term practical decisions on risk and forecasting. That's the one set of assistance. The other set of assistance is in terms of modeling techniques. We have a very detailed modeling system that we have set up with them. They can then do their games of playing land use impacts, climate impacts, impacts of new dams, of inter-basin transfers, whatever, and they can come to us for help. Important is, that they pose the questions. But I think the cherry on top in our case is that we (the University of KwaZulu-Natal) have convinced our water utility to fund a Chair in Water Resources starting 1 January 2012. And they have committed many millions of South African Rand (ZAR), which is not much in Euros, but nevertheless, they have made a long-term commitment to fund this. So this is where I think one can get positive spin-offs from a university to the utility to the water managers, and from the water managers to the university.

Improving communication between managers and scientists

Bogardi: How does one improve communication between the two, i.e. between water governance institutions and research?

Stratenwerth: What I would first of all like to stress a bit is that water managers do not have clear-cut borders, or clear-cut playing fields for that matter. So I think this is where science comes in, in terms of explaining the interlinkages, lets say between food security, energy and other issues, not just at a basin scale but also at a national and international scale. There is a part of the story that is not within the range of water managers, but they are nevertheless influenced by it. And therefore science can play a role, in particular also social and economic science, in terms of explaining these interlinkages and identifying possible ways to, let`s say, regulate them to some extent. Whether we will ever be able to get the institutional and legal regulatory framework right in order to enable water managers at the local or river basin management level 'to regulate' these elements remains an open question.

Gupta: Social science does two things. We diagnose the relationship between scientists and policy-makers and we diagnose existing institutions. So this includes, what you already mentioned, the complexity of society. But social scientists also look at existing explicit and implicit norms and rules in a society, and why they are useful or not useful in terms of addressing certain issues. And it's the combination of the natural science and this focus on rules and norms, that can help deal with issues. So in the case of Ghana, if you look at the history of the country, you find that when the British were there, they removed the role of the tindanas in water management. The tindanas are the spiritual leaders. And the reason for their removal was that through this process, the British gained more control over the Ghanaian people. Today, the situation is that the local people don't listen to the laws so much because the consequence for disobeying is no longer the same. So with some of these issues the importance lies in understanding the situation holistically. And I think many of the social scientists are actually spending a lot of time with institutions, with people, doing stakeholder research doing trans-disciplinary science, and whereby the researchers actually define their questions based on what the policy-makers want.

Nachtnebel: I liked your comment very much. To me water management has a well-defined framework, based on institutions, the legal system, the economic system, the physical system and finally on human capacity. And within this framework some people try to do something they call Integrated Water Resources Management (IWRM). But speaking about basins in Europe, what does IWRM mean at the moment? Right now we are just interested in satisfying the requirements of the European Water Framework Directive[1]. That's it. So we do a lot…but it is only one part. And we are increasingly realizing that there is more, more than water quality. For example there is river morphology, which so far hasn't been addressed, or flood risk, a directive that was only implemented last year in Austria. So these are aspects that were missing in the European Framework Directive. I realize that you cannot address everything at the same time, i.e. you start with water quality and then you add floods, morphology, etc. So maybe in 50 years, we will achieve something that we can actually call IWRM.

Gupta: IWRM as a concept, like many others, was developed in the richer countries. We don't even implement them here. Nevertheless, through various agencies we transfer them to poorer countries like Ghana. But because the resources available in the country are not adequate, in the implementation process concepts such as IWRM or water pricing eventually fail. So one of the questions is, to what extent are we exporting ideas that may not be feasible in the countries that we are sending them to?

I like what Tariq Banuri (United Nations Commission on Sustainable Development) once said to me; "The world is a third world country. Everything you find in Pakistan, you find at the global level. So if you want something to be solved in Pakistan and it works in Pakistan, then it might also work at the global level." So it's the opposite of following best available practice and best available science from the richest of richest of countries.

Bogardi: So development agencies are bringing foreign concepts into third world countries and consider their implementation a precondition for funding. How can one transport these concepts more effectively? How can local knowledge and science fit together?

Biney: Local knowledge and imported knowledge should fit together. But unfortunately this is not the case, because over the last century or more, local knowledge has largely been suppressed and ignored. Local knowledge has not had the opportunity to develop like imported knowledge has, and so today you cannot expect that they can be integrated into each other. But to make the picture even bleaker, when we discuss imported knowledge we also see what Mr. Stratenwerth addressed earlier: that the research agenda is not set in Africa. And for African scientists this agenda constitutes a means for survival. You grab whatever is dangled in front of you and hope that you settle down better in the future and turn your attention to local issues. But you will probably never do that, because the next time you find yourself in Addis Ababa working for UN-Water, still promoting the international agenda.

Holleman: I am from the Helmholtz Centre for Environmental Research (UFZ) in Leipzig and I am doing research on Mongolia, and in this case not only the concept of IWRM is brought in from western countries, but also water problems themselves. These are caused by mining activities, controlled by companies in other countries. So in this case - how can one build on local knowledge when the problem is not local?

Bogardi: Do we have local knowledge in Europe? Does it influence the way we manage basins in France and Germany? And going beyond local knowledge…do local value systems impact the way we manage a basin in Atlantic France compared to Mediterranean France?

Rossignol: In the south of France we have a different river management system to the North of France, for one due to the level of precipitation (a geographical reason), but also for cultural and historical reasons. We have had research projects that analyzed differences in historical settlement patters for the Loire, Seine and other rivers. These included a focus on the places where people settled along the river, where they built bridges, how and where urban centres developed and grew. And we found that in the course of the 20th century we have urbanized and extended our cities to areas where our predecessors, a long time ago, had tried not to go. So there is a local expertise, and an historical expertise that we could learn from, even policy makers.

Nachtnebel: I fully agree that there is local knowledge and local experience and that they are both important. Yet on the other hand I disagree because when you go to mountainsides or valleys and you find old farmhouses that are 400 years old, standing somewhere on a slope, rather remote from the river and the people tell you; "See, our ancestors knew where to build houses and where it would be safe." I would say; "They didn't know anything! They built houses everywhere. Most houses have been washed away, and what remains, has remained for a pretty long time…" And up until now we still build our houses in flood planes. So I think two things are important here; local experience and local knowledge, which you will find in every culture, but also science and its explanations of natural processes.

Leentvaar: I am from the Institute for Water Education at UNESCO-IHE. I think with respect to the Netherlands, and Europe at large, local knowledge is floating away. People don't tend to have any regional knowledge in relation to water, or local knowledge of water management in particular. With every flood we have in the Netherlands, within three months after the flood, people are handing in the applications to rebuild houses in the same places along the same river.

Gupta: I think my comment about traditional knowledge was misunderstood. I said that social scientists diagnose institutions and exemplified this with the case of the tindanas, which immediately led to a discussion about local knowledge. But what I was actually

[1] http://ec.europa.eu/environment/water/water-framework/index_en.html

trying to say that one of the roles of a social scientist is to understand how institutions function. What is the adaptive capacity of an institution? What are the resources? What rules and norms exist? What is the educational level? And therefore, given what they have, what is the best way to address the problem? The solution may be very different in the Netherlands to a water basin in Ghana. Therefore, a key element of water policy must be the diagnosis of existing social institutions that deal with the problems.

Water in the global governance system

Bogardi: Are scientists ready to provide answers? And if they are, then why are they not being heard?

Subramanian: I am from the Center for Development Research (ZEF) in Bonn. The discussion here appears to suggest that science is superior. Science however is only one player within the whole system, in which river managers make decisions. There is politics behind it. There are people behind it. The media is a big player nowadays. These do not negate the role of science, in particular the role of applied science, but we need to remember what role they play in relation to science.

Bogardi: Can we have a look at first-world river basins and the interaction between different actors (stakeholders)? Has science been successfully integrated and how?

Muller: We keep on saying that the sciences are necessary for more objectivity and in order to have a broader perspective than policy. But yet I think we also need to be careful of policy-driven science. Let's looks at the following hypothetical scenario: In 2017 a major hurricane hits Miami and wipes out a large part of it. There are also floods in London and the Netherlands, and probably a very serious drought in northern China. At a governmental level the consensus is that something has to be done about this. They begin to discuss geo-engineering as an option, the deliberately manipulation of the planet's climate…

The mechanisms for this have been researched. But let me ask, does anyone here know what the consequences are for freshwater? Has anyone looked into that? No! Because we (as scientists) are policy defined. We are told to look at global warming in a particular way. The impact of geo-engineering on freshwater has not been validated or legitimated as a research question. But I can tell you, within five years, it might well trigger the policy agenda, and then suddenly we will be asked for answers. Policy debates not only close down science by the way of funding, but also by the way it frames the question, and our researchers only respond to the questions they pose because they are in turn driven by funding.

Stratenwerth: I don't think research has started on this issue, but people are planning to develop a research agenda on the impact of geo-engineering on water resources. But there are much more prominent examples for your argument, for example the impact of bio-energy on water, where the agenda was also set by the climate and energy efficiency community and a lot of funds have gone into that without taking into consideration the effects on water. So I think it is another example, where water research was late in responding to the issue, and the agenda was ill-defined.

Gupta: We need to also not forget that - to some extent - manipulative processes are going on. For example in 1990 when climate negotiations were taking place simultaneously with the Montreal Protocol negotiations, there was a discussion whether CFC (chlorofluorocarbons) replacements should be introduced. Greenpeace said "No!" But it was politically convenient to introduce them nevertheless. Here, science was not quick enough to step into the climate debate. Greenpeace as an NGO reacted faster than science, and it serves as a good example to highlight how scientists don't want to get involved and come up with ideas on an issue until it has been researched thoroughly, and the result is a political stop-gap.

Nachtnebel: What we are discussing now is not dialogue between scientists and managers but water policy making. Let us return to the panel question.

With regards to the Danube River Basin, it has an International Commission for the Protection of the Danube River (ICPDR) that serves as a platform for experts, scientists, NGOs and governmental representatives. They have expert working groups where these different actors engage. But when I say that the commission does not manage the river basin, then who does? It might be different in other case studies, but for the Danube River Basin I think it is done at a national level. But through this overarching forum that has been developed, issues are first discussed at a regional, basin-level not the national level. Here, the different stakeholders can exchange information, and also build up trust between 'upstream and downstream'. So in that sense I would say water management is also carried out at a regional scale, and this is a big achievement.

Leentvaar: With the permanent working groups of the International Commission for the Protection of the Rhine (ICPR) there is also this nice mixture between scientists and policy makers. And it works. It works because there has been a long-term trust building process between the two. If you don't develop this mutual basis between scientists and policy makers, also at a personal level, then it will never work out.

Bogardi: With respect to the other basins represented here, are they managed regionally or at the basin scale?

Biney: I think there are some instances where you can use the river basin as a unit, hydrological considerations, basin-wide monitoring for example. These are technical objectives for which the basin as a unit is management-relevant. But when it comes to politics and practice, then you have to move beyond the basin level, i.e. when you consider the influence of the world economy on the Volta Basin, or malaria mitigation as another example. You cannot control malaria in the Volta Basin to the exclusion of the Niger and Senegal Basin. So for some cases you can use the river basin as a unit for management, and for others you have to go beyond the basin. In the Volta Basin for example, the actors that have a lot of power with regards to the management of the Volta basin are not located within the basin (Abidjan, Accra). But you need to always keep a balance between a focus on the basin, the sub-regional and the global scale.

Rossignol: I would also give a 'yes and no' answer like Biney. The Loire river basin is an interregional basin, with nine regions involved. We don't have one river basin manager, but rather many different ones at different scales (at the scale of the whole basin, sub-basins, corridors, and along the river) who together have to set priorities, concerns, define action plans and funding schemes. In addition, we have a scientific committee at the scale of the river basin that advises the managers. And I think the scientific input should definitely occur at the basin scale.

Bogardi: What do researchers on water governance have to say about these 'yes and no' answers?

Gupta: I think from the perspective of water governance this discussion highlights the need to not just look at one level when dealing with a particular issue of river basin management. We need to look at the interactions between different levels and also from the perspective of different disciplines i.e. not just looking at it from the water perspective but linking water, land, ecosystems, development, food, agriculture, etc.

Coelho Maran: My PhD was exactly on this question; is the river basin the right scale for management? And there are some examples around the world where it is really difficult to tell. We have so many different sectors that play a significant role in water management but each has its own boundaries. So what is important in each case study is to understand how a particular river basin is interconnected with the other levels to form a polycentric system.

Anderson: My name is Jafet Anderson from the Swiss Federal Institute of Aquatic Science and Technology (Eawag), Switzerland. No matter what discipline, there is always an element of uncertainty in our research. To what extent does this impact on how research is taken up by practitioners? And what needs to be changed?

Stratenwerth: The problem with the scientific assessment of risk and uncertainties is that it is often used as an excuse for inaction, i.e. because scientists cannot prove exactly what will happen, one does not have to act. But this again boils down to a communication problem. The communication of risk assessed by research needs to draw upon people`s lived experience with it. For example when discussing adaptation strategies in Germany, we looked at ensembles of regional models, trying to explain the regional impact of climate change on certain parameters. We added more and more models in order to reach a probabilistic assessment of their 'uncertainty'. But in terms of bringing across the message, we learnt that if you can show that a certain community, a certain system, is not really able to cope with climatic variations or climatic extremes, then you can show (even with some uncertainty) that there is a valid trend that the impact will be even more severe in the future.

Biney: Yes, the uncertainty in science should be considered 'healthy'. It highlights the objectivity of the scientific process itself. Science that tries to give us quick answers is not the solution. River basin managers are not necessarily looking for a definite answer in terms of whether it is/will be A or B, as long as the uncertainties can bring out options or alternatives. And with respect to uncertainties in science, we also need to remember that science is only one part of the decision making process.

Pahl-Wostl: As Mr. Stratenwerth said, when discussing the issue of uncertainty, we are also coming back to the problem of communication. Within the science-policy interface it is not just about simplifying your message and communicating it to policy makers or operational managers, but it is also important to look at how the latter frame their questions. We have organized a series of workshops with scientists and policy makers alike, focusing on the EU Water Framework Directive in relation to a series of projects. For us, it was clear that uncertainty would be one of the main topics. During the course of the workshops however, no one was initially interested in the issue. We said, "That was not possible! How on earth can these people not be interested in uncertainty?" The problem was that uncertainty as an abstract concept was meaningless to them. We had to discuss uncertainty in relation to the individual steps of the Directive, and then it became meaningful to them. So again, it is a matter of communication.

I also agree that there is a certain reluctance for policy makers to adopt uncertainty, which in turn can have some very profound consequences. I am an advisor to the implementation of the Delta model for the Dutch government. A governmental organization built a big model to support the implementation process. As the stakeholder-policy interface expert, they asked me how they could make the model 'discussion proof'. All the NGOs were going to come and argue about the model. I responded that you can't make a model 'discussion proof', and that it is exactly this process that is essential, not the model and its level of uncertainty. So I think I agree with Mr. Biney, what comes out of stakeholder discussions around uncertainty, and the resulting options are important.

Kienzle: I just want to highlight the human element of some of the things that have been mentioned. What if we were to develop a tool to get all stakeholders around one table? Then you discuss uncertainties with them, such as "what will happen if temperatures rise? What if this and this were to happen?" You use a screen to visualize the different models and the changes that can be plugged in. This is something that we are implementing right now as we speak in the Bow River Basin in Canada. It is a long-term dialogue, involving all users around one table. It is a trust-building process between scientists and water managers, who end up meeting regularly. And I think the only way to build trust, is through such a slow, long-term process.

Bogardi: Is the point made about long-term cooperation something that you intend to follow?

Biney: Yes, it is something we will consider seriously - the issue of long term dialogue. But it also requires scientists to come out of their labs and initiate the dialogue with us.

Outlook

Rossignol: With regards to local knowledge, we not only have a limit in local knowledge but also in scientific local knowledge. With respect to the Loire River Basin, some links between managers and the scientific community have been established over the years, and when the managers had question then they would always turn to the same scientists. But in my opinion, it is important to open the forum and to bring in other research teams, other experiences, other fields of expertise, and not just local scientific expertise. And linked to this, we as managers also need a mechanism whereby research results and research data can be shared, and this includes research teams sharing their data with other research teams. That is something that hasn't been done systematically.

Yang: I am from the Swiss Federal Institute of Aquatic Science and Technology. One of the questions we have tried to answer in this session is what is the role of scientists in river basin management? Based on my own experience, I agree with previous comments that it is very important to publish your research results in academic journals. But then on the other hand you also need to publish reports or briefings in a very simple language to communicate with river basin managers and the other stakeholders. And so I consider the role of scientists in terms of decision support. Scientists however shouldn't overestimate their roles - they are not the ones to make decisions but are rather specialists in a very particular field (I myself being a specialist in the field of virtual water analysis) and cannot advise on decisions in all other fields. I cannot advise the Chinese government on what they should do about their water scarcity problem, but I can provide the necessary information on how much water is flowing between regions, from which sector, and so forth.

Nachtnebel: With regards to Mr. Kienzle and Mrs. Yang…I agree with you both. Cooperation between scientists and water managers needs to be long-term and premised on trust and confidence. And scientists also need to lower their expectations in terms of what impact their input can have on water management. For example, with regards to the Danube Basin we have been given the task of establishing a water balance. This was done for each individual country with national data. It took us two years to reach an agreement in the compilation of the data in order to establish a homogenous water balance for the whole basin. We published some data about new trend loads in the river, after which the respective countries accused each other in terms of whose responsibility this was. Then scientists were invited and stated that high nutrient loads are most likely coming from the upstream areas. I was the one that had to convey this information to the governmental agencies responsible. They wanted to kick me out. So as you can see, creating models for the entire Danube Basin has taken a long time. You won't win the Nobel peace prize for this type of work, but it will provide a useful basis for decision-making. I don't think the data that was generated is perfect, but at least we have agreed on a basis and that is the way science can support daily water management problems.

Stratenwerth: What I have learnt is that we need to improve the framework conditions for dialogue, between applied research and river basin managers, and this includes the way we organize and finance research. In addition, there is a continued need for basic research in order to develop new 'mindsets'. For example, no government involved in river basin management originally asked for the virtual water concept - it was something that was developed within science, and which today helps us understand certain developments and interlinkages between various sectors, internationally as well as within countries. And I agree that what we need is on the one hand this basic research, and on the other more publicly and politically understandable versions of it. But that is not the only thing you need for the dialogue at the management level. Here you also still need trust building, an improvement of the institutional settings in which you, on a long-standing basis are working together.

Sustainability of basin organizations – The Mekong as case study

Bastien Affeltranger

Associate Researcher, IQHEI, Laval University, Quebec, Canada

E-mail: b.affeltranger@hotmail.com

Abstract

A river basin is not only a geographical cradle where states and communities use natural resources as basis for development. A basin is also a playground for (geo)political influences coming from inside and outside watershed boundaries. The rise, development, successes or shortcomings of river basin organizations (RBOs) as institutional systems do reflect this global realm of influences.

Needless to say that these influences do not necessarily converge towards the same goals – be these environmental, social or economic ones. Although such diversity is not, in itself, a problem, diverging goals may feature conflicting values or approaches to possible « futures » of the basin. The RBO hence emerges as an arena for competing priorities in terms of how water resources should be used. Availability of appropriate governance is a key condition for this arena not to turn into a battlefield.

The Mekong – the river and the basin – appears to have served, for decades, as playground to riparian and global players. Its relatively long history of institutionalized river basin management helps understand how global influences mix with riparian stakeholders, resulting in a complex web of options for basin development. The very history of the Mekong RBO does hence reflect water-based competition, as much as it does reflect efforts to reach water-based consensus. This ambiguity can be seen clearly in what is called here the *politics of hydrological data.*

Introduction

Although hydrological data are critical to successful *Integrated Water Resources Management* (IWRM), many obstacles limit information exchange. On transboundary river basins for instance, availability of water-related information has a direct influence on the performance of River Basin Organizations (RBOs). Geopolitical research on the Mekong basin shows that intergovernmental agreements are no guarantee for smooth exchange of hydrological data. Rather, bureaucracies in riparian countries often have a limited capacity to contribute to the circulation of water-related information. Limitations include technical, organisational, financial and political features. All cristallize into the politics of hydrological data and emerge as a useful analytical approach to hydropolitical situations.

The *politics* of hydrological data emerges from two converging trends on transboundary basins: first, the institutional dynamics of water resources governance; second, the informational dynamics of hydrological knowledge generation. Success of environmental regimes and RBOs in transboundary basins depends on how the politics of hydrological data is considered by stakeholders in water resource management.

This paper is organized as follows. First, a brief summary of Mekong basin institutional history is provided. Second, information management is introduced as a challenge of integrated water resources management (IWRM). The exchange of hydrological data is presented as a condition of sustainability of river basin organizations. Third, the Mekong case serves as an illustration of these concepts. Results focus on the capacity of water bureaucracies in Mekong countries to engage in hydrological co-operation. Influence on the Mekong River Commission (MRC) is discussed.

Context: the Mekong as hydropolitical crucible

Hydrological co-operation on the Mekong begins in the middle of the 20th century with the formal signing of the Geneva Accords. Since that time, the basin has been host to three major environmental regimes[1]:

» 1957–1977: Mekong Committee (Kingdom of Cambodia; Laos PDR; Kingdom of Thailand; Vietnam SR)

» 1977–1995: Interim Mekong Committee (same countries, yet without Cambodia, then called Democratic Kampuchea)

» 5 April 1995 – present: Mekong River Commission[2]. Same countries as in 1957-1977. PR China and Myanmar participate in the Mekong Dialogue Forum.

The Mekong river basin offers an excellent case study to analyze issues of environmental governance since multiple interests – technical, economical, social, political – converge and (sometimes) collide. The Mekong appears as a playground for riparian countries and extra-regional players – such as international agencies, donor countries or non-governmental organisations (NGOs). All engage in complex interactions, often with vested interests or hidden agendas. The resulting system features the following issues:

» Access to or control over natural resources (water; forestry; biodiversity);

» Influence on cultural, economic and political matters;

» Access to foreign direct investment (FDI) and international support;

» Access to political visibility at regional and international levels;

» Control over knowledge generation and development discourses for the basin.

In February 2000, the Mekong River Commission Secretariat organised an Expert Meeting on flood warning systems (Hewitt, 2002). This event was a privileged moment for a first contact with the technical and political dimensions of hydrological data exchange in the Mekong basin. The following observations could be made:

» *Humanitarian goals and information exchange.* Improvement of flood warning is not always a sufficient incentive for riparian states to increase hydrological data exchange on transboundary basins.

» *Government discourse vs. individual strategies.* Although Government discourses tell a lot about countries' readiness to share hydrological data, the response capacity of national bureaucracies is often a matter of concern.

» *Hydrodiplomacy: signed agreements vs. implementation.* States are often praised for signing inter-governmental agreements on transboundary basins. However a closer attention should be paid to how these agreements materialise.

» *Data management often taken for granted.* Although legal and institutional features of environmental regimes have motivated much hydropolitical research, the management of hydrological data deserves more attention.

» *Geographical representations as political instrument.* Stakeholders that have the capacity to influence representations and perception of water resources can gain advantages in situations with imperfect information. Hydropolitical discourses shape hydrological reality.

» *Control of data and information enables riparian authorities* to influence the construction of geographical representations in environmental controversies, such as water-sharing issues.

The *politics* of hydrological data emerges from two converging trends in transboundary basins: first, the institutional dynamics of water resources governance; second, the informational dynamics of hydrological knowledge generation and decision-making. The *politics* of hydrological data can be defined as a virtual space of interaction used by stakeholders to share, construct or deconstruct geographical representations of water-related issues. Building blocks in this space are: knowledge (perception, data, information) and communication (discourse and symbolic economy). In this space, geographical representations of water coexist, merge or clash. As a result, the politics of hydrological data is the place where different *futures* for the basin converge or collide, and where they conduct a dialogue or ignore each other.

The success of environmental regimes and RBOs does hence depend on how this political space is populated by stakeholders in water resource management, and how these interact with each other. Identification of success featurs does, however, require a preliminary reconstruction of the *politics* of hydrological data - in short: why, how and by whom are hydrological data being politicized?

[1] States appear in alphabetical order.

[2] In addition, PR China and Myanmar (Birma) and MRC have been holding joint Dialogue Meetings annually since 1996.

IWRM and environmental information

Water resource management: an information gap?

Availability and accuracy of hydrological data contribute to sound decision-making in water resource management. This is for instance the case when assessing or forecasting the state of the resource. Water managers missing such data run the risk of developping misperceptions or biased representations to govern over the assessment of resource availability. Information is also needed for understanding societal patterns of water utilization and pricing patterns (if any). Missing information may lead to inefficient or unfair allocation among users – an acknowledged source of social tensions. Water-related information is needed, as it carries a description of the natural and social environment.

However, information management, considered as a social construct, has been given little attention by scholars in IWRM and sustainable development. This is quite surprising, as circulation of hydrological data is often discussed in intergovernmental agreements on shared river basins[3]. While development of hydrological knowledge has been identified as a vehicle for trust-building on shared resources, lack of information exchange is an obstacle to successful water management (Robertson, 2004). Research is also needed because of the globally increasing volume of *virtually unprocessed* environmental data. Developments in environmental informatics and remote sensing, for instance, coexist with a growing gap in terms of data processing capacities. This is a matter of concern, as stakeholders in natural resources management are increasingly seeking information in order to scrutinize decisions made by others, or to make their own ones.

The international community has acknowledged the role of information exchange in governing transboundary river basins. This is for instance the case with Article 9 of the 1997 *United Nations Convention on the Law of the Non-navigational Uses of International Water Courses* (UN 1997). Intergovernmental agreements advocate for open exchange of environmental information: *United Nations Principles on Remote Sensing* (1986); *Framework Convention on Climate Change* (1992); statement from the *International Oceanographic Commission* (1993) etc. Technical programmes advocate the same way: *Flow Regimes from International Experimental and Network Data* (FRIEND[4]) project (started 1985); *World Hydrological Cycle Observing System* (WHYCOS[5]) initiative (launched 1995) etc.

However, technical and political obstacles limit the implementation of the above agreements. This is for instance the case with the *Aarhus Convention* (1998)[6]. Although the Convention advocates for public access to environmental information as a condition to social justice, it is mostly democratic, industrialized states that have so far signed or endorsed this text. Authorities usually remain reluctant to make environmental decision-making more transparent (Zaharchenko & Goldenman, 2004). Market-oriented or business considerations may also act as limitating factors. For example, the World Meteorological Organisation (WMO) discourse on meteorological data exchange has evolved towards a less policy: the 1995 WMO Congress resolution revised this policy by providing a two-tiered data exchange system. Dissemination and pricing patterns would now be established depending on data categories and data utilization purposes.

Obstacles to the circulation of environmental information

Obstacles to the unrestricted access to, and circulation of environmental information feature various dimensions: technical, organizational, economical, political and ethical:

- *Technical obstacles.* As observed in 2001 by William Cosgrove, a past president of the *World Water Council*, the volume of collected hydrological data is globally decreasing (Cosgrove, 2001). Existing hydrometric networks worldwide suffer from a chronic lack of investment. This is particularly the case in developing countries, where limited public budget impacts on data collection and maintenance capacities. Civil or military conflicts also impact existing networks.

- *Organisational obstacles.* A global WMO study has identified several organisational weaknesses in National Hydrological Services (NHSs). These include: limited budget; lack of skilled staff; low salaries etc. In addition, competition among staff and organisations for data is witnessed in instable institutions – such as those undergoing reforms of the State aparatus[7].

- *Economical obstacles.* Raw (unprocessed) hydrological data have been increasingly considered as resources for developing information-based products and services with market value (Erlich, 2007), such as client-specific weather forecasts and warning services[8]. In industrialized countries, tensions and conflicts have arised from the privatization of these data: the marketing potential (business opportunity) is a strong incentive for individuals, agencies and governments to restrict the access to environmental data (Minster et al., 2001).

[3] *As indicated by Aaron T. Wolf (Professor, Oregon State University), based on his analysis of the Transboundary Freshwater Dispute Database (TFDD): www.transboundarywaters.orst.edu/*

[4] *For more information please visit http://typo38.unesco.org/index.php?id=724 (accessed July 2007).*

[5] *For more information please visit http://www.whycos.org (accessed July 2007).*

[6] *Convention on access to information, public participation in decision-making and access to justice in environmental matters, done on 25 June 1998 in Aarhus (Denmark), www.unece.org/env/pp/documents/cep43e.pdf*

[7] *On information control as a strategy for securing power or influence in organisations, see Crozier, M. 1963. Le phénomène bureaucratique. Paris : Editions du Seuil. 382 p*

[8] *See for instance the very high number of research projects dedicated to environmental information management that have been funded recently by the European Commission Information & Communication Technologies, 5th and 6th Framework Programmes*

» *Political obstacles.* In democracies, (civil) society usually has a legal right to comment environmental decisions (natural resources, energy etc.) made by authorities. In non-democratic countries however, commenting political decisions is a rather dangerous act. In both cases, civil society needs accurate information for contributing to the debate. However, artificially maintained situations of imperfect information tend to bias the balance of power in environmental controversies.

» *Ethical obstacles.* The circulation of environmental data and information also raises ethical questions. In short: should data collected by public (taxpayer's) money be made available for free to the public (or with a price that corresponds to the marginal cost of data reproduction, printing etc.)? This question is very much connected with the expected role of science and knowledge in social development.

Riparian countries of transboundary basins are usually reluctant to support an unrestricted exchange of environmental information. Obvious geopolitical reasons help explain this conservative strategy. More research and insights are needed, however, to understand the impact of this attitude on the performance of RBOs.

Assessing the performance of river basin organisations

The institutional dimension has been well identified as one of the social features contributing to so-called "second order" cause to water scarcity (Ohlsson & Turner, 2000), as well as a condition to the sustainable management of water resources (Gleick, 1993). This is also the case in transboundary basins, where the combination of institutional and organizational flexibility (Wolf, 2002) is needed for environmental regimes to adapt to changes in natural, social and political contexts (Hooper, 2003). Assessing the performance of RBOs has now become a distinct issue in the broader field of explaining success and failure in environmental regimes (Bernauer, 2002).

In that respect, few lines have been written on the unique role played by the management of water-related information as a condition to the institutional sustainability of these regimes. Collection and processing of hydrological data, however, has been clearly identified as a priority function that conditions the emergence and operation of a RBO (Hooper, 2006a). More: the performance of basin organizations depends very much on the existence of an efficient information management system (IMS) – in particular for environmental and social data (Hooper, 2006b). Unavailability of information will impact on two sustainability pillars of RBOs: technical credibility (of decisions made) and political legitimacy (of decision-making). Without accurate information, RBOs cannot be players in water-related controversies.

Mediating environmental debates is an indicator of how successful environmental regimes are in transboundary basins. Establishing sustainable RBOs requires an in-depth investigation of bstacles to the circulation of environmental information.

The Mekong: from hydrological data to RBO sustainability

An early recognition of the hydrological data challenge

Prior to establishing the Mekong Committee, the United Nations Economic Commission for Asia and the Far East (ECAFE[9]), Lower Mekong countries and their partners conducted several technical surveys. In all reports, the lack of hydrological data emerges as a potential obstacle to the development of the basin. Later studies did confirm these observations, advocating for a basin-wide policy on hydrological data.

The so-called Wheeler Report[10] (1958) for instance, specifically recommended a five-year program of hydrological investigation, costing US$9.2 million. Wheeler stressed that priority should be given to data collection, with a focus on promising mainstream sites for water resources development. The rather holistic study conducted by Geography Professor G. White (1963) drew similar conclusions – advocating that social and economic development of the basin would require an appropriate policy on hydrological data. At the time of these studies however, acquisition of hydrological data or knowledge had no other purpose but planning hydropower and irrigation development. Today's policies on hydrological data serve a broader spectrum of decisions, such as environmental impact assessment (EIA).

Although flood mitigation had been an early objective of intergovernmental co-operation on the Lower Mekong, major floods in 1966 prompted riparian governments and their partners to consider hydrological data management as a strategic issue in itself. This topic progressively developed into an autonomous activity for the Mekong Committee – establishing dialogue, technical co-operation

[9] *Now called: United Nations Economic and Social Commission for Asia and the Pacific (ESCAP).*

[10] *Wheeler Commission. 1958. United Nations Mission Report. Programme of Technical Studies for Comprehensive Development of the Lower Mekong Basin. 23 January 1958. United Nations ECAFE.*

and information exchange. A first *Strategic Master Scheme for Hydro-Meteorological Network* was drafted in 2001 (MRC, 2001).

However more than ten years after the birth of the Mekong River Commission, hydrological data management remains a matter of concern on the Mekong basin. Despite obvious achievements of the MRC, most respondents interviewed for this research tend to agree that major obstacles still hinder the exchange of information.

Navigating through political and institutional instability

Access to and quality of hydrological data are still problematic in several countries of the basin. Identified limitations to data exchange feature two categories of obstacles – some *within* national bureaucracies of Mekong countries, such as retention of information; some at transboundary level, such as government reluctance. In addition, two context-level elements should be considered, that do influence countries' capacity to engage in hydrological data exchange:

» *Institutional instability.* Most Mekong countries, if not all, have undergone major changes over the last 20 to 25 years. An example is the transition from central-command to decentralised systems, and to privatization and market economy. The role and capacity of the state is being redefined – or even challenged. Water management bureaucracies or agencies are in the front-line of these changes. This has resulted in institutional instability of hydrological administration: organizational changes, power relations and budget allocation criteria. Even performance of civil servants is discussed. In this context, hydrological data appear as an asset or a *resource* to navigate through these rough institutional waters.

» *Competition over water.* Water is a matter of competition among users in the Mekong basin. Competition depends on the type of use; location of the country; season etc. See for instance the well documented controversy on dams developed in Yunnan and elsewhere for irrigation or hydropower purposes. Authorities in riparian countries therefore consider water-related information as a strategic resource. In short: sharing hydrological information opens the door to a more transparent understanding of downstream hydrological impacts caused by upstream water development projects. Hydrological data are like a Pandora's Box, with a potential to fuel additional water claims from downstream countries.

These macro-level features have made riparian states and water institutions reluctant to commit further into hydrological co-operation. Resistances appear both within and among countries. Besides, attitudes of riparian states on transboundary water issues are usually the result of domestic tensions in the water sector, as it is for instance the case in Thailand.

Revisiting the value of hydrological data

As water becomes a strategic resource, so does water-related information – influencing the ontology of hydrological data. In short: the value of hydrological data features technical, organizational, social and political dimensions. We introduce the concept of *total value* of hydrological data, as a social construct mirroring the role played by water resources in riparian countries, economies and State apparatus. A first typology of the total value of hydrological data is proposed below:

» *Operational value:* Enabling informed decision-making, better return on investment and reduced negative externalities such as environmental impacts;

» *Economic value*
- *Micro-level:* Data is a resource that can be sold to make up for insufficient budget (organization level) or salary (individual level).
- *Macro-level:* Selling or dissemination of hydrological data can justify business activity, possibly after preliminary processing of raw data.

» *Organizational value*
- *Power & status:* Control over data helps civil servants negotiate power and salary deals despite institutional instability. Hydrological data serve as currency in organizational transactions;
- *Budgetary:* Exclusive access to data gives priority for reporting to authorities and potentially accessing various types of public funding;

» *Hydropolitical value*
- *Transboundary:* Non-transmission of data helps authorities in upstream countries to conceal downstream impacts of water development projects;
- *Domestic:* Control over data reduces transparency in environmental decision-making or controversies, thus limiting public scrutiny or claims;

» *Cultural value:* Non-dissemination of available data is perceived as a way to avoid blame or loss of face – in particular when quality of data is doubtful.

Further implications for the Mekong River Commission

The MRC: an asset for the Mekong basin

Establishing an environmental regime on the Mekong basin has always been a challenge to riparian and donor countries, and their partners. It is a fact that this institutional process has mirrored the objectives, views or appetites of these players. Starting operation in 1995, the MRC has somehow been a catalyst – or a target – of these tensions. In particular, criticism has focussed on the alleged limited capacity of the Commission to establish – and implement – a basin-wide policy for the sustainable development of the area. Debated issues included:

- The MRC Secretariat (MRCS) is too much research-oriented, producing no water resource development infrastructure, but only reports and conferences;
- The paradigms referred to by the MRCS are too much driven by sustainable development paradigms, with "green imperialism" from donor countries (Affeltranger & Lasserre, 2003);
- The views, activities or discourse of the MRCS are perceived by MRC Member States as infringing on countries' sovereignity over land and resources;
- Although the Mekong has featured numerous cases of hydropolitical tensions or controversies, the MRC seems to have avoided taking part in these debates;
- Regardless of its added-value in the past, the MRC is now perceived as an unnecessary obstacle to further development of water resources (e.g.: dams; irrigation) (Affeltranger, 2007).

Mekong countries have however demonstrated a high level of resilience in developing hydrological co-operation ever since the late 1950s. Political turmoil in riparian countries and the influence of the Cold War, could be absorbed in this institutional process. The MRC could also catalyse co-operation with China since 2002 – daily hydrological data from two Yunnan stations sent to the MRC during each flood season. In addition, the annual *Dialogue Forum* initiave has become a place where all Mekong countries can interact – discussing issues not limited to water resources. The MRCS has progressively evolved into a more mature organization. It now relies on a unique knowledge base and multidisciplinary expertise – covering a broad spectrum of environmental, technical and social issues. However, difficulties remain that limit co-operation on hydrological data.

Line agencies as last frontier to hydrological co-operation?

Line agencies are services – usually State administrations – in MRC countries that interact with MRCS staff. Those services include: water resource management; meteorology; fisheries; agriculture; land-use planning etc. National Mekong Committees (one per country) operate as a hub between line agencies and the MRCS. The present research has demonstrated that improving MRCS contribution to basin management and governance requires a *parallel* improvement of the co-operation capacity in line agencies. Developing this capacity is a condition to the sustainable co-operation process between MRCS and line agencies. Capacity features include:

- *Financial capacity.* The budget of hydrological or meteorological departments is extremely limited in most Lower Mekong countries. Low salaries often force civil servants to look for complementary sources of income and jobs (e.g.: tourism, taxi driving, teaching etc.). This multitasking pattern reduces actual time in office and degrades professional motivation. Official duties in basin management can be jeopardized. Situations of vested interests also appear.
- *Human resources.* Technical skills are usually quite low, as well as using English as a professional language. This has a direct impact on transboundary hydrological co-operation. In services or agencies created recently, experience in international co-operation – for instance with the MRC Secretariat – can be limited.
- *Political capacity.* Ministries actually making water-related decisions in MRC Member States may not be always represented in National Mekong Committees (NMCs). Says a western diplomat: *"depending on ministries and individuals, the readiness to cooperate, and the actual capacity to cooperate, varies a lot among Lower Mekong countries".* Consequently, NMCs only have a limited capacity to influence water-related policies and projects in their country.

These weaknesses of line agencies in Mekong basin countries have a direct influence on the availability and circulation of hydrological data. Symptoms include:

- *Data are simply not available in countries.* When available, data series may be neither consistent, nor scientifically robust. As a consequence, the MRCS needs to undertake a resource-consuming (both time-wise and money-wise) process of data reconstruction. Property rights for hydrological data has also been a matter of endless discussions between the MRCS and MRC Member States. Only recently did MRC Member States come to a signed agreement – and implementation remains a matter of concern.
- Due to a *lack of public budget or political will*, line agencies in MRC countries often lack resources (staff and financial) for operation and maintainance of hydrometric networks. This can be the case even when networks have been installed with donors' assistance. This is a major obstacle to data-sharing[11].
- *Institutional inconsistency.* High-level agreements for sharing of

[11] *This situation has become a major disincentive for many extra-regional donors to the MRC.*

hydrological data have been signed under the aegis of the MRC. In practice however, states as central authorities do not always have sufficient influence to force their own bureaucracy to implement these agreements. Says an ADB expert: *"the national bureaucratic machineries are not keeping pace with the agreements signed by Mekong governments"*.

Development of parallel, competing sources of knowledge over water

Discussions with MRCS staff and other resource persons in Mekong countries clearly show that the above-described lack of hydrological data has been increasingly compensated by a production of parallel water-related knowledge. This process is a social response to the situation of "imperfect information" on environmental issues. In practice some segments of society develop their own information sources and explanatory patterns for understanding their environment – and for acting upon it. This kind of empirical knowledge or heuristics may be biased by value judgments. Generated knowledge may also be instrumentalized for specific purposes. Says a senior expert in hydraulic modelling: *"some day, these parallel, unconfirmed and ideologically motivated descriptions of the river basin will have become the [single] reference or truth on the state of the Mekong basin"*. Such parallel knowledge even appears as an obstacle to efforts made for developing a hydrological science of the Mekong.

There might be reasons for hope, though. Several Lower Mekong states have increased public budget devoted to hydrological data management. WMO and other international organisations or donor countries have been supporting data-sharing protocols and procedures. Although the implementation of these initiatives has often been difficult, minds and practices are evolving progressively. New practices emerge for disseminating environmental information. New pricing patterns for hydrological data are being progressively introduced. Questions remain, however, on the future role that public administrations should play in the field of environmental information. Tensions have already appeared in most Mekong countries, with pressures from private sector agents asking for a profit-oriented marketization of hydrological data. Such tensions are similar to those already characterising countries in the Western world (Minster et al., 2001).

Conclusion: information management and Mekong River Commission sustainability

The Mekong River Commission has never been the only one catalyst to water-related co-operation in the (Lower) Mekong basin. Despite the successive environmental regimes developed from 1957 to 1995, riparian countries have maintained hydrological co-operation on a bilateral basis. This included water resources management and development, training programmes and information exchange. It also appears that in several occasions, riparian governments have kept the MRC away from major hydro-political controversies. These include: blasting reefs on the Upper Mekong; interbasin water transfers from Mekong tributaries; dam-building etc. The MRC would never be officially involved in these projects – neither as a political facilitator, nor as a provider of technical information for decision-support. *"The MRC seems to be shying away from any transboundary conflict"*, says a western academic.

Despite the tremendous volume of data placed under its responsibility however, the MRC could not become the scientific and technical reference for water resource management. Missing such an undiscussed knowledge base jeopardizes the sustainability of the Mekong basin. Absence or low quality of hydrological data have a potential to increase the risk of negative externalities (ecological, technical, economical, social etc.) in water-related decision-making. The MRC case confirms that RBOs should play a critical role in providing science-based support to decisions made over water and other natural resources:

- An efficient basin organisation should be capable of offering an non-political knowledge base on water resources, so that Member States and/or basin stakeholders can make well-informed decisions;
- The institutional capacity of a basin organisation can be measured, at least partly, by the autonomous capacity of this organization to produce high quality, non-political hydro-meteorological data;
- A sustainable RBO should be able to perform the following two tasks:
  - Producing water-related knowledge that is relatively free from preconceptions, biased representations or vested interests;
  - Serving as a dialogue forum so that different projects for the basin, and geographical representations, can be discussed;
- An RBO can be a sustainable institution only if it can establish a hydrological co-operation with line agencies (in member states or riparian countries) that are sustainable themselves.

Hydrological data are critical to complete RBOs' missions, as they should serve as a reference to make decisions over water resources. The Mekong case has demonstrated that building up such a "shared knowledge base" is not an easy task. The *politics* of hydrological data is both a cause and a consequence of the competition over transboundary water resources.

References

- Affeltranger, B. 2007. Le contrôle de la vérité – Géopolitique de l'information hydrologique : le Mékong. Ph.D. Thesis in Geographical Science. Laval University (Québec, Canada), 317 p.
- Affeltranger, B., Lasserre, F. 2003. La gestion par bassin versant: du principe écologique à la contrainte politique – Le cas du Mékong. *VertigO* Vol.4 Nr.3.
- Bernauer. T. 2002. Explaining success and failure in international river management. *Aquatic Science* 64. 1-19
- Cosgrove, W.J., 2001. The global perspectives of water resources in the 21st century - solutions, conflicts, visions. In: *Proceedings, Hydrological challenges in transboundary water resources management,* 25-27 September 2001, Koblenz, Germany
- Crozier, M. 1963. Le phénomène bureaucratique. Paris : Editions du Seuil. 382 p.
- Erlich, M. 2007. Osiris – an Example of Citizen-Oriented Technology Development in the area of Dissemination of Information on Flood Risk Management. *Advances in Natural and Technological Hazards Research* 25, 43-60
- Gleick, P.H. 1993. Water and conflict – Freshwater Resources and International Security. *International Security* Vol. 18 Nr. 1, 79-112
- Hewitt, M.M. (editor). 2002 *Proceedings of the International Expert Meeting on Early Warning for the Mekong River*, 27th February – 1st March 2000, Phnom Penh. MRC Conference Series No.3, 75 p.
- Hooper, B.P. 2003. Integrated Water Resources Management and River Basin Governance. *Water Resources Update* 126. 12-20
- Hooper, B.P. 2006a. Integrated river basin governance and key performance indicators. *IWA Yearbook* 2006. 35-38
- Hooper, B.P. 2006b. *Key Performance Indicators of River Basin Organizations*. US Army Corps of Engineers ® and Institute for Water Resources (IWR). 86 p.
- Minster, J.B., Bretherton, F.B., Bromwich, D.H., Carroll, M.A., Donzier, J., Glover, D.M., Leavesley, G.H., McCabe, M.J., et al. 2001. Resolving Conflicts Arising from the Privatization of Environmental Data. Committee on Geophysical and Environmental Data. National Research Council. National Academy Press, 99 p.
- MRC (Mekong River Commission) 2001. Strategic Master Scheme for Hydro-Meteorological Network in the Mekong River Basin. Mekong River Commission, Phnom Penh. 104 p.
- Ohlsson, L., Turton, A.R. 2000. The turning of a screw – Social resource scarcity as a bottle-neck in adaptation to water scarcity. *Stocholm Water Front* 1
- Robertson, K. 2004. Design considerations for an international facility to promote co-operation between States sharing common water resources. *UNESCO Conference on Water*, 25 June 2004, Paris
- UN 1997: United Nations Convention on the Law of Non-navigational Uses of International Water Courses, Adopted by the General Assembly of the United Nations on 21 May 1997, http://untreaty.un.org/ilc/texts/instruments/english/conventions/8_3_1997.pdf
- Wheeler Commission. 1958. United Nations Mission Report. Programme of Technical Studies for Comprehensive Development of the Lower Mekong Basin. 23 January 1958. United Nations ECAFE.
- White, G.F. 1963. Contributions of geographical analysis to river basin development. *Geographical Journal*, Volume 129 (December 1963), pp. 412-432.
- Wolf, A.T. 2002. The importance of regional co-operation on water management for confidence-building: lessons learned. In: *Proceedings, 10th OSCE Economic Forum on Co-operation for the sustainable use and the protection of quality of water in the context of OSCE,* 28-31 May 2002, Prag, Czech Republic
- Zaharchenko, T.R., Goldenman, G., 2004. Accountability in Governance: The Challenge of Implementing the Aarhus Convention in Eastern Europe and Central Asia. *International Environmental Agreements: Politics, Law and Economics* 4, 229-251.

Connectivities and linkages within the Volta Basin

Charles A. Biney

Volta Basin Authority
Ouagadougou, Burkina Faso
E-mail: cbiney@gmail.com; c.biney@abv-volta.org

Abstract

The Volta is a transboundary river, which is shared by six countries in West Africa; Bénin, Burkina Faso, Cote d'Ivoire, Ghana, Mali and Togo. Characterized by a north-south gradient in rainfall distribution, the basin spans various ecological zones, from the Sahelian through the Sudanian to the Gulf of Guinea. The main water uses in the basin include hydropower production, domestic and industrial water supply as well as rainfed and irrigated crop production and livestock watering.

Within the last five decades, the basin has experienced significant ecological and environmental changes as a result of increasing anthropogenic and other natural influences. Major developments that have contributed to large scale hydrologic and biogeochemical impacts include hydropower dam construction, rapid expansion of small reservoirs and urbanization. Specific impacts include flooding, deforestation, erosion and the spread of water-borne diseases.

During the last two decades, and with increasing availability of data and information, institutional and policy reforms have been initiated in the riparian countries leading to adoption of Integrated Water Resources Management principles and establishment of transboundary water resources management processes. In spite of these achievements, sustainable water resources management in the Volta basin still faces many challenges including the impacts of poverty, climate change and inadequate institutions.

Water governance in the future will take into account not only connectivities and linkages within the Volta basin, but also driving forces originating from outside the basin such as global/ regional trade, international policies and atmospheric and oceanic impacts. To achieve this requires, among others, the creation of wider collaborative networks, collection of new data and information, awareness creation especially at the policy and decision-making level and institutional capacity building.

The Volta basin

Surface Water Resources

The Volta River Basin is spread over parts of six West African countries - Bénin, Burkina Faso, Cote d'Ivoire, Ghana, Mali, and Togo (Figure 1). The major sub-basins (Figure 2) are the Black Volta; the White Volta with its major tributary, the Red Volta; the Oti River; and the Lower Volta. The basin covers an estimated area of 400,000 km2 that stretches from approximately latitude 5o 30'N in Ghana to 14o 30'N in Mali. The widest stretch is from approximately longitude 5o 30'W to 2o 00'E but the basin becomes more narrow towards the coast of the Gulf of Guinea. The basin has low relief in general with altitudes varying between 1 and 920 m. Mean altitude is about 257 m, with more than half the basin in the range of 200 to 300 m.

Although the Oti or Pendjari sub-basin, which takes its source from Benin and flows through Togo before entering Ghana in the north-eastern border, accounts for only about 18% of the total basin area (Table 1), it contributes about 26% of the annual flow into the Volta Lake (Volta River Authority (VRA), Ghana, personal communication). This is because its catchment is the most hilly and mountainous (>900 m) in the whole Volta Basin.

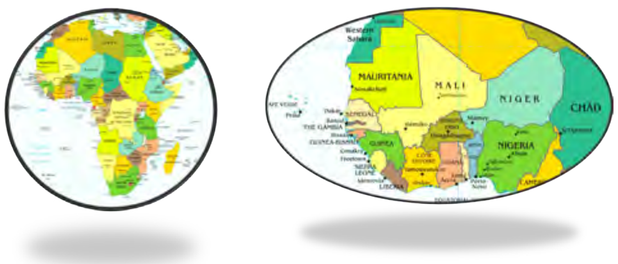


Figure 1. Section of Africa showing Riparian Countries of the Volta Basin

Figure 2. Hydrographical Network of the Volta River Basin (Lemoalle and de Condappa, 2009)

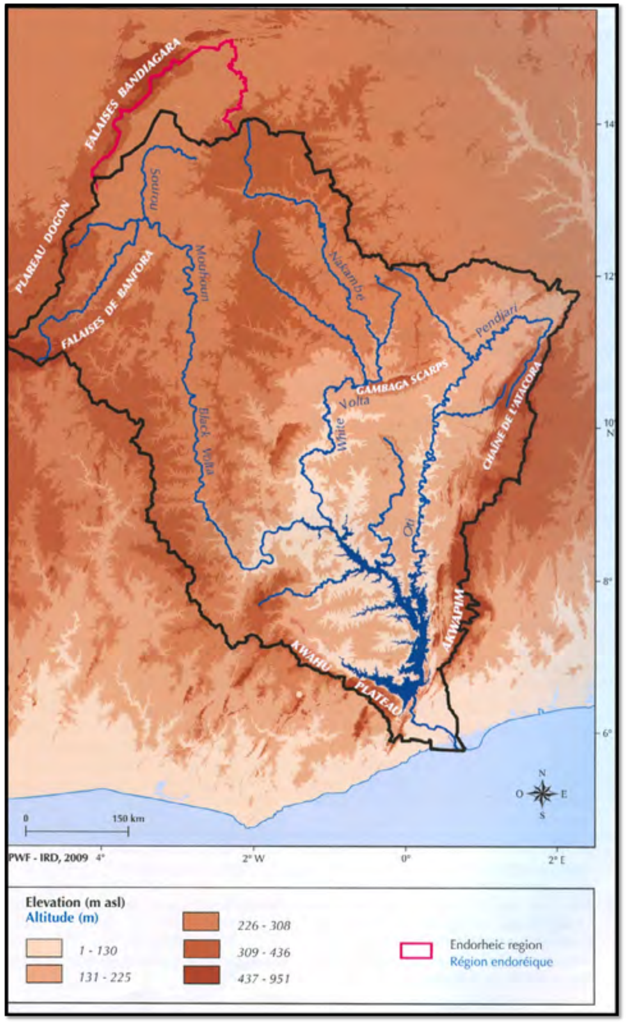


Table 1. Characteristics of Major Sub-Basins

Sub-basin	Area (km2)	Mean Flow (m3/s)	% Contribution
White Volta	104,749	220	20
Black Volta	149,015	200	18
Oti	72,778	280	26
Other tributaries	73,456	Varied	36

(Volta River Authority, personal communication)

Smaller tributaries to Lake Volta and the Volta River downstream of the lake constitute the Lower Volta. The smaller tributaries contribute about 36% of the annual flow into Volta Lake (VRA, personal communication). Below the Kpong Headpond, the Lower Volta River flows for 100 km before it empties into the Gulf of Guinea. At the estuary (Figure 3), the Anlo-Keta Lagoon Complex and the nearby Songor Lagoon are protected areas of international importance. They serve as feeding grounds for large concentrations of more than 70 species of migratory and resident water birds as well as breeding sites for 3 species of marine turtles (EPA, 2004). They were designated Wetlands of International Importance according to the Ramsar Convention 1992.Other important wetlands in the basin include La Mare aux Hippopotames on the Mouhoun in Burkina Faso and the Bui National Park on the Black Volta, the floodplains on the Pendjari in Benin and another Mare aux Hippopotames on the Oti at the border between Togo and Burkina Faso, all of which are Ramsar Sites because of their diverse wildlife population. (IUCN et al., 1992;IUCN/PAGEV, 2005; Lemoalle and de Condappa 2009)

Groundwater resources

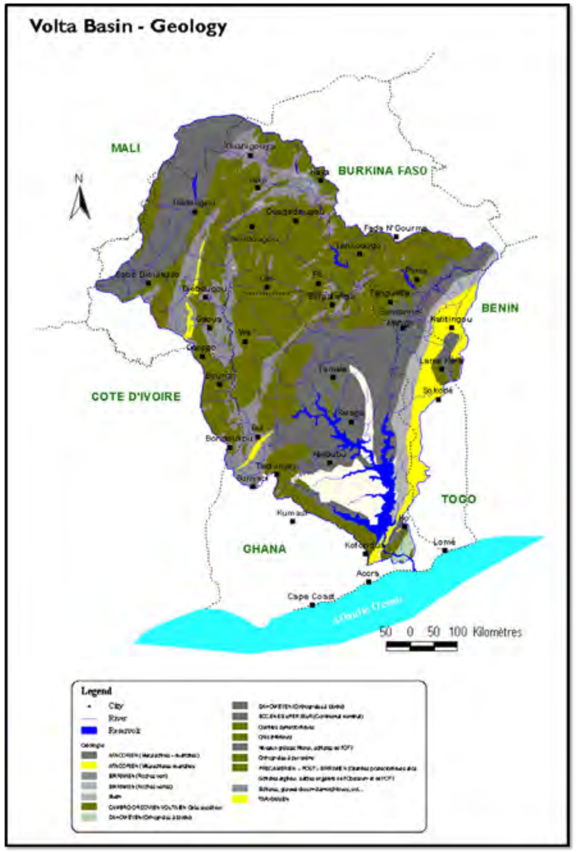
The geology of the main Volta (Figure 4) is dominated by the Voltaian system, which together with the basement complex dominate the hydrogeological systems (Barry et al., 2005). The thickness of the aquifer varies from several metres up to roughly 100 m, while the mean thickness is approximately 20 m.

The groundwater potential varies over the basin (Figure 5). For example, the north-western area of the basin where the headwaters of the Black Volta originate has good groundwater potential while the Middle Voltaian Obosum Sediments in Ghana have generally low groundwater potential (Martin and van de Giesen, 2005). In general, the mean yield from boreholes in the basin is relatively low, between 2 and 9 m3/h (Sommen and Geirnaert, 1988; Dapaah-Siakwan and Gyau-Boakye, 2000).

Figure 3. River Volta Estuary at Ada, Ghana (EPA, 2004)

Overall, data on the occurrence of groundwater in the Volta basin is inadequate since there is no systematic monitoring of groundwater. The GLOWA-Volta Project has compiled a database on urban and rural boreholes and wells in Burkina Faso and Ghana. Based on water balance calculations, water table fluctuations and isotope analysis, Sommen and Geirnaert (1988) estimated an annual recharge in the basin ranging from 2 to 16% of annual precipitation (i.e. 17 to 136 mm/y).

Figure 4. Geological Map of the Volta Basin (Barry et al., 2005)



Since 1970, the number of drilled wells equipped with hand pumps has increased from several hundreds to almost 20,000. This notwithstanding, on a basin-wide perspective, the mean abstractions from groundwater for urban and rural use (2001) is less than 5% of the estimated annual recharge, according to Martin and van de Giesen (2005). Lemoalle and de Condappa (2009) also state that groundwater overexploitation may occur only locally within the basin.

Figure 5. Groundwater Potential in the Volta Basin (Lemoalle and de Condappa, 2009)

Rainfall

The climate of the Volta Basin is characterized by great variability in rainfall distribution as a result of the following factors (Lemoalle and de Condappa, 2009):

» Spatial variability, with a south-north gradient of increasing aridity;

» Medium-term variability, with alternating dry and wet periods at the scale of the basin as a whole;

» Strong spatial and short-term variability within a given rainy season.

Rainfall distribution over the basin has a sharp north-south gradient, depending on the seasonal displacement of the Inter Tropical Convergence Zone (ITCZ). The farther north the ITCZ moves, and the longer it stays there during the northern summer, the more abundant the rains will be. This north-south gradient has been used as the basis for identifying the following 3 main agro-climatic zones of the basin (Figure 6) according to the FAO classification for West Africa:

» The Sudano-Sahelian zone, which occurs southwards of a drier Sahelian zone, and covers most of Burkina Faso and a small part of Mali. It has an annual rainfall range of 500 and 900 mm. Millet, sorghum and maize are the main food crops, alongside cotton, groundnuts and some sedentary cattle livestock raising;

» The Sudanian zone, comprising the northern half of Ghana and those parts of Cote d'Ivoire, Benin and Togo, with 900 to 1,100 mm rainfall per year. This is a transitional zone where both cereals and tubers are produced. Livestock raising is also common;

» The Guinean zone, covering the southern part of Ghana with annual rainfall in excess of 1,100 mm. Here, the rainfall is bimodal, the first rainy season occurring from April to July and a second from August to October. The main crops include yam, cassava and plantain.

In the medium term, there have been large variations in rainfall in West Africa in the last 100 years. After a wet period from 1950 to 1970, precipitation has systematically remained below the long term average (Lemoalle and de Condappa, 2009). With respect to short term variability in time and space, Lemoalle and de Condappa (2009) report that dry periods of 5 days or more during the rainy season pose a considerable risk for rain-fed crops. The probability of such interruptions is higher in the north. Studies conducted by the African Monsoon Multidisciplinary Analyses (AMMA) Project have also shown that in the Sudano-Sahelian zone annual rainfall often varies by a factor of 2 within a range of 80 km (AMMA, 2009).Temperature and Humidity

The annual mean temperatures in the basin vary from about 27° C to 30° C. Daily temperatures can be as high as 32° C to 44° C, whereas night temperatures can be as low as 15° C (Barry et al, 2005). Generally, temperatures are higher in the upstream of the basin and decreases downstream (Figure 7).

Humidity varies between 6% and 83% depending on the season and location. Relative humidity can reach a maximum of 80% in August, which is the wettest month of the rainy season. Total evaporation in August is generally lower than 100mm.

Figure 6. Agro-climatic Zones of the Volta Basin (Lemoalle and de Condapa, 2009)

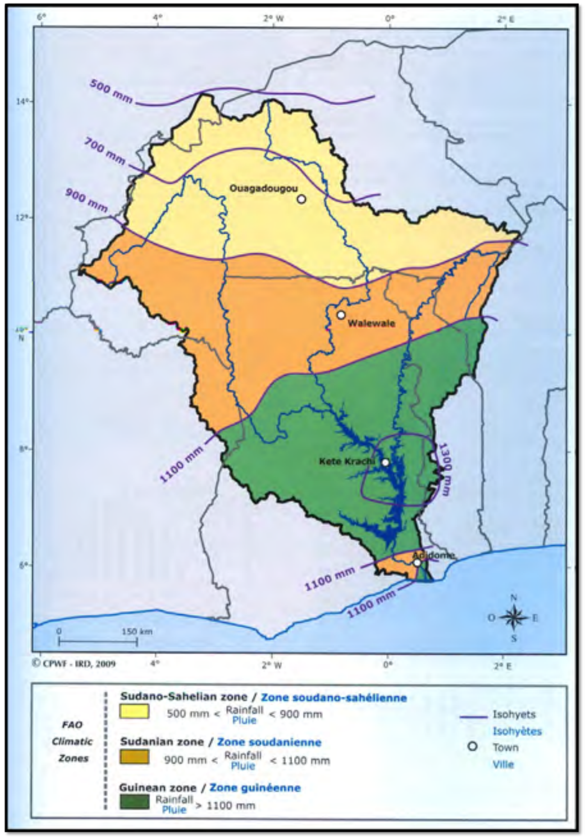
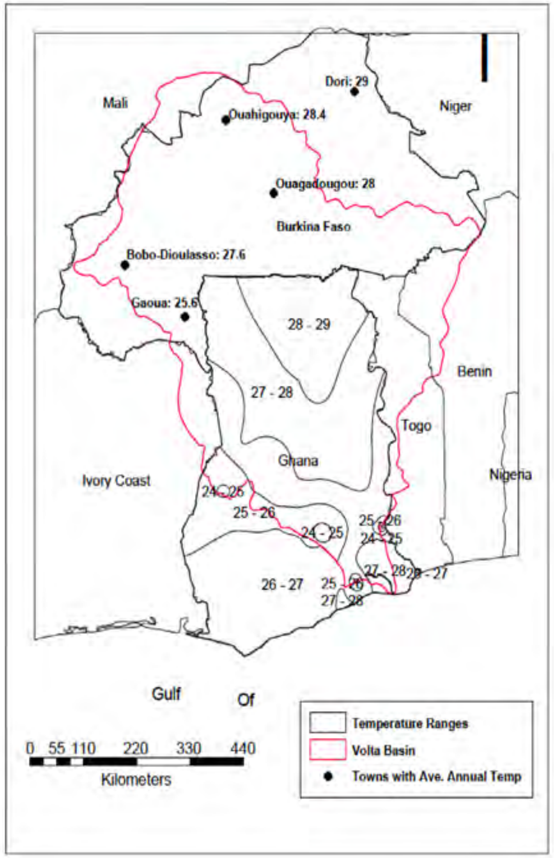


Figure 7. Spatial Distribution of Temperatures in the Volta Basin (Barry et al., 2005)



Population trends

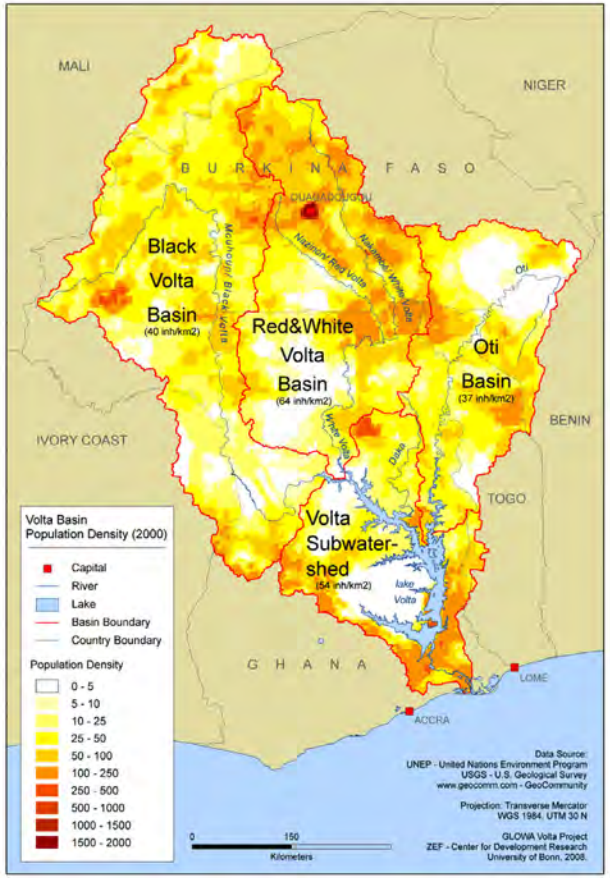
The major population areas in the basin include Ouagadougou, Tamale and Bolgatanga in the White Volta sub-basin and Bobo Dioulasso in the Black Volta sub-basin (Figure 8). Others are the Kara region of Togo in the Oti basin and the lower reaches of the Volta Lake and Lower Volta River in southern Ghana. Demographic statistics estimate that the basin population was 18.6 million in 2000 and will reach 33.9 million in 2025. The indication is that the population of the basin will double between 1990 and 2020, a period of 30 years. If this trend continues, the population will double again before 2050 to 45 million. The current growth poses a problem of matching the population with the available natural resources, especially those of water. Between 64% and 88% of the basin population live in rural areas, relying heavily on natural resources for their livelihoods, which is a challenge for their sustainable management. This high population growth in the basin will also impact on available infrastructure and facilities and have social and political implications.

The basin area also experiences population migration. In Ghana, for example, the decline in upstream fishing activities due to the creation of the Volta Lake has resulted in people moving to settle in the immediate surroundings of the Lake. Other migratory movements took place during the 1985 drought. In addition, people continue to move to urban areas in search of better opportunities while migration for the purposes of agriculture and livestock breeding will remain for long and be potential sources of conflicts (VBA Pre-Investment Study, 2009).Economic Profile

The riparian countries of the Volta basin are generally poor with weak economies based mainly on export of primary commodities. The 2009 Human Development Report (UNDP, 2009) groups most of them in the Low Human Development bracket with Human Development Index below 0.5 (Figure 9).

According to the World Bank (2010), the Gross National Income (GNI) of sub-Saharan Africa (SSA) is about 12% of the world average. Correspondingly, energy and power uses are low along with CO2 emis-

Figure 8. Population Density in the Volta Basin (GLOWA Volta 2008)



sions (Figure 10). Other indicators such as access to improved water sources and sanitation are also low compared to the world average.

The major consumptive water uses in the Volta basin are domestic and industrial water supply, crop irrigation and livestock production. Hydropower generation is the major non-consumptive use followed by fisheries while recreation and tourism are growing in importance.

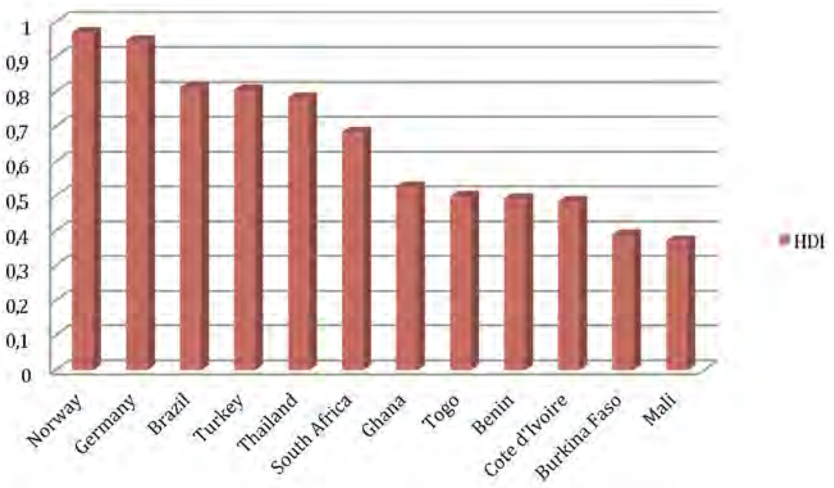


Figure 9. Human Development Index (HDI) of Volta Basin Countries and Other Areas

The water demand for domestic and industrial activities is projected to increase due to rapid population increases and industrial expansion (Andah and Gichuki, 2005). Even higher increases in water demand, more than 700%, are expected for irrigation as more food needs to be produced for the expanding population and rainfed agriculture becomes less reliable due to climate change. Thus increases in total water demand (Figure 11) of more than 1000% are projected between 2000 and 2025.

Projections using the Water Evaluation and Planning (WEAP) model on water demand and availability for various uses from 2005 to 2030 (IUCN/PAGEV, 2007) indicated among others that there will be sufficient water to meet domestic and industrial demand up to 2030 in all the towns and cities except Ouagadougou, which will experience shortages in the dry months, starting from 2013. In 2015, 88% of Ouagadougou's demand will be met, while only 78% will be met in 2030. With respect to irrigation in the Bagre scheme, only 42% of the demand will be met by 2030. The conditions will worsen in very dry years.

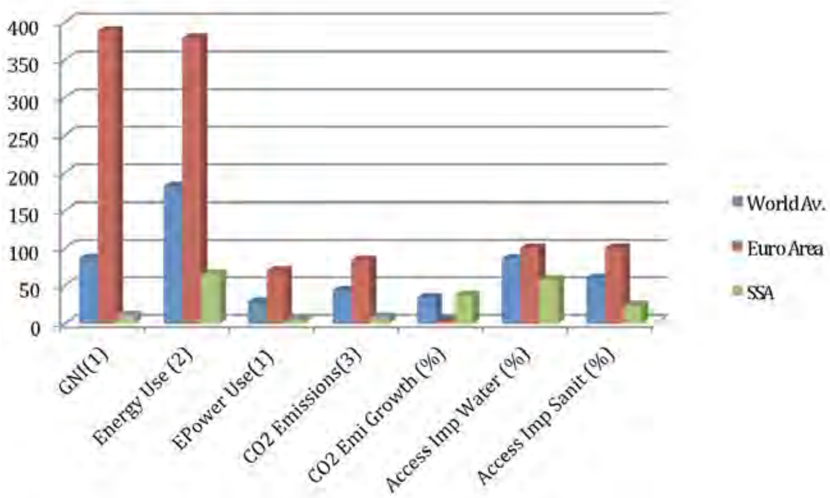
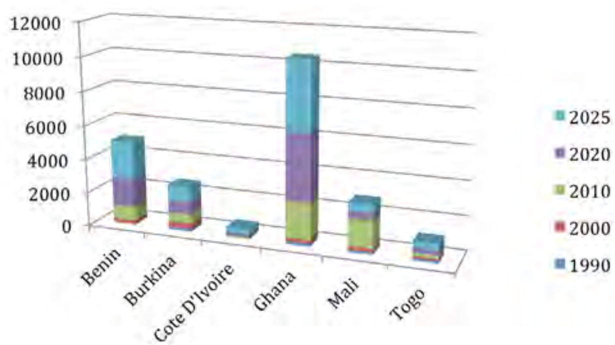


Figure 10. Comparison of Selected Socio-Economic Indicators

Figure 11. Total Water Demand (Million m³//year): 1990–2025



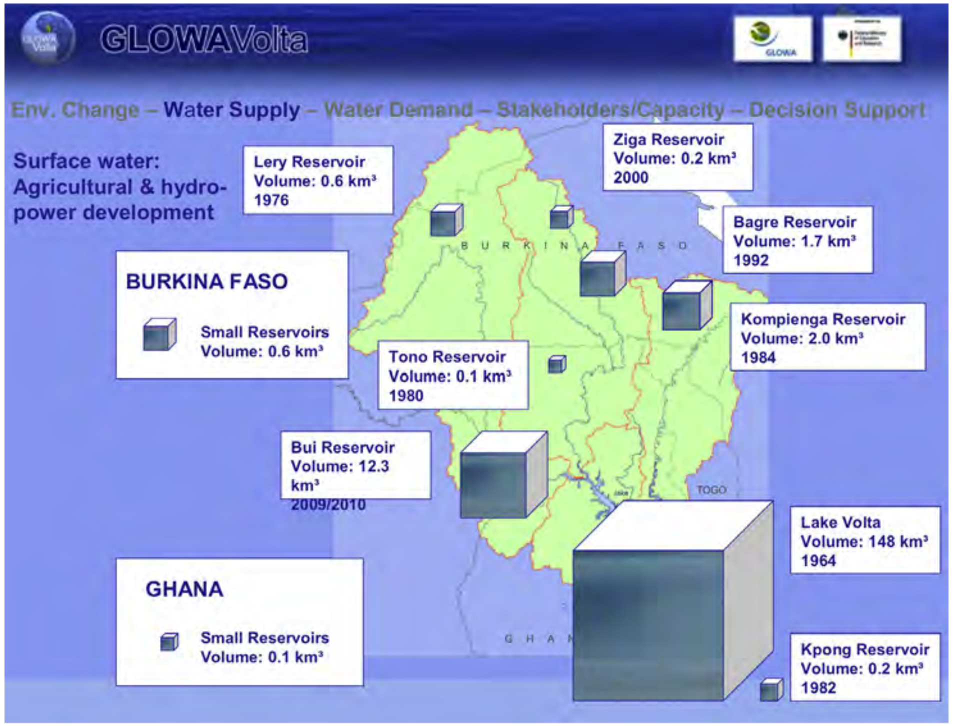
Development and Impacts

Large dams and reservoirs

In the last fifty years, several large dams (Fig 12) have been constructed in the Volta basin with the primary purpose of generating electricity but also to meet the increasing water needs of the growing population and of agriculture and industries.

The damming of the Volta River at Akosombo in 1964 created one of the largest artificial lakes in the world, covering an area of about 8,500 km2 with a total storage capacity of about 148 billion m3. A smaller and shallower impoundment, the Kpong Headpond, of roughly 38 km2 in surface area with a storage capacity of 2,000 x 106 m3, was completed in 1981, when another hydroelectric dam was constructed at Kpong, 20 km downstream of Akosombo. Akosombo has an installed capacity of 912 MW while Kpong has 160 MW. The Akosombo dam is operated to generate a relatively constant output of power daily and seasonally for domestic and industrial use In addition to power generation, irrigation and fisheries, the dam provides flood protection due to its very large storage capacity relative to inflow. It is also important for navigation especially in the perennial areas in Ghana, where local road networks may be insufficient. Additionally, the Volta Lake Transport Company transports people and goods between Akosombo and northern Ghana.

Figure 12. Location of Major Dams in the Volta Basin (GLOWA Volta)



Currently at Bui in Ghana, where the Black Volta passes through a gorge, the Bui Dam is being constructed with an installed capacity of 400 MW. Several small and medium size dams have been constructed in Burkina Faso, at Bagré (16 MW) and Ziga on the White Volta, Kompienga (14 MW) on the Oti River and Toéssé and Lery on the Black Volta with a total storage capacity of 4.7 billion m3 (IUCN/PAGEV, 2005; VBA Strategic Plan, 2009).

In Benin, a 15 MW hydroelectric dam has been constructed on the Oti River with a reservoir storage capacity of 350 million m3. Others include the Baye Reservoir in Mali and several small dams in Togo with a total volume of 33.6 million m3 There are 43 minor dams in Côte d'Ivoire with a total storage capacity of 2.97 million m3 (Andah and Gichuki, 2005).

In all the riparian countries, there are plans to construct more dams in the Volta basin. These include Samendeni and Noumbiel (62 MW) on the Black Volta in Burkina Faso and Juale (87 MW) on the Oti and Pwalugu (48 MW), Kulpawn (36 MW) and Daboya (43 MW) on the White Volta in Ghana as well Pouya (Natitingou) on the Oti in Benin (IUCN/PAGEV, 2005).

In spite of its socio-economic importance, development of rivers for hydropower and other uses has also come at a high cost in terms of riverine communities and ecosystems. Water storage behind dams disrupts the natural variability in the flows that sustain floodplain agriculture, fishery production, groundwater replenishment and stabilization of beaches. This is quite evident in Africa where traditional food production systems are quite dependent upon the annual replenishment of waters and nutrients to the floodplains, wetlands, estuaries and deltas.

The negative impacts of the Akosombo and Kpong dams in Ghana have resulted in fragmentation of the river, land and associated ecosystems leading to social, environmental and ecological changes both upstream and downstream. The Akosombo dam constitutes a barrier to fish migration and interrupts sediment transport. But most important, it distorts the natural river flows by storing and releasing water in rhythm with the patterns of electricity demand in the service area rather than the seasonal patterns of rainfall and runoff in the catchment area (WRC, 2008). The smaller Kpong Dam operates as a run-of-the-river facility with minimal storage.

The Volta Lake covers about 4% of the landmass of Ghana. Construction impacts upstream included displacement of a large population of 80,000 and the loss of arable lands and forests due to inundation. As attempts at resettlement were not very successful, the activities of the dislocated population resulted in intensified and destructive land use in the basin. The seasonal rise and fall of the Volta Lake is 2 to 6 m and the area covered by the seasonal fluctuation is about 100,000 ha. The loss of forest cover and land disturbances on steep slopes has increased sediment deposition into the reservoir, which could shorten its useful life.

Downstream, the impacts of the construction of the Akosombo and Kpong dams have resulted in a drastic reduction in floodplain agriculture, as there is no natural flooding, which will leave rich alluvial deposits to improve soil fertility in the overlying upland areas. The lack of natural flooding has also enabled the formation of a sandbar at the Volta estuary at Ada, which elongates at a rate of 3 km every 10 years when there is no intervention (VRA, personal communication). This can reduce the intrusion of seawater from a distance of 35 km upstream, to only 3 km upstream resulting in the elimination of a once lucrative clam and prawn fishery industry. Many other commercially valuable species have severely declined or disappeared, including blue crab, shrimps, shad and herring as a result of the disappearance of lagoons in the coastal zone, unable to receive replenishment during the flooding season. Before the dams were constructed, annual shoreline erosion was about 2 to 5 m; currently, it is estimated at 10 m in several locations, including Togo and Benin (WRC, 2008).

Furthermore, the warm, less saline and silt-free waters discharged from the two dams into the Lower Volta have favoured the proliferation of exotic aquatic weeds, which provide a suitable environment for the snail vectors of bilharzias (Biney, 1990) leading to an increase in cases of urinary schistosomiasis, as well as an appearance of intestinal *schistosomiasis* which was not present prior to dam development (Gordon and Amatekpor, 1999). There have also been increases in the occurrence of malaria. These negative impacts have led to widespread migration of young people from the Lower Volta basin to urban areas, where they do not have enough skills to be optimally employed.

On the other hand, the regulation of flows downstream also had positive impacts on water-borne disease vectors. River blindness, for example, was eradicated from the immediate downstream area of the Volta Lake, in the Kpong Headpond because of the inundation of the breeding sites of the vector, Simulium damnosum fly, which thrives in highly oxygenated, fast flowing waters. The prevalence of trypanosomiasis too reduced drastically because large areas of tsetse-infested forests were drowned. Since 1973, no new cases have been recorded around the Lake.

With respect to the Bagre Dam, commissioned in 1994 on the White Volta River in Burkina Faso, its most significant impact is the opportunity afforded Burkina Faso to increase its irrigated agriculture as well the addition of cheap electrical energy which tended to be very expensive because of the use of diesel generating plants. It has also served as a good flood control structure and thus reduced the incidence of annual flooding of downstream areas in southeast Burkina Faso and northern Ghana which used to lead to loss of life and property (Figure 13) almost every wet year.

However in years that rainfall in the basin is so excessive that the dam spillway gates have to be opened, the spill flow goes to add to the already wet conditions downstream, exacerbating flooding and thereby raising tensions between the two neighboring countries. In 2008, the height of the dam, which also provides opportunities for fishing, was increased by 1.5 m to enlarge its storage capacity in order to improve its flood control capability. However, after two successive years of above average rainfall, flooding occurred in these areas in 2009 and 2010. In 2010, 17 people died in the three northern regions of Ghana from flooding-related incidents when the spillways of Bagre were opened amid heavy rains and flooding in the area (Ghanaian Journal, 2010).

The construction of the three proposed dams in Ghana on the White Volta namely Pwalugu, Kulpawn and Daboya would go a long way to solve both drought and flood problems in the flood prone flat areas in northern Ghana as well improve dry season irrigated agriculture, navigation, recreation, water supply and fisheries, among others

Small reservoirs

In response to continuing drought conditions there has been a rapid expansion in the number of small reservoirs in recent decades in the Sudano-Sahelian and Sudanian zones of the basin. Water stored in these reservoirs, usually with areas of less than 100 ha, is used to supplement rain-fed agriculture, allows for dry season irrigated agriculture and ensures the availability of water for domestic purposes during dry periods (Annor *et al.*, 2009). Small reservoirs are also important for fisheries.

The highest concentrations of small reservoirs occur in Burkina Faso where almost 80% of the about 2,000 reservoirs are located in the Volta basin (Figure 14). According to Lemoalle and de Condappa (2009), the oldest reservoirs are over 100 years old, but more than half were built between 1974 and 1987 as a result of the Sahelian drought. There are also high concentrations of small reservoirs in the Northern regions of Ghana. However, unlike in Burkina Faso, most of them were constructed earlier, between 1950 and 1970 (Figure 15), probably in reaction to the dry period of the 1940s.

Figure 13. Distribution of Small Reservoirs – Northern Volta Basin (Lemoalle and de Condappa, 2009)

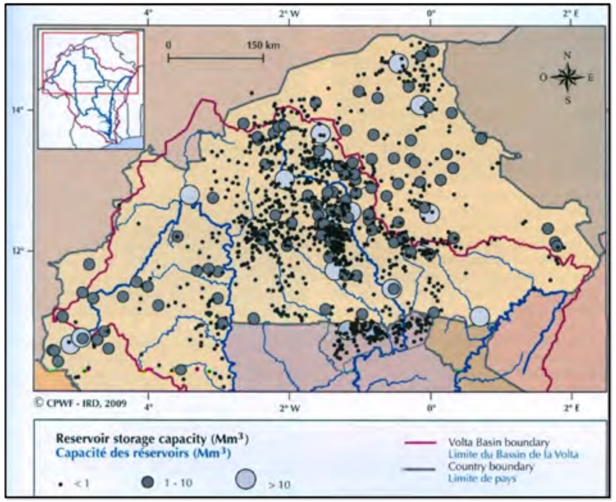
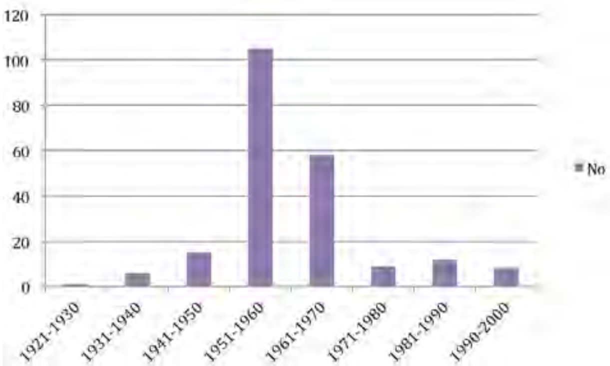


Figure 14. Construction of Small Reservoirs in Upper East Region, Ghana



Further expansion of small reservoirs in the northern part of the basin is expected in the future. According to Andah and Gichuki (2005), it is difficult to quantify the effects of these reservoirs on the basin because of incomplete information on their location and sizes. However, a simulation of the increase in reservoir numbers using the WEAP model (de Condappa et al, 2009) indicated that the impact on the Volta Lake would be small in terms of both stored water volume and inflow to the lake. The impact on hydropower generation would thus be minimal compared to other stresses such as climate change. On the other hand, small reservoirs have contributed to the spread of some water related diseases in the basin including malaria and guinea worm infections.

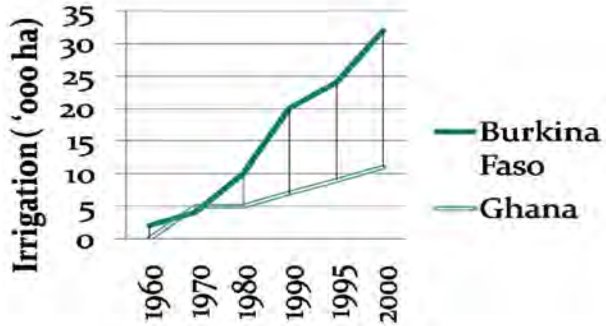
Agricultural production systems

Within the Volta basin, there have been increases in agricultural production over the last 30 years to meet rising demand locally and internationally. Since most of the cultivation is still mainly rain-fed, these increases have largely been due to expansion of agricultural land in the basin. Andah and Gichuki (2005) have estimated that agricultural production in the basin, which has higher rural populations than the national averages, is about 40% of the entire economic output of the basin. Rain-fed agriculture is the main activity of the rural populations. For example, in Mopti and Bankas areas of the Volta basin in Mali, considered the granary of the region, 85% of the population is engaged in agricultural production.

The main cropping systems which contribute to food production are distributed in the agro-climatic region of the basin mainly as a function of rainfall and soil characteristics, with a successive north-south dominance of millet, sorghum, maize to be replaced by cassava, yam and plantain (Lemoalle and de Condappa, 2009). The rich savanna grassland provides good fodder for livestock production. Surface water uses by livestock is probably relatively small but it is an important water use by many people in the upstream part of the basin.

Forests in the Basin are cut to provide firewood and charcoal, and to provide lumber. The forests in the Togo section of the basin for example, provide over 50% of the country's production of sawlog. Forests in the region have been severely overexploited.

Figure 15. Irrigation Development in Burkina Faso and Ghana



Additionally, expansion of irrigation infrastructure in the basin has enabled the development of irrigated agriculture, which is particularly developed in the Sudanian Zone in Burkina Faso. While there were, less than 3 000 ha of irrigated land in the basin in 1960 this has grown ten times within 30 years (Figure 16). Notable areas include the Bagre Irrigation Scheme on the White Volta in Burkina Faso and the Sorou Valley shared by Burkina Faso and Mali. Crop production under irrigation is however negligible in the basin. There are many plans to expand large irrigation systems in the basin; these include expansion of the Bagre and Kpong Irrigation Schemes in Ghana and Burkina Faso respectively and creation of new schemes in connection with the Bui and Samendeni dams (VBA Preinvestment Study, 2009).

Specific impacts of agricultural production include land degradation especially in areas where forests have been cleared in the Guniean Zone, loss of top soil, erosion and salinisation. In the Sudano-Sahelian and Sudanian Zones land degradation has also occurred as a result of over-grazing and land clearing for cash crops such as cotton.

Fisheries production systems

Fish production, using gill nets, hook lines and traps, is an important activity in the basin. It is widespread along rivers and in small reservoirs but the most important areas are the large reservoirs, the Volta Lake, Bagre and Kompienga reservoirs and in some floodplains such as the upper Mouhoun and Sorou Rivers (Lemoalle and de Condappa, 2009). Annual fish catch in Bagre was estimated at 975 tonnes between 1994 and 2004 while that for Kompienga was 1,200 tonnes between 1991 and 1997. In Ghana, the Volta Lake produced about 87,500 tonnes of fish in 2000, about 98% of the inland fish production (Braimah, 2001). A survey in 1998 revealed that there were 1,232 fishing villages located around the Volta Lake (Figure 12) and 71,900 fishers with 24,000 canoes. 139 fish species occur in the Volta Lake. The lake's potential yield of about 40,000 tonnes per annum has been exceeded annually since 1995 (Braimah, 2001). Since the mid 1990s there has been increasing deployment of more active gear, such as winch nets, with unapproved mesh sizes. This situation is extremely dangerous for a fishery that is already experiencing over-exploitation.

The Oti River in Togo and Benin also offers significant fishing opportunities. Prior to the construction of the Lery dam on the Mouhoun in Burkina Faso, fishing in Mali was on a subsistence level but it has since moved to a commercial scale. The Keta Lagoon in Ghana, which is part of the estuarine complex of the Volta, has a potential annual fish yield of about 4,000 tonnes (FAO, 2004). The most important commercial lagoon species are tilapia, grey mullets, crabs, shrimps and oysters. It is however over-exploited and suffers from pollution due to local domestic and commercial discharges. Like many other coastal lagoons in eastern Ghana, its characteristics have changed since the construction of the Akosombo dam.

Over the last two decades, fish farming has also increased in popularity in both small and large reservoirs. Particularly, there has been a rapid expansion in cage fish culture in the Volta Lake and Kpong Headpond. Ghana's aquaculture production tripled over the last five years to almost 4,000 tonnes annually and still had the potential for continued high growth. The major problem associated with aquaculture production is habitat modification as a result of construction of facilities along river banks and in wetlands (Gordon and Amatekpor, 1999). Localised pollution may also occur resulting in reduced dissolved oxygen concentrations and increased turbidities (Biney, 1990) Industry

As is typical of most Sub-Saharan African countries, industrial activities are centered near or within the national capital cities. Also, in all the coastal countries, most industries are located along the coast because of ease of accessibility to export and import facilities and more developed infrastructure (Biney, 1990; Kouassi and Biney, 1999). Apart from Ouagadougou, all the national capitals of the riparian countries are located outside the Volta basin. Thus industrial activity in the Volta basin is relatively low, compared to other areas of the West African sub-region.

In the Volta basin, most industries are located in the major population centres such as Ouagadougou, Bobo Dioulasso in Burkina Faso and Tamale in Ghana. According to Lemoalle and de Condappa (2009), there are no significant withdrawals of water for industries in the basin. Polluting discharges may however occur. In a study on water quality of the Mohoun and Nakambe Rivers in Burkina Faso (Lindou, 2008), the main sources of pollution identified were from the industrial zones of Bobo Dioulassou and Ouagadougou. The study showed that although the industrial sector is not well developed in Burkina Faso, it constitutes a principal source of pollution. The major industries involved were beer and other beverage producers. Textile factories located downstream of Akosombo are also known to have caused localised pollution (Biney, 1977) but the situation has improved with installation of treatment facilities.

Climate change

Climate change refers to the build-up of man-made gases in the atmosphere that trap heat from the sun, causing changes in weather patterns on a global scale (www.nsc.org/ehc/glossary.html). The Intergovernmental Panel on Climate Change (IPCC) refers to climate change as any change in climate over time, whether due to natural variability or as a result of human activity (www.wwf.org.hk/eng/conservation/climate/glossary.php).

The phenomenon of global climate change is expected to produce various impacts. On a global scale, the impacts include increases in ambient temperatures, melting of glacial ice, sea level rise, salinisation of fresh water resources, and displacement of populations leading to increased migration and reduced water and food security (UNDP Human Development Report, 2006). According to the IPCC (2008), globally, the negative impacts of future climate change on water resources are expected to outweigh the benefits. For example, changes in water quantity and quality are expected to affect food availability leading to decreased food security and increased vulnerability of the poor.

Climate change is a major challenge to sustainable development in Africa. Although the continent contributes less than 4% of total greenhouse gas emissions, its countries are among the most vulnerable to climate change, which derives from multiple stresses coupled with low adaptive capacity (UNECA et al., 2010). Firstly, the geographical location of many African countries is characterised by an already warmer and relatively dry climate, with extensive marginal areas characterised by poor soils and high rainfall variability. Secondly, the economies of most African countries rely heavily on climate-sensitive sectors such as agriculture, fisheries, forestry, other natural resources and tourism. Thirdly, the continent is unable to respond adequately to the direct and indirect effects of climate change because of widespread poverty, poor economic and social infrastructure, conflicts, limited human and institutional capacities, and inadequate technologies and financial resources. Vulnerability to climate change in Africa is particularly high for the poor, who tend to live in environments that are most susceptible to droughts, floods and other extreme weather events. Also, with the fastest population growth in the world, Africa is likely to increase its share of global emissions of greenhouse gases (World Bank, 2010), which calls for development pathways to control emissions and improve adaptation strategies.

Current and projected impacts of climate change threaten Africa's economic growth as well as achievement of the Millennium Development Goals (MDGs), among others. These include:

- Increased water stress and water-related conflicts;
- Constrained agricultural output and hence increased food insecurity;
- Increased energy constraints;
- Rising sea level, degrading coastal livelihoods, infrastructure and environment;
- Loss of biodiversity, forests and other natural habitats;
- Expanded range and prevalence of vector-borne diseases including malaria; and
- Increased risks of disasters, conflicts, instability and security threats.

West Africa is among one of the most vulnerable regions to climate change because some of its physical and socio-economic characteristics predispose it in such a way as to be disproportionately affected (Niasse et al., 2001). Such characteristics include the highly visible contrast between wetlands and arid zones and continuing poverty.

Within the Volta basin, several studies such as those of GLOWA (www.glowa.volta.de) and the Challenge Program for Water and Food (www.waterandfood.org) have predicted negative impacts including increasing temperatures, reduced rainfall and decreased availability of water resources, water quality deterioration and spread of some water-related diseases. In an analysis of the impact of climate change on hydropower generation using the Water Evaluation and Planning Model, de Condappa et al., (2009) predicted that increases in ambient temperature up to 2 oC would affect the Volta Lake by slightly reducing the water level but changes in rainfall patterns would have a much greater impact. They concluded that hydropower generation such as observed in the relatively wet late 1990s would be sustainable only in a wet climate. Other studies on the Black Volta basin (Laube et al., 2008), have predicted reduced water availability arising from changes in reduced seasonal rainfall and river flows, which will be further diminished by higher temperatures and evapo-transpiration. While these factors alone have the potential to negatively affect the operations of the Bui hydropower project on the Black Volta, others such as deforestation and erosion could further reduce the lifespan of the reservoir. It is apparent that even for the Bui dam, which is currently under construction, the potential impacts of climate change were not taken into account during the planning stages.

With water resources already stressed by non-climatic factors such as rapid population growth and development, pollution and deforestation, the impacts of climate change will further aggravate the situation. These impacts will also lead to negative socio-economic consequences, which if unmitigated, will tighten the poverty and disease cycle and bring further hardship to the population of the basin.

Water governance in the Volta basin

The last 30 years has seen some progress made in water governance in the Volta basin. This initially began as part of national development activities to improve livelihoods and also in line with world-wide recognition of environmental concerns in reaction to modifications of river basins by hydraulic infrastructure and other human activities.

Ghana for example, has been involved in water governance and policy reform since the 1980s, during the International Drinking Water Supply and Sanitation Decade (IWSSD). The reform gained momentum after the review of the IWSSD, which resulted in the establishment of institutions to increase access to safe drinking water and sanitation, creation of favourable conditions for increased private sector participation and independent regulation of tariffs. Reform aimed at protection of water and the general environment is rooted in the 1985 Ghana Environmental Action Plan (WRC, 1999). Further to this, an Environmental Protection Agency (EPA) Act, passed in 1994, conferred regulatory and enforcement powers on the EPA. These reforms were aimed at ensuring a sound development and management of natural resources and the environment to avoid exploitation of resources in a manner that might cause irreparable damage to the environment.

Specifically on water resources, since there was no coordinated management at national level, the sector lacked an integrated national policy and comprehensive plans for the utilisation, conservation, development, and improvement of water resources. The water related institutions had been created and assigned specific roles with single purpose objectives or mandates without consideration of the linkages or interdependency of each other's functions and roles. The Water Resources Commission (WRC) was therefore established by an Act of Parliament in 1996 to regulate and manage Ghana's water resources and coordinate policies in relation to them.

At the sub-regional level, the Economic Community of West Africa States (ECOWAS), as a result of the West African Conference on Integrated Water Resources Management held in March 1998 in Ouagadougou, adopted an Action Plan for Integrated Water Resources Management (IWRM) and establishing a Water Resource Coordination Centre which, among others is responsible for coordination and implementation of the Action Plan.

Although the Volta had grown in importance during the last 5 decades, it had remained one of the few large transboundary river basins in Africa without formal legal and institutional arrangements among the riparian countries for managing its water resources until recently. Mechanisms and institutions to manage and spearhead prudent and sustainable utilization of the water resources in the basin were absent. With increasing awareness of the importance of managing the water resources of the Volta basin in a more holistic manner in line with the ecosystem approach, in which the river basin is seen as an ecosystems continuum and water as an integral part of ecosystems (Marchand and Toornstra, 1986), the Volta Basin Authority (VBA) was established by the Heads of State of the riparian countries in January 2007. In order to improve transboundary water resources management towards achieving water security, VBA has a mandate to *promote permanent consultation and sustainable development of the water and related resources of the Volta basin for equitable distribution of benefits towards poverty alleviation and better socio-economic integration*.

In spite of the progress made, challenges still remain, mainly arising from development of water resources in the basin as described above and from inadequacies in governance practices. The UNEP-GEF Volta Project on 'Addressing Transboundary Concerns in the Volta River Basin and its Downstream Coastal Area' has recently identified the following 8 priority transboundary concerns (UNEP-GEF Volta Project, 2010):

» Changes in water quantity and seasonality of flows

» Degradation of Aquatic Ecosystems

» Degradation of Surface Water Quality/Pollution

» Invasive Aquatic Species

» Land Degradation/ Loss of Vegetative Cover

» Loss of Biodiversity

» Water related diseases

» Coastal Erosion

Other challenges include insufficient political support, lack of financial resources, gaps in information, insufficient stakeholder participation and poor institutional coordination and collaboration.

Within the Volta basin, several international programmes and projects are being implemented on the development and management of the water resources. This is due to the fact that before the establishment of the VBA, several institutions and organizations, in response to the increasing pressure on the water resources of the basin, initiated various projects to provide information and develop solutions for sustainable management of the water and other resources of the Volta basin. Although these projects have many common objectives including sharing of information, involvement of stakeholders and transfer of results to basin authorities and decision makers, in general however, they are being executed separately without significant exchanges and interaction at the basin level.

Thus the VBA, in connection with its objective to coordinate activities, has developed a Strategic Plan, which outlines the key priorities of the VBA and aims to facilitate its partners to better focus on priorities of the Volta basin while avoiding duplication of efforts. The five Strategic Objectives of the 5-year Strategic Plan are:

» Strengthening policies, legislation and institutional framework;

» Deepening knowledge about the basin;

» Coordination, planning and management;

» Communication and capacity building for all stakeholders;

» Effective and sustainable operations.

The way forward

Development in the Volta basin, as in the rest of the world, will continue. As Africa's economy improves, even more diverse development will be expected. According to the African Development Bank (AfDB), economic growth in Africa is expected to rise to 5% in 2010 and could reach 7% in 2011 (Engineering News, 2010). As the global financial crisis abates and demand for commodities begins to increase, the economies of African countries, including those of the Volta basin are expected to grow.

As hydropower is largely undeveloped in Africa and less than ten percent of its potential has been tapped (UNECA et al., 2010), this is one sector where increased development is likely to occur. According to AfDB, Africa must invest heavily in transboundary river basin management, irrigation and major storage infrastructure to facilitate rational management and ensure that water is available when and where required. Water for irrigation is also a high priority for economic development and stability, yet few countries can afford adequate investment in efficient irrigation systems. In order to close the infrastructure gap with other parts of the world, meet the Millennium Development Goals, and achieve national development targets within the next 10 years, the estimated annual capital cost of water resource infrastructure is approximately $10 billion. Of this, almost 80 percent is for the development of large multipurpose hydropower storage, and about 10 percent is for development of large storage capacity for urban water supply and small-scale infrastructure projects.

As already indicated in this paper, the construction of large dams has caused the most significant impacts in the Volta basin. Their negative impacts have become increasingly apparent and include displacement of people, increased erosion and flooding, loss of land and loss of income from downstream fisheries. For future development, more consideration should therefore be given to the development of micro-hydropower facilities, which are more sustainable for managing water resources for electricity generation. Recommendations from Environmental and Social Impact Assessments should also be strictly implemented and monitored. For already existing facilities, there is the need to investigate and implement options that can mitigate the loss of livelihoods as exemplified by current initiatives with respect to the Akosombo and Kpong dams in Ghana, described below.

Led by the Water Resources Commission of the Ghana Ministry of Water Resources, Works and Housing, with its partners including the Volta River Authority, Environmental Protection Agency, Water Research Institute, Volta Basin Research Project of the University of Ghana, International Water Management Institute and VBA, a project '*Reoptimization of Operations of Akosombo and Kpong Dams to Restore Downstream Livelihoods and Ecosystems*', has been initiated. This is part of a Global Dam Reoperation Program organized by the Natural Heritage Institute of California, US, an international conservation organization, to demonstrate the technical and economic feasibility of re-optimizing the world's major irrigation, hydropower and flood management systems to enable their storage dams to be re-operated to restore their formerly productive floodplains, wetlands, deltas and estuaries in ways that maintain the existing water supply, power generation and flood control benefits (WRC, 2008).

The initial expected change will be the release of a flow pattern from the Akosombo and Kpong dams that more closely mimics the natural conditions that occurred before the dams were built. The project will also improve power reliability and reduce flood risks. This would be accomplished by re-operating Akosombo more as a run-of-the-river facility that would try to imitate the natural hydrograph through the dams and downstream to the mouth. This would allow the dams to recreate to some measure, the annual flood event to reconnect and replenish the floodplain, while continuing to prevent catastrophic flood events. This change in operations would require a change in the scheduling of hydropower production. During high runoff periods, much more power would be produced than during the low inflow periods. Thus, a mix of hydropower and added thermal generation to meet total system demands would vary from season to season, although the annual contribution of each would not change appreciably. Additional thermal capacity would be necessary for the low flow periods.

The project aims to assemble the necessary data and create the necessary analytical tools as follows:

- To evaluate a range of operational scenarios the project will create a computer simulation of the physical processes and infrastructure operations in the entire Volta River system, but at a higher level of resolution for the reservoir and the downstream river system;
- Through consultations with stakeholders, construct a range of water management scenarios that will be evaluated and compared using a computer model to identify those that are hydrologically feasible and most robust in achieving the project objectives;
- The project will explore the range of freedom in the scheduling of power generation at those facilities relative to the demand requirements of the integrated grid system and the supplies of power from other generators. Towards this, a power system planning model will be constructed for the grid system at its current state of integration with Nigeria, Benin, Burkina Faso, Cote d'Ivoire, Niger, Nigeria and Togo (West Africa Power Pool Zone A). The model will also account for current hydro and thermal generation connected to that grid, including plants now under construction, as well as future additions to electrical supplies, which are also dynamic;
- The model will be operated to, among others, ascertain the physical and economic limitations on the ability of Akosombo and Kpong dams to release water and generate power, including the need to ascertain the feasibility of retrofitting the dam with additional turbines to permit larger releases of water during the times when a controlled flood is desired and to determine whether these scenarios provide climate adaptation benefits in a future of more intense droughts and floods in the Volta River system;
- Those scenarios that are judged to be hydrologically feasible will then be subjected to an economic, legal, political and institutional feasibility analysis.

In addition to large reservoirs, the impacts of climate change are equally if not more important as they have a major impact on key sectors, such as agriculture, infrastructure development and on levels of poverty and disease, among others.

Adaptation strategies that are currently common in Africa (IPCC, 2008; IWMI, 2009) include improvements in rain-fed agricultural systems through improvements in physical infrastructure including water harvesting systems, dam building, water conservation and agricultural practices; drip irrigation, development of drought-resistant and early-maturing crop varieties and alternative crop and hybrid varieties. It is clear from the above examples that most of the water-related adaptation strategies involve surface water supply and demand options, which are not adequate because climate change impacts on water resources affect other systems and sectors of development, notably water quality and pollution, groundwater availability, human health, energy, coastal and riverine settlements, forestry and natural ecosystems (Easterling et al., 2004).

Africa has a limited number of scientists, facilities and data sources. Its expertise in addressing climate change issues is meager. Thus, it does not have sufficient scientific data and information for adequate understanding of climate change vulnerability and impacts on the continent. According to UNECA et al. (2010) more information is required in order to:

a) Inform ongoing international negotiations which are critical for the future of Africa;

b) Assist in transformation to a low-carbon development pathway;

c) Monitor and evaluate impacts and the effectiveness of remedial measures;

d) Understand the uncertainties and manage the associated risks.

As indicated in Section 4 above, several programmes and projects have carried out studies in the Volta basin during the last decade on the impacts of climate change and variation and other global changes. Notable amongst them is the GLOWA Volta Project (www.glowa.volta.de), of the University of Bonn, which has the central objective of analysis of the physical and socio-economic determinants of the hydrological cycle in the Volta basin in the face of global change. Over a 10-year period (May 2000 to November 2010) the project, which is financed by the Federal Ministry of Education and Research, has trained more than 400 experts and assembled significant information and tools including:

» Volta Basin Water Allocation System that allows incorporating the impact of possible future climate conditions and projected water demand;

» GLOWA Volta Geoportal, which has recently been transferred to the VBA;

» High-resolution Regional Climate Modeling for the Volta Basin;

» Predicting the Onset of the Rainy Season in the Volta Basin.

The challenge is how to continue and build on these studies with involvement of more institutions from the riparian countries whose governments continue to invest minimally in research and development. Areas for further research and studies should include climate modeling, environment monitoring, and climate risk management to support the large number of diverse adaptation initiatives. Many critical resource issues including water, land and biodiversity have to be addressed in coherent and coordinated ways. This requires more innovative approaches such as sustained observations in the form of basin-wide monitoring networks and improved data sharing. Satellite technology, for example, can be used to monitor rivers and soil conditions for efficient transboundary water resource management.

Within the Volta basin, research should also focus on improving knowledge and management of transboundary groundwater resources as well as on how to integrate management of groundwater resources into the scope of activities of river basin organizations.

It is also recognized that other global interactions, in addition to climate change, can and will continue to significantly affect development activities. These include trade, global economic fluctuations and natural or man-made disasters. Thus water resources management in the Volta basin will be linked to other global initiatives such as the UNEP Ecosystem Management Programme (UNEP, 2010), which provides an effective framework for the holistic management of ecosystems and the Global Earth Observation System of Systems (GEOSS). The GEOSS aims to empower the international community to protect itself against natural and human-induced disasters, understand the environmental sources of health hazards, manage energy resources, respond to climate change and its impacts, safeguard water resources, conserve biodiversity (IEEE, 2010). This crosscutting approach avoids unnecessary duplication and ensures synergies between systems.

Climate change also has to be recognized as presenting diverse opportunities for Africa that could serve as a catalyst to build more efficient, low carbon economies that can guarantee Africa's future development. To realize this goal, Africa has to develop more specific policies for climate change to guide, among others, design of appropriate legal and regulatory frameworks and investment of resources in development and acquisition of green technologies and products. This requires raising the status of water on the political agenda.

Politically, Africa has made progress in establishing an enabling environment for water management at the pan-African level. In recent years, African Heads of State have demonstrated increased political commitment and leadership. Ministers made a series of commitments during 2008, at meetings in eThekwini (Durban), Tunis and Sirte. The African Union dedicated part of its June 2008 Summit in Sharm El-Sheik to water and sanitation. These events have all increased awareness of regional water security and sanitation issues but much remains to be achieved.

To make the 'political process' more effective, development research should link hydrologic issues with socio-economic impacts to highlight the advantages and disadvantages of various scenarios of water resources management. By extension it means that research outputs should be more user-friendly to attract the attention and allow comprehension by politicians in developing countries. Scientists should dialogue more with politicians than they are doing now.

As the VBA continues to implement its Strategic Plan, it has to take into account the above challenges in order to ensure sustainable water resources management that will effectively support improvements in livelihood. The Volta basin, in this sense is an opportunity for sustainable development. The fact that the basin is under-developed and has comparatively few water development infrastructure and other investments at this moment, should be seen more as an opportunity than a disadvantage. The opportunity is presented for future and planned development to take into account the impacts of climate and other global changes and the need to develop, adapt and use low carbon technologies. Development can also take advantage of the experiences of more developed basins. For example, over-building of infrastructure in the basin is a future threat that should be resisted in spite of the well known concerns about under-development in Sub-Saharan Africa. In effect, long-term sustainability concerns should over ride short-term needs for income generation.

References

- African Monsoon Multidisciplinary Analyses (AMMA), 2009. www.amma-international.org
- Andah. W. and Gichuki, F. 2005. Volta Basin Profile, CPWF Baseline Report No. 8, Enhancing Agricultural Productivity Through Strategic Research. 59p.
- Annor, F.O., van de Giesen, N., Liebe, J., van de Zaag, A., Tilmant, A. & Odai, S.N. 2009, 'Delineation of small reservoirs using radar imagery in a semi-arid environment: A case study in the upper east region of Ghana', Physics and Chemistry of the Earth, 34 (4-5): 309 - 315.
- Barry, B. Obuobie, E., Andreini, M., Andah, W. and Pluquet, M., 2005. The Volta River Basin; Comparative study of river basin development and management. IWMI, Comprehensive Assessment of Water Management in Agriculture.
- Biney, C. A., 1977. Pre-impoundment studies of the Lower Volta in the area of the proposed second Volta dam. Inst. Of Aquatic Biol. Tech Rep. 72, Accra, 11p.
- Biney, C.A, 1990. A review of some characteristics of freshwater and coastal ecosystems in Ghana. Hyrobiologia 208, 45-53.
- Braimah, L.I. 2001. Lake Volta Fisheries Management Plan. Fisheries Sub-sector
- Capacity Building Project. Ministry of Food and Agriculture.Ghanaian Journal, 2010. 17 dead after dam spill in neighbor nation. http://www.theghanaianjournal.com/2010/09/10/17
- de Condappa, D. Chaponniere, A. and Lemoalle, J., 2009. A decision support tool for water allocation in the Volta basin. Water International, 34, 71-87.
- FAO, 2004., Ghana Fishery Profile: http://www.fao.org/fi/fcp/en/GHA/profile.htm
- Dapaah-Siakwan and Gyau-Boakye, 2000 Dapaah-Siakwan, S. and Gyau-Boakye P., 2000. Hydrogeologic framework and borehole yields in Ghana. Hydrogeology Journal 8, p. 405-416.
- Environmental Protection Agency, 2004 Environmental Sensitivity Map for Coastal Areas of Ghana, Volume I – Atlas, UNOPS-UNDP. Accra, 82p.
- Easterling III, W. E., Brian, H. H., Hurd, H. and Smith, J. B., 2004. Coping with Global Climate Change. Pew Center on Global Climate Change report, 52p.
- Engineering News, 2010., http://www.engineeringnews.co.za/article/africas-
- Glowa Volta Project, 2007. Partners Capacity Needs Assessment Workshop, June 2007, Accra, Ghana
- GLOWA Volta 2008 www.glowa-volta.de/population.html
- Gordon C. and Amatekpor, J. K.(eds), 1999. The Sustainable Integrated Development of the Volta Basin in Ghana. Volta Basin Research Project.

- IEEE, 2010. A Blueprint for Water for the World: Pathway for a Blue Revolution, 52p
- IPCC, 2008. Climate Change and Water Resources. Technical Paper V.
- IWMI, 2009 – Water Policy Brief No. 31, 8p.
- IUCN, UNEP and WCMC, 1992. A Directory of African Wetlands, 807 p.
- IUCN/PAGEV, 2005. Pre-water Audit for the Volta River Basin, West Africa, Ouagadougou, 54p.
- IUCN/PAGEV, 2007. Water Audit of the Volta Basin, Ouagadougou, 79p.
- Kouassi, A. M. and Biney C. A., 1999. Overview of the marine environment problems of the West and Central African region. *Ocean & Coastal Mangt.* 42, 71-76.
- Laube, W., Leemhius, C. and Amisigo, B., 2008. Impact of Climate Change on the Black Volta Basin and the Bui Dam. GLOWA Volta Policy Brief. Bonn, 3p.
- Lemoalle, J. and de Condappa, 2009. Water Atlas of the Volta Basin. Challenge program for Water and Food, Colombo and Institut de Recherche pour le Développement, Marseille, 96p.
- Lindou, P. L., 2008.Contribution à l'étude de la qualité des eaux de surface du bassin de la Volta au Burkina Faso: Diagnostic, suivi de la qualité et états des lieux des sources de pollution. M.Sc Thesis. International Institute for Water and Environmental Engineering, Ouagadougou
- Marchand, M. and Toornstra, F. H., 1986. Ecological Guidelines for River Basin Development. Centrum voor milieukunde Rijksuniversiteit Leiden, The Netherlands.
- Martin, N. and van de Giesen, N.,2005. Spatial distribution of groundwater production and development potential in the Volta River basin of Ghana and Burkina Faso. *Water International*. 30, 239-249.
- Niasse, M., Afouda, A. and Amani, A. (Eds.) 2001. Reducing West Africa's Vulnerability to Climate Impacts on Water Resources, Wetlands and Desertification. Elements for a Regional Strategy for Preparedness and Adaptation. IUCN Report, 88p.
- Sommen, J.J. van der and W. Geirnaert 1988. On the continuity of aquifer systems on the crystalline of Burkina Faso. In: I. Simmer (ed.), Estimation of Natural Groundwater Recharge, NATO ASI Series Vol.222, p.29-45.
- The World Bank, 2010. The Little Green Data Book 2010, Washington DC, 248 p.
- UNECA, AUC and AfDB., 2010. Science, Technology, Innovation and Capacity Building for Addressing Climate Change. 7th African Development Forum, Addis Ababa. Issue Paper No. 10, 6p.
- UNEP, 2010. Blue Harvest: Inland Fisheries as an Ecosystem Service. WorldFish Center, Penang, Malaysia, 68p
- UNEP-GEF Volta Project, 2010. Report of the Causal Chain Analysis workshop for the Development of the Transboundary Diagnostic Analysis (TDA) of the Volta River Basin *UNEP/GEF/Volta/RR 5/2010*
- UNDP, 2009 – Human Development Report. Overcoming Barriers: Human Mobility and Development, New York, 229p.
- Volta Basin Authority, 2009. Study on Pre-investment Programme for the Volta Basin Ouagadougou, 38p
- Volta Basin Authority, 2009. Strategic Plan 2010-2014, Ouagadougou, 35p.
- Water Resources Commission, 1999. Ghana Water Vision, 2025
- Water Resources Commission, 2008. Reoptimization of Operations of Akosombo and Kpong Dams on the Volta River in Ghana to Restore Downstream Livelihoods and Ecosystems and to Buffer the Effects of Climate Change. Accra, 28p.

Impacts of national and international actors on river basin management – case of River Rhine

Esra D. Bozkir[1], Jan Leentvaar[1,2,3], Ine D. Frijters[2] & Maarten A. Hofstra[1,2]

[1] UNESCO-IHE Institute for Water Education, Delft and
[2] Ministry of Infrastructure and Environment, the Netherlands

[3]Corresponding author, E-mail: j.leentvaar@unesco-ihe.org

[*] The authors would like to thank to Falk Schmidt for helpful comments and suggestions on earlier drafts of this paper.

Abstract

As a case of success in transboundary river regime development, the Rhine river case represents an example, where the actions of different actors played significant roles in shaping the transboundary river regime and making it function up to now. This paper provides an overview of the Rhine regime formation with an emphasis on cooperation among national and international actors involved in the process as the determinant of the success in regime formation. It aims to present key drivers for and features of the cooperation, which made the cooperation efficient and this regime unique. Even though behaviour of actors would vary and cooperation negotiations would follow a different path in other transboundary river cases, Rhine case may still serve as the example of an alternative approach which leads, for example, to the development of a sustainable river management plan at the end.

Keywords

Rhine regime, river management, knowledge dissemination, NGO's

Introduction

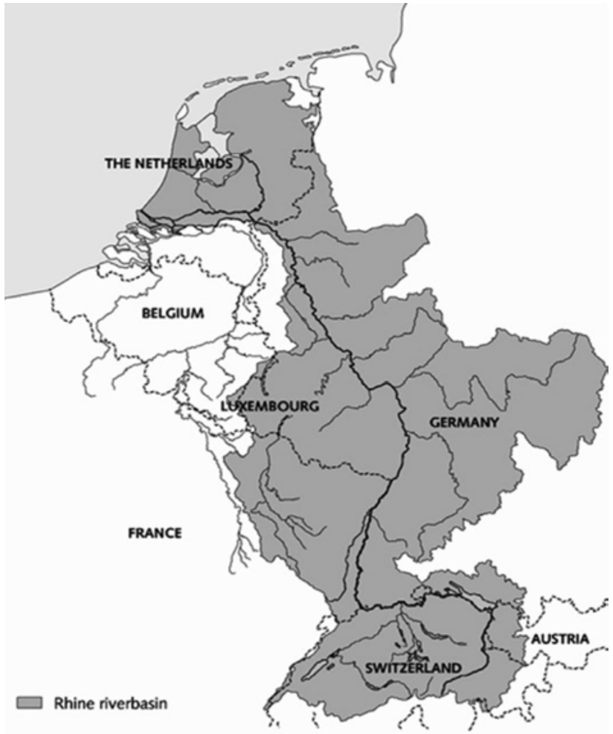
International governance of environmental resources is developed and also transformed under the influence of different groups. Two main groups of actors can be classified as states and non-state actors, where the latter one involves international organizations, the corporate sector, expert groups and the global environmental movement including civil society groups (O'Neill, 2009). The role and the level of influence of actors can vary in different cases. Even though the only decision-making authorities in democratic societies are the respective governments, other actors would make an impact and cause a change in the behaviour of decision-makers.

In this paper, we identify the main actors involved in the Rhine river basin and examine their respective role in shaping the regime. The regime is defined as "principles, norms, rules and decision-making procedures that govern state behaviour in specific issue-areas of international relations". In addition to the actor groups, the interaction and cooperation among them will also be addressed as an influencing factor in the process of regime building. Finally, a section of this paper links our findings with insights from international regime theories. The overall aim of this paper is not to measure the overall effectiveness of the Rhine river regime, but to put an emphasis on the role of efficient transboundary cooperation in solving river management problems.

Characteristics of the Rhine river basin

Although the Rhine is a relatively small river, it is one of Europe's best-known and most important rivers. Its length is 1,230 km, of which 880 km is navigable. From its source in Switzerland, the Rhine flows via France, Germany, and the Netherlands into the North Sea. The catchment area of 170,000 km^2 also covers parts of Italy, Austria, Liechtenstein, Luxembourg, and Belgium (Figure 1).

Figure 1. Rhine Basin



Physical and geographical situation

The Rhine river basin can be considered as representing four distinct river ecosystems. The High Rhine, upstream of Basel and located mainly in Switzerland, includes two important reaches of ecological importance, particularly with respect to the protection of reserves of international importance for fish and migratory birds.

The Upper Rhine reach is located between Basel and Bingen. Flood mitigation measures were initiated in the 1860s together with inland navigation. From 1930 onwards, several major hydraulic works were constructed, including eight barrages for hydropower, two storage dams, and dikes. This reach is the most important reach for the rehabilitation and protection of the alluvial areas along the Rhine. The alluvial areas of the Rhine comprise alluvial forests, wooded fringes near water bodies, reed plains with many stagnant pools, and water-filled swamps. They form complex habitats for many species of flora and fauna, which are difficult to restore once they are lost. This is why efforts are made to preserve the alluvial forests and meadows and to extend these areas to the recently created habitats.

The Middle Rhine is located between Bingen and Cologne. Its landscape, with the river, alluvial areas, and steep slope, is unique in the whole of Central Europe. The fifteen islands in the Rhine are among the areas of particular ecological importance. Alluvial forests or their remnants have survived only on those islands, which have already been placed under protection. Narrow strips of such forests exist in some bays in the valley.

The Lower Rhine consists of the lower river reach between Cologne and the German–Dutch border and the branches of the delta in the Netherlands. The lower river reach covers major cities and industries, for which major flood control works were constructed around 1900. The delta is a major floodprone area with potential flood damage up to €1,100 billion, when the river discharge exceeds the channel capacity.

Since the Rhine has become a navigable waterway and flood control measures have been taken, such as the construction of dikes along the Upper and Lower Rhine, large stretches of floodplains have been lost. Along the Upper Rhine, the loss of alluvial areas has reached dangerous proportions. Between 1955 and 1977, more than half of the former flooding zones along the Upper Rhine were protected against inundation and are now inhabited and used for farming. Consequently, the habitats of animal and plant species depending on the alluvial areas have been reduced drastically. These radical measures increased the sensitivity of the Rhine ecosystem to disturbances.

Table 1. Spatial variations in the functions of the Rhine catchment area

	Switzerland	France	Germany	Netherlands
Drinking water			x	x
Process water	x	x	x	x
Irrigation				x
Hydro-power	x	x		(x)
Amenity	x		x	x
Fishing water				x
Navigation	x	x	x	x
Sewer	x	x	x	x

(After Dieperink, 1997)

Functions

There are significant differences in the spatial variation in the functions of the Rhine catchment area (see Table 1 for the states along the main flow of the Rhine). The Rhine is Europe's most densely navigated shipping route, connecting one of the world's largest seaports, Rotterdam, the Netherlands, with the world largest inland port, Duisburg, Germany. Vast industrial complexes are built along the river, for example the Ruhr, Main, and Rijnmond areas. Most of Europe's important chemical production plants can be found along the Rhine.

Rhine water is used for industrial and agricultural purposes, for energy generation, for the disposal of municipal wastewater, for recreational activities, and for the production of drinking water for more than 20 million people. Furthermore, the Rhine is a natural habitat for a diversity of plant life and many birds, fish, and other species. All these interests are represented by different group of actors.

Obviously, so many different claims on the river inevitably lead to conflicts or problems: water quality problems, problems in river ecology, and high water problems.

Historical, political, and economic characteristics of the basin

The Rhine riparian states have a common historical background. Throughout history parts of the Rhine River have functioned as the border between states. The Rhine regions are connected through several conflicts, part as aggressor and part as conquered region. Some Rhine regions were hard-hit by violent conflict, especially in Alsace-Lorraine.

Historically, the development of the states has been unique but along the same lines. There are differences in culture, but the major values are comparable. The Rhine itself was hardly the object of violent clashes, although the river was of importance to ensure a

Table 2. Socio-economical data of Rhine states

	Inhabitants	GNP	Per capita in $	Language
Austria	8.1 M	191 B	25,220	German
Belgium	10.3 M	231 B	24,630	French/ German
France	58.9 M	1.3 T	23,670	French
Germany	82.0 M	1.9 T	25,050	German
Italy	57.7 M	1.1 T	20,010	Italian
Liechtenstein	32000			German
Luxembourg	438000	18.6 B	44,340	French/ German
Netherlands	16.0 M	364.9 B	25,140	Dutch
Switzerland	7.2 M	7.2 B	38,120	French/ German

Note: M = Million, B = billion, T= Trillion
Source: Data from World Bank, 2000.

safe border against aggressive neighbouring states and as a major shipping route.

All states are democracies and have developed to a similar level economically (Table 2) and technically.

As seen from Table 2, there is considerable similarity in development between the countries. One other similarity, with the exception of Switzerland, is that all states are member states of the European Union. This means that European Law and regulations bind all but one country.

Development of the cooperation in the Rhine river basin

To explain the processes of cooperation, negotiation, and mediation from a historical perspective is no easy task in this region. There are many examples of cooperation between states or regions; in historical times alliances between states to oppose an aggressive third party were preferred.

In historical times, negotiation was widely used all over Europe. Much of this was because of the existing royal families and their policies that, for the most part, dealt with exchanging land for dynastic purposes through marriage or giving land in order to appease a neighbouring aggressor state.

When negotiation did not bring the preferred outcome, a third monarch sometimes was asked to mediate.

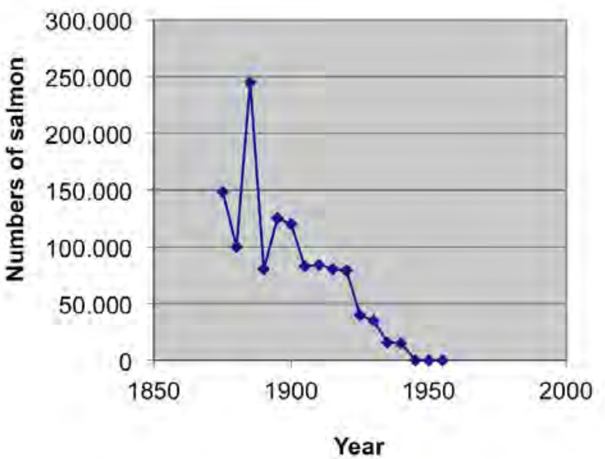
Before 1986

Negotiations among riparian states of the Rhine River concerning different uses of the Rhine date back to the 19th century. The first attempts of cooperation between countries emerged as a response to basic economical interests of the nations. The importance of shipping on the Rhine for the economies of riparian countries brought them together to reach an agreement on navigation rights along the length of the river. In 1815, Central Commission for Navigation on the Rhine (CCR), which is the oldest functioning river commission in the world, was created to ensure free navigation for all riparian states. CCR has the main task of maintaining a uniform legal regime governing navigation along the full length of the river. The delegation of each member state is composed of four representatives and two substitutes. Committee resolutions are made unanimously, thus, each member state has de facto a right of veto. By rotation, each member state chairs the committee for a period of two years. Once decisions are approved by the committee, they become legally binding for all members.

Another important economic activity of the Rhine region, salmon stocks, required international action to prevent over-fishing from the early times of 19th century. The Salmon treaty, which aimed sustaining salmon stocks, has been finalized in 1885. However, canalization of the river for navigation with hydropower generation and industrialization have caused a severe decline in water quality. The effect was a decrease in and in the end an elimination of salmon population in the Rhine (Figure 2) (Mostert, 2009).

Increasing pollution of the Rhine starting from early 1930s, especially the salt discharge from French potassium mines, was a serious threat to the drinking water supply and horticulture needs of the Netherlands. The initiatives of the Dutch drinking water sector to solve this issue could not be brought to a conclusion due to economic recession and the political situation in Europe, which led up to the Second World War (Mostert, 2009). Directly after the war, the Dutch government attempted to raise the topic of pollution in the Rhine for an international cooperative approach with other riparian states (Verweij, 1999). As a response to these efforts of the Dutch government, in 1950, the International Commission for the Protection of

Figure 2. Number of salmon in the Rhine



the Rhine against Pollution (ICPR) was created by Switzerland, the Federal Republic of Germany, France, Luxemburg, and the Netherlands. The Commission became formal with the Berne Convention, which was signed in 1963. The ICPR with its independent secretariat was assigned to act as a coordinating body for monitoring the nature and proposing measures for the protection of the Rhine against pollution (Bernauer et al., 1996). However, the Berne Convention did not transfer any legislative power to the ICPR, so the commission was not able to enforce any rules or sanctions. Before further steps were taken by the ICPR in terms of strengthening scientific cooperation another platform, the International Commission for the Hydrology of the Rhine, was established in 1970, following the advice of UNESCO. The Commission's aim has been to promote regional scientific cooperation in order to develop hydrological measures and forecasts in the entire Rhine river basin.

The next step in development of the cooperation has occurred in 1972, when the first conference of Rhine ministers was held in the ICPR. Involvement of ministers set the stage for discussing threshold values of polluters in an institutionalized manner (Bernauer & Moser, 1996). It brought two new treaties to the agenda of the ICPR. The chloride issue, which dated back to 1930s, finally became a formal treaty in 1976. Additionally, the Rhine Chemicals Treaty, which addressed the discharge of dangerous chemical substances, was also signed in the same year. However, both conventions have failed in the ratification and implementation processes due to the conflicting national interests of the riparian states, which even led to a diplomatic crisis between the Netherlands and France in 1979.

Decisions that were taken to solve the chloride issue were based on the reduction of the chloride load by injection into the subsoil with an agreement on technical and financial aspects (Dieperink, 2010). The Chloride Convention was ratified by the Netherlands, Germany and Switzerland within two years. However, demonstrations of environmental groups and local authorities in the Alsace region, which were concerned about the potential harm of the subsoil chloride load for their groundwater resources, forced the French government to step back and not ratify the convention. As a result of this decision, the Netherlands protested the decision of France by recalling the Dutch ambassador in Paris. Even though France ratified the convention in 1983 after a change of government, the issue of chloride pollution remained unresolved until 1986. However, the developments after the ministers' involvement added a new layer to the transboundary cooperation. Most importantly, information exchange between riparian states accelerated. As an advantageous outcome of this information flow, mutual understanding between nations regarding their perception of Rhine pollution and views about technical solutions of the problem started to be built up (Bernauer & Moser, 1996).

Up to 1986, in addition to interstate negotiations on the process of Rhine cooperation, non-state actors also appeared at the stage and first raised their voices to influence the decisions of their respective governments. They played significant roles on issues related to water quality such as in the case of Alsace public protests against Chloride Convention.

Starting from the early 1970s, interest groups in the Netherlands have begun to raise their voices against the pollution of the Rhine, since they rely heavily on Rhine water for the drinking water supply and irrigation. In addition to that, drinking water companies from the entire region unified at the Rhine catchment level under the umbrella of the international association of waterworks in the Rhine basin (IAWR). Through publishing reports on policy statements and the convening of conferences, the IAWR aimed to raise public awareness on the pollution of the river (Dieperink, 2000). Additionally, the IAWR published annual reports on the water quality of the Rhine.

On the side of non-governmental activities, Reinwater, the Dutch Clean Water Foundation collaborating with horticulturists from the West region of the Netherlands initiated legal procedures against potassium mines, which damaged the plants with the high salt loads. At the end these efforts have given positive results and the horticulturists actually received financial compensation from the potassium mines (Dieperink, 1998). In addition, local media has played an important role in increasing public attention on this issue.

Even though several cooperation attempts had been made and inter-state negotiations had been carried out until 1987, the process was quite slow and the results were not very effective in terms of reaching a consensus for the protection of the river. The pollution level of the Rhine was decreased by the year 1985 (Figure 3), however, this pollution reduction was not a result of cooperative action, instead, it was riparian countries' own efforts to control the pollution within their own jurisdiction.

1986 – Turning point for Rhine cooperation

The trigger for a new impulse in transboundary cooperation in the Rhine case was the Sandoz accident at an industrial area in Basel at the Swiss-German border. In November, 1986 a fire at the Sandoz chemical storehouse, which contained pesticides, dyes and various raw and intermediate materials, caused hazardous chemicals flown into the Rhine through fire fighting water (Giger, 2009). Massive fish deaths and damage to the aquatic life in the downstream region were among the severe consequences of this accident. Surface water intake for drinking water purposes had to be closed down.

As it is already cited in the literature (Verweij, 1999; Frijters & Leentvaar, 2003), a shift in policy practices may require such a shock in the form of serious accident. The disaster that the Sandoz accident caused opened the way to accelerate the negotiation process among riparian states in order to rehabilitate the water quality of the Rhine. The steps that were taken after this point were actually what made this regime unique.

The Sandoz accident had high publicity through media coverage and environmental groups' demonstrations. The responsible ministries were involved in the negotiation process on how to clean up the river thoroughly. Directly after the accident occurred, ministries of riparian states came together at a Rhine Ministers conference to discuss the Rhine pollution issue. Verweij (1999) further points out that another condition of policy shifts is the presence of policy entrepreneurs who use the political space created by the occurrence of shocks to have alternative policy approaches adopted. In the Rhine case this figure has been the Dutch Minister of Water Management, Ms. Neelie Kroes. She introduced the idea of creating an action plan with an aim of bringing back the salmon in the Rhine by the year 2000. Even though the aim of the proposed action plan was seen ambitious and hard to achieve, it became the slogan for the improvement of the river, which also motivated several interest groups in taking actions.

After 1986

The Rhine Action Programme (RAP) had many outstanding features compared to other traditional international agreements. First of all, the programme was not formal and it was non-binding. It was the initiative of the Dutch minister to hire a private consultant team in order to outline an international agreement on the protection of the Rhine basin and to build up the necessary intergovernmental support for this programme (Verweij, 1999). Another important feature of the final report of the consultant team, which was turned into Rhine Action Programme by the governments at a Ministerial Rhine Conference at the end of 1987, was that there were a limited number of goals to be achieved.

The identified goals to be reached by the year 2000 were as follows:

» The ecosystem of the Rhine should be improved to such an extent that higher species, such as salmon, would again become indigenous.

» The production of drinking water from the Rhine had to be guaranteed for the future.

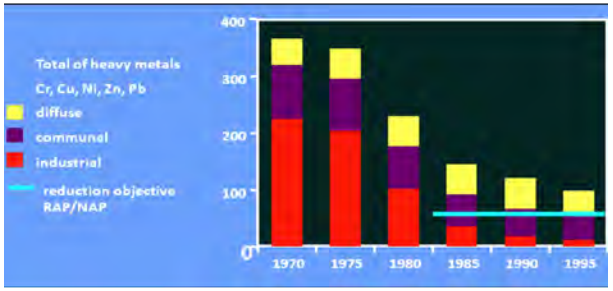
» The pollution of river sediments had to be reduced to such an extent that sediment could at any time be applied on the land or dumped into the sea without negative consequences for the aquatic environment.

» An improvement in the protection of the North Sea was necessary.

In order to achieve these goals, the ministers decided to implement some demanding activities such as 50 % emission reduction by 1995 compared to 1985 for 43 substances and groups of substances ("Reduction objective RAP/NAP". See Figure 3). However, the means of implementation of these activities were not specified within the report, instead, "the best available technology (BAT)" is fixed for those industrial branches whose wastewater has a considerable influence on the quality of the Rhine. Following such a flexible but pragmatic approach enabled government officials to concentrate fully on how to clean up the Rhine and get away from the legal formalities, and defending their national interests and regulatory approaches (Verweij, 1999).

The implementation of the Rhine Action Programme has proven to be very successful. Measures have been taken all along the river to prevent pollution, and in 1994 the ICPR could report that most of the reduction goals had been reached. In the field of industrial sources the 50 % target had almost completely been met. For instance for heavy metals the reduction by the industry was far more than 50%. However, since it was not easy to identify and reduce heavy metal

Figure 3. Heavy metal load on surface water (tons/year)



loads coming from communal and diffuse sources, reduction rates of these polluters did not reach the 50% target (see Figure 3).

The most challenging goal and actually the slogan of the action programme, involved improving the Rhine ecosystem to such an extent that migratory fish species, such as salmon, can return to their spawning grounds and become indigenous again (Wieriks et al., 1997). Even though this objective required costly actions, such as building fish passages around dams and weirs and hatching fish eggs in special hatcheries, the goal has been achieved by the individual member states with the financial support of the European Commission. The salmon and sea trout returned to the River Rhine.

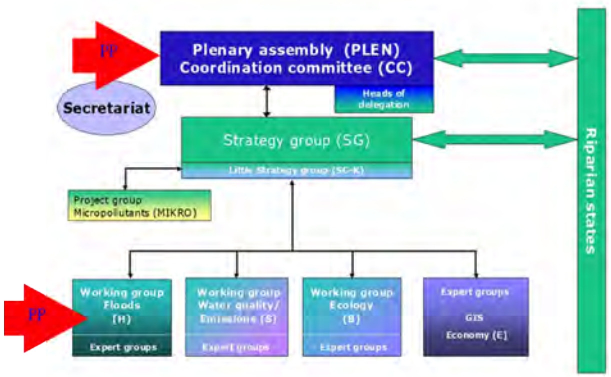
It is clear that the RAP was effective in several respects. In addition to increasing the rate of information flow, it also introduced clear reference points for all parties by setting pollution reduction targets with defined time-frames and elaborating BAT recommendations. Furthermore, the non-binding nature of the RAP accelerated agreement and made it possible to get quick results in terms of BAT recommendations (Bernauer et al., 1996).

Another issue, which has been brought up to the agenda of the ICPR in 1990s was the flooding of the Rhine. The occurrence of extremely high floods in the middle and lower Rhine regions in 1993 and 1995, which caused evacuation of inhabitants, triggered the idea of further integration of the Rhine river management, as well as additional political commitment (Wieriks et al., 1997). On the basis of the very positive results of the Rhine Action Programme, the ministers involved charged the ICPR with the development of an international action plan to control flooding. The Action Plan on Flood Defense for the Rhine was adopted at the 12th Ministers Conference in 1998. The key concept of the plan, in addition to dyke reinforcement, is to lower peak water levels by decreasing peak discharges and creating more room for the river (Mostert, 2009). In 2005, the first balance was drawn within the implementation of the Action Plan on Floods (1995-2005). It reveals that almost all measures planned until 2005 have been implemented effectively and successfully at the costs estimated (ICPR, 2010).

The Action plan on floods was conceived in phases and implemented as a part of the new Rhine Action Programme, "Rhine 2020". Given that the RAP was planned to end in 2000, a new action programme, which would replace the former RAP was required. Rhine 2020 was adopted in 2001 as the "Programme on the Sustainable Development of the Rhine". It aimed to determine the general objectives of Rhine protection policy and the measures required for their implementation for the next 20 years, including measures for flood mitigation, water quality improvement and groundwater protection. Salmon 2020 was also included to the new programme with the aim of sustaining salmon population in the Rhine. Parallel to Rhine 2020 programme, there were other developments at the Rhine and also at the European level.

As a result of the extended scope of activities, the ICPR necessitated drafting a new treaty, which would allow it to extend its scope of activities and replace the former Berne Treaty, which was based on cooperation in the Rhine against pollution. The new treaty, named as "The Convention on the Protection of the Rhine", was signed in 1999 and took effect in 2003 as the new basis for international cooperation in the Rhine basin. At the same time, the EU was in the process of finalising a new Water Framework Directive (WFD). With the aim of implementing comprehensive water protection in the European river districts, the new WFD was adopted in 2000. In order to achieve good water status in all European basins by the year 2015, the WFD includes precise guidelines and schedules for the implementation.

Figure 4. Public participation in ICPR structure



From 1976 on, the EU has become a member of the ICPR. However, during the first decades its role in the Rhine management was relatively small. From 2000 onwards the importance of the EU has increased, since member states are obliged to report to the EU on their progress of the WFD implementation.

The action programme of "Rhine 2020" also implements requirements of the WFD as well as the Swiss water policy in the Rhine basin, as Switzerland is not a member of the EU (ICPR, 2010).

Another important aspect of the international cooperation, the involvement of NGOs, was also addressed more concretely during the same time period as a result of the new treaty. Starting from 1996, NGOs found their way to get involved to the work of the ICPR as observers, external experts or as a member of a national delegation. The number of recognized NGOs has increased and reached to seventeen in the past ten years. As shown in Figure 4, public participation through involvement of NGOs can be carried out in two stages of ICPR structure. The influence of the public participation by NGOs is most substantial on the level of the permanent working groups, as on that level the NGOs can include their scientific knowledge into the reports written by the working groups. At a later stage, the strategy group and the plenary assembly approve reports and conclusions. At this level, NGOs cannot make a major influence on the work of the ICPR anymore.

More recently, in 2007, the EU Directive on the Assessment and Management of Flood Risks, which entered into force 26 November 2007, aims at reducing and managing negative impact of floods on human health, the environment, cultural heritage and economic activities (ICPR, 2010). Accordingly, to respond to the requirements of the EU, the 14th conference of Rhine Ministers in 2007 charged the ICPR to equally support the co-ordination of the implementation of the Floods directive in the Rhine river area on the basis of the work done so far (ICPR, 2010).

The historical evolution of the Rhine regime can be seen as a success of constructive cooperation. However, attributing this success to one or another dynamic of the system would not be very easy. Mostert (2009) claims that the Rhine Action Programme and its more business-like approach do not constitute a complete explanation of the water quality improvement in the Rhine river and that other interconnected factors such as the EU and its binding directives, domestic legislation, the activities of environmental NGOs and the waterworks in the Rhine basin, growing environmental awareness, technological innovation and changes in the structure of the industry in the basin, should be taken into account while drawing lessons from the example of the Rhine regime. In order to have a summarized picture of the actors involved and their relative scales (bold) of impact in various stages of Rhine regime can be seen in Table 3.

At this point, the success story of the river Rhine should be linked, briefly, with theories explaining the emergence of international collaboration. As this collaboration is often fostered and institutionalized by international regimes, this line of analysis, i.e. regime theory, has contributed a lot to understanding of such processes. This step should provide a brief analysis of the Rhine case, based on literature that lays out at the same time the basis for potential future work.

Table 3. Actors and their impacts on the Rhine regime

1950 – 1970	1970 – 1986	1986 – 2000	2000 – present
The Netherlands Germany France Luxembourg Switzerland	**The Netherlands** **Germany** **France** **Luxembourg** **Switzerland** EU IAWR Reinwater Other NGOs and IGOs	**The Netherlands** **Germany** **France** **Luxembourg** **Switzerland** **EU** NGOs IGOs Other basin states	**The Netherlands** **Germany** **France** **Luxembourg** **Switzerland** EU NGOs IGOs **Other basin states**

Theoretical aspects of the Rhine cooperation

Theories of international relations have addressed at some length the emergence of international collaboration, using transboundary water management more often than not as case studies (Haggards et al., 1987; Levy, Young, Zürn, 1995; Hasenclever et al., 1996; Lindemann, 2006). These theories are usually divided into power-based, interest-based, or knowledge-based approaches. The schools of thought that are linked to these theories are neoliberalism, realism and cognitivism in their respective order. Lindemann (2006) specifically applies these theories into water regime formation.

Power-based approaches assume that a hegemon state is a necessary condition for the formation of international regimes, which is explained as "hegemonic stability theory" (Haggard et al., 1987, p.500). It is further claimed that the strength or the effectiveness of regimes decline when power distribution between the members of the regime becomes equal (Hasenclever et al., 1996). However, the Rhine case clearly indicates that this theory is not able to explain the reasons behind the formation of Rhine regime and it does not reflect the nature of cooperation in the Rhine. Even though the Dutch government played a significant role in shaping the regime, it would be hard to identify the Netherlands' position as a hegemon state.

The second approach, interest-based arguments (neoliberal approach) claim that international regimes arise when self-interested parties approach a problem within the frame of contractualism and coordinate their behaviour to gather shared gains (Lindemann, 2006). This neoliberal approach develops often ideas from economic theories of institutions that focus on information and transaction costs (Hasenclever et al., 1996). There are two main approaches of neoliberal regime theory, which are contructualism and situation-structuralism. Referring to the leading work of Robert Keohane (1989) in this area, Hasenclever (1996) states that contructualist theory operates under a specific situation precondition: the states active in a particular issue-area must share common interests that can be attained only through cooperation. Contructualist theory argues that regimes facilitate cooperation by providing states with information or by reducing their information costs. Hence, under such circumstances, states have an incentive to cooperate in order to gain this extra payoff as a result of this cooperation. On the other hand, situation-structuralism theorists draw attention to the nature of situations, which can be influential when states make choices about cooperation (Hasenclever, et al., 1996).

Under the main umbrella of interest-based theory, Lindemann (2006) indicates the ways of achieving cooperation as: 1) the improvement of information exchange and the promotion of confidence; 2) embedding the conflict in a positive interactive complex; 3) the creation of package solutions by constructing linkage strategies 4) the use of arbitration, mediation and intervention.

The Rhine case and particularly the creation of the ICPR provide empirical evidence to these interest- based theoretical assumptions. The Chloride and Chemical Conventions of 1976 could be examples of situation-structuralist approach. However, when we consider that these agreements could not reach a fruitful end, we would come to the conclusion that even this approach was part of an effective regime building process in the Rhine; it was not able to sustain the continuity of cooperation. Again from the evidence it would be inferred that the Netherlands adopted a strategy, which introduced new knowledge to the other riparian states, in order to lower information costs in form of uncertainty. In addition, the information on water quality, which was disseminated by the water supply firms, reduced the complexity in demonstrating the existing levels of pollution (Lindemann, 2006). However, interest-based theories still lack to provide an overall explanation for the cooperative action of riparian states in the case of Rhine Action Programme. At this stage, knowledge-based theories could help us to understand further the strong bounds built in the Rhine with the Rhine Action Programme.

The knowledge-based theories arose as a result of a dissatisfaction with aforementioned theories and argue that knowledge itself play a significant and independent role in the formation of international regimes (Lindemann, 2006). These theories, so-called cognitivism, assume that international cooperation is affected by perceptions (and misperception) of the actors, the capacity to process information and learning; therefore, cognitivists claim that this approach would provide an important insight in explaining the content of regime rules and how they evolve (Haggard et al., 1987).

The Rhine case was also an example of a transboundary cooperation, which is largely affected by the institutionalized exchanges of information among government authorities involved in implementing environmental standards. Increasing knowledge also increased their capacity on finding solutions for pollution reduction (Bernauer & Moser, 1996).

Furthermore, another insight from cognitive approaches would help to place and understand the role of ICPR within the Rhine regime. Building on the basic idea that knowledge must be shared by policy makers in order to make an impact on regime formation, international relations scholars introduced epistemic communities as "channels through which new ideas circulate from societies to governments as well as from country to country" (Haas, 1992). Lindemann (2006) states that "epistemic community reduces uncertainty and influences the options considered in the formation of international regimes by developing a common set of interpretations and establishing a relatively independent source of scientific evidence".

In this respect, when we divide the evolution of ICPR into two time spans, before and after ministers' involvement in 1972, we could see that the role of the ICPR in the first period had been fuzzy in terms of influencing the behaviour of riparian states through information exchange. However, in the latter time span, the ICPR became particularly effective in performing the functions Haas (1992) has captured under the term "epistemic communities" such as international information flow and change in perceptions.

In addition to these theoretical approaches, Lindemann (2006) is sensitive to context-specific variables for the emergence of international collaboration in river basins and he lists other influential conditions in the Rhine cooperation evolution. In fact, case-specific factors such as the European integration process and the Sandoz accident were important determinants of the success of Rhine regime.

Conclusion

In this paper we attempt to address the national and international actors and their respective roles in shaping the Rhine regime. In this respect, the analysis pictured us several individual and interlinked actions, which aimed to foster cooperation in the Rhine and develop more sustainable river regime.

The nature of the problem in the Rhine basin was not related to an international conflict on water allocation or water use; it was about the increased pollution, which threatened the biodiversity in the river, the drinking water supply and the horticulture of downstream countries. Therefore, in theoretical terms, we were unable to make a link between success of Rhine regime and power-based, hegemonic stability approaches of international relations theories. Rather, the success story of Rhine cooperation was an outcome of several different conditions, which are peculiarly combined in the Rhine case. The prominent condition of successful Rhine regime could be attributed to the knowledge dissemination and mutual understanding and trust among riparian states, as well as the interest of riparian states in improving water quality for their own benefits and image in the international arena. In this respect, establishment of the ICPR and its function as a learning facilitator has formed the grounds of both knowledge-based and interest-based cooperation actions.

However, drawing general conclusions from the Rhine case as a success story of international cooperation needs to consider other factors as background conditions. The triggering Sandoz accident, the EU involvement in the process and the high level of socio-economic development of all riparian states were some of those factors. In the case of "best available technology" recommendations, it was clear that the application of these recommendations required economic strength to cover the costs. Furthermore, the introduction of EU directives has established concrete rules, brought a legal overarching status and has been an impetus for continuity of Rhine cooperation, in which the very much knowledge- and learning-focused work of the ICPR is embedded.

Even though it is hard to measure the exact level of impacts that each actor had on the process of Rhine regime development; we would mention that beside the EU, riparian states and their respective ministers; water supply companies and environmental NGOs played significant roles in shaping the Rhine regime. The main point in the Rhine regime formation is that it has not been the success developed only by the efforts of states or individual groups, but the success arose as a result of interaction between states and other non-state actors.

Bibliography

- Bernauer, T. & Moser, P., 1996. *Reducing Pollution of the Rhine River: The Influence of International Cooperation*. IIASA, WP-96-7.
- Bernauer, T., 2002. Explaining success and failure in international river management. *Aquatic Sciences*, 64, 1-19.
- Dieperink, C., 1998. From open sewer to salmon run: lessons from the Rhine water quality regime. Water Policy, 1, 471-485.
- Dieperink, C., 2000. Successes in the International Cooperation in the Rhine Catchment Area. *Physics and Chemistry of the Earth*, 25 (3), 341-347.
- Dieperink, C., 2010. International water negotiations under asymmetry, Lessons from the Rhine chlorides dispute settlement (1931 – 2004). *International Environmental Agreements: Politics, Law and Economics*.
- Frijters, I. D. & Leentvaar, J., 2003. Rhine Case Study. UNESCO-IHE. 42 p.
- Haftendorn, H., 2000. Water and International Conflict. *Third World Quarterly*, 21 (1), 51-68.
- Giger, W., 2009. The Rhine red, the fish dead - the 1986 Schweizerhalle disaster, a retrospect and long-term impact assessment. *Environmental Sciences and Pollution Research*, 16 (1), 98-111.
- Haas, P. M., 1992. Introduction: Epistemic communities and International Policy Coordination. *International Organization*, 46 (1), 1-35.
- Haggard, S. & Simmons, B. A., 1987. Theories of International Regimes. *International Organization*, 41(3), 491-517.
- Hasenclever, A., Mayer, P., Rittberger, V., 1996. *Mershon International Studies Review*, 40(2), 177-228.
- Hofius, K., 1991. Co-operation in Hydrology of the Rhine Basin Countries. *Hydrology for the Water Management of Large River Basins (Proceedings of the Vienna Symposium, August 1991*). IAHS Publ. no. 201.
- ICPR, 2010. European Water Framework Directive. ICPR:Koblenz, <http://www.iksr.org/index.php?id=111&L=3> (accessed 27.11.10)
- ICPR, 2010. Action Plan on Floods. ICPR:Koblenz,<http://www.iksr.org/index.php?id=123&L=3> (accessed 27.11.10)
- Levy, M., Young O. R., Zürn M, 1995. The Study of International Regimes. *European Journal of International Relations*, 1, 267-330.
- Lindemann, S., 2006. Water Regime Formation in Europe. A Research Framework with Lessons from the Rhine and Elbe River Basin. Edited by Forschungsstelle für Umweltpolitik. Berlin: FU Berlin.
- Keohane, R. O., 1989. Neoliberal Institutionalism: A Perspective on World Politics. In International and State Power: Essays in International Relations Theory, edited by Robert O. Keohane, 1-20. Boulder: Westview Press.
- Kliot, N., Shmueli, D., Shamir, U., 2001. Institutions for management of transboundary water resources: their nature, characteristics and shortcomings. *Water Policy*, 3, 229-225.
- Mostert, E., 2009. International co-operation on Rhine water quality 1945 – 2008: An example to follow? *Physics and Chemistry of the Earth*, 34, 142-149.
- O'Neill, K., 2009. *The Environment and International Relations*. NY: Cambridge University Press.
- Van der Keur, P., Henriksen, H. J., Refsgaard, J. C., Brugnach, M., Pahl-Wostl, C., Dewulf, A., Buiteveld, H., 2008. Identification of Major Sources of Uncertainty in Current IWRM Practice. Illustrated for the Rhine Basin. *Water Resources Management*, 22, 1677-1708.
- Verweij, M., 1999. A Watershed on the Rhine: Changing approaches to international environmental cooperation. *GeoJournal*, 47, 453-461.
- Wieriks, K. & Schulte-Wülwer-Leidig, A., 1997. Integrated water management for the Rhine river basin, from pollution prevention to ecosystem improvement. *Natural Resources Forum*, 21(2), 147-156.
- Wolsink, M., 2006. River basin approach and integrated water management: Governance pitfalls for the Dutch Space-Water-Adjustment Management Principle. *Geoforum*, 37, 473-487.
- Zeitoun, M. & Warner, J., 2006. Hydro-hegemony – a framework for analysis of trans-boundary water conflicts. *Water Policy*, 8, 435-460.

Impacts of the governmental water policy on land use and streamflow in the arid Heihe River watershed, Northwest China

Changsheng He[1,2], LiFu[2], Yi Luo[3], Lanhai Li[4], Carlo Demarchi[5] & Ninglian Wang[6]

[1] *Center for Dryland Water Resources Research and Watershed Sciences, Key Laboratory of Western China's Environmental Systems (MOE), Lanzhou University, Lanzhou 730000, China.*

[2] *Department of Geography, Western Michigan University, Kalamazoo, Michigan 49008-5424, U.S.A.*
E-mail: he@wmich.edu

[3] *Institute of Geographic Sciences and Natural Resources Research Chinese Academy of Sciences, Beijing 100101, China.*
E-mail: luoyi.cas@gmail.com

[4] *Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, P.R. China.*
E-mail: lilh@ms.xjb.ac.cn

[5] *Department of Geological Sciences, Case Western Reserve University, Cleveland, Ohio 44106-7216, U.S.A.*
E-mail: carlo.demarchi@case.edu

[6] *Cold and Arid Regions Environmental and Engineering Research Institute, The Chinese Academy of Sciences, Lanzhou 730000, P.R. China.*
E-mail: nlwang@lzb.ac.cn.

Abstract

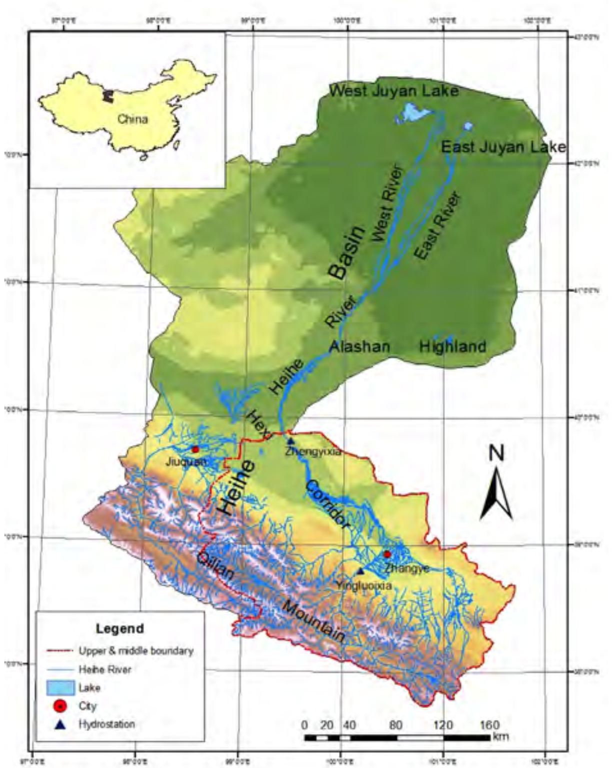
Increasing withdrawals of water for large agricultural irrigation, growing industrial development, and rapid urbanization have depleted much of the river flows downstream in the arid Heihe River Watershed, Northwest China, causing shrinking oases, accelerating desertification, and intensifying water tensions among different jurisdictions and ethnic groups. In 1997, The State Council of China issued an executive order to mandate the release of the required amounts of water downstream for rehabilitating the endangered ecosystem in the lower reach of the Heihe Watershed. This paper adapts the Distributed Large Basin Runoff Model (DLBRM) to the Heihe Watershed for understanding the distribution of glacial/snow melt, groundwater, surface runoff, and evapotranspiration in the upper and middle reaches of the watershed, and for assessing the impacts of the water allocation policy by the State Council of China on the land use pattern and streamflow of the Heihe Watershed. The results of the simulated daily river flows of the 1990-2008 show that Qilian mountain in the upper reach area produces most runoff in the Heihe watershed, and implementation of the water allocation mandate of the State Council of China has led to significant changes in the crop pattern, i.e. reduction of rice paddy area and expansion of wheat and corn areas in the middle reach, and increased streamflow to the lower reach.

Keywords:
Distributed Large Basin Runoff Model, (DLBRM), Heihe Watershed in Northwestern China, Water Allocation, and Land Use/Cover Change.

Introduction

Dry lands, including arid, semi-arid, and areas that are characterized by scarce and unpredictable precipitation, account for approximately 41 percent of the global land surface and are home to nearly 2.5 billion people (Reynolds et al. 2007). During the past few decades, however, improper water resource management has resulted in numerous problems worldwide, including poor food security, increased human diseases, conflicts between different users, limitations on economic development and human welfare, desertification, salinization, sand storms, water pollution, and so forth (United Nations World Water Development Report 2003; Reynolds et al. 2007). In China, the increased withdrawals from the upper and middle reaches of the Yellow River depleted groundwater in much of the basin and contributed to desiccation (i.e. no measurable flow in the river) of the lower reaches in 22 of the years between 1972 and 2000. This desiccation has created serious economic and environmental problems throughout North-Central China, including water rationing, under-capacity industrial production, educed crop yields, water pollution, wildlife habitat depletion, coastline recession, and sea water intrusion (He et al. 2005). In arid Northwest China, irrigated farming accounts for more than 80 percent of total water usage. Over the past few decades, the increased withdrawals for agricultural irrigation in the Hexi Corridor of the Heihe River Watershed (the second largest inland river or terminal lake in the nation, with a drainage area of 128,000 km2) since the 1970s have depleted much of the river flows to the lower reach, shrinking the East Juyan Lake and drying up the West Juyan Lake, endangering aquatic ecosystems, accelerating desertification, intensifying water conflicts between the middle reach of Gansu Province and lower reach of the Inner Mongo-

Figure 1. Map of the Heihe Watershed



lian Autonomous Region (IMAR), and damaging relationships among Han, Mongolian, and Hui ethnic groups (He et al. 2009) (Figure1). To mitigate the water conflicts and rehabilitate West Juyan Lake, the State Council of the People's Republic of China (the executive branch of the central government) has issued a "Water Allocation Plan for the Heihe Watershed Mainstream", mandating water allocation to the lower reach each year (Pan and Tien 2001; Feng et al. 2002).

This study simulates the hydrological processes of the upper and middle reaches of the Heihe Watershed to determine the amount of water flowing downstream annually from the middle reach (at Zhengyixia Station). It describes our collaborative work to adapt the Distributed Large Basin Runoff Model (DLBRM) to the Heihe Watershed for understanding the hydrological processes of the river system and thereby provides partial basis for implementation of the central government's water allocation plan. We first describe the physical features of the Heihe watershed, then briefly introduce the structure, input, and output of the DLBRM, discuss the simulation results of the DLBRM, and finally assess recent changes in the cropping pattern for implementation of the Water Allocation Plan in the Heihe Watershed.

Methods

The study area

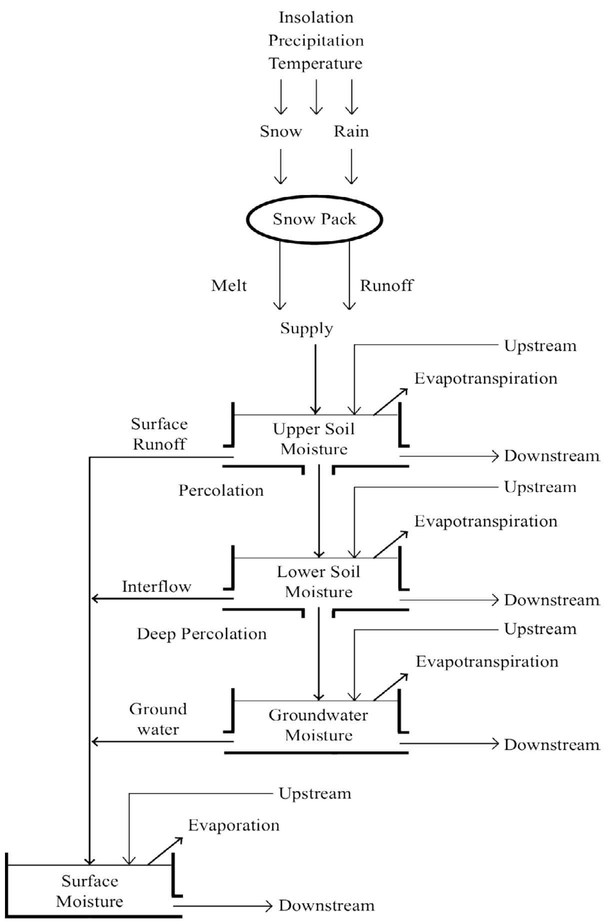
From the headwaters in the south to the lower reach in the north, the Heihe Watershed physically consists of the Qilian Mountain, the Hexi Corridor, and the Alashan Highland (Figure 1). The Qilian Mountain is situated at the south of the watershed, with a peak elevation of 5,584 m. Ice and snow cover it year round above 4,500 m. Mixed alpine meadow and permafrost dominate between 3,600 to 4,500 m. While the main vegetation is forest and grassland with a mean annual precipitation of 250—500 mm in the 1,900-3,600 m range, the landscape below 1,900 m is dominated by hilly or grassland desert with a mean annual precipitation of 200—250 mm (Pan and Qian 2001; He et al. 2009). Located in the middle reach of the Heihe Watershed, the Hexi Corridor hosts over 90% of the total agricultural oases in the watershed and supports more than 97 percent of the Heihe Watershed's 1.8 million inhibits in two metropolitan areas: Zhangye (population 1.25 million in 2000) and Jiuquan (population 0.49 million in 2000). Irrigation supply is from both surface water withdrawals and groundwater pumping. North of the Hexi Corridor is the Alashan Highland (the area north of Zhengyixia with mean elevation 1,000 m), an extremely dry desert with an annual precipitation below 50 mm. Spotty oases appear intermittently along the streams, lakes, and irrigation ditches. Since it is extremely dry, the Alashan Highland is a large source of frequent sandstorms (Cheng et al. 1999; He et al., 2009).

The total annual water withdrawal in the Heihe in 1995 was about 3.36 billion (109) m^3 and 86 percent of that was used to irrigate 288,000 ha of farmland mainly located in the Hexi Corridor (Pan and Qian 2001; He et al. 2009), leaving less than 0.5 billion (109) m^3 of annual flow to the lower reach (north of the Zhengyixia Station). Competitions for the limited water resources have caused intense conflicts between water users in the Hexi Corridor and those in Alashan Highland in the lower reach. To address this pressing issue, the State Council has mandated the allocation of 0.95 x 109 m^3 of water to the lower reach under normal climatic conditions for rehabilitating the downstream ecosystems. Implementation of such a mandate means reducing the current water use by 0.58 x 109 m^3 for agricultural irrigation (potentially taking about 40,000 ha of farmland out of irrigation) and domestic supply in Zhangye City alone in the middle reach (Pan and Qian 2001; The City of Zhangye 2004), a potential loss of about $240 million annually for the city. No action, however, would mean the continuing deterioration of ecosystems in the lower river reaches.

Description of the DLBRM

To answer the question, "How much water flows downstream from the upper and middle reaches (at the Zhengyixia station) in the Heihe Watershed?", this study uses the Distributed Large Basin Runoff Model to simulate the hydrology of the Heihe Watershed at daily intervals over the period of 1978-2000. The DLBRM was developed by the National Oceanic and Atmospheric Administration's (NOAA) Great Lakes Environmental Research Laboratory and Western Michigan University. It represents a watershed by using 1 km2 (or other size) grid cells. Each cell of the watershed is composed of moisture storages of the upper soil zone (USZ), lower soil zone (LSZ), groundwater zone (GZ), and surface, which are arranged as a serial and parallel cascade of "tanks" to coincide with the perceived basin storage structure (Figure 2). Water enters the snow pack, which supplies the basin surface (degree-day snowmelt). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Excess supply is surface runoff. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Mass conser-

Figure 2. Tank cascade schematic of Distributed Large Basin Runoff Model.



vation applies for the snow pack and tanks; energy conservation applies to evapotranspiration (ET). The model computes potential ET from a heat balance, indexed by daily air temperature, and calculates actual ET as proportional to both the potential and storage. It allows surface and subsurface flows to interact both with each other and with adjacent-cell surface and subsurface storages. The model has been applied extensively to riverine watersheds draining into the North America's Laurentian Great Lakes for use in both simulation and forecasting (Croley and He 2005; 2006; Croley et al. 2005; He and Croley 2007a). The unique features of the DLBRM include: 1) use of readily available climatological, topographical, hydrological, soil, and land use databases; 2) applicability to large watersheds; and 3) analytical solutions for mass continuity equations, (mathematical equations are not shown here due to space limitations; for details, see Croley and He 2005; 2006; He and Croley 2007a).

The DLBRM requires 16 input variables for each of the grid cells. To facilitate the input and output processing for the DLBRM, an ArcView-DLBRM (AVDLBRM) interface program has been developed to assist with the model implementation. The interface was written in ArcView Avenue scripts by modifying the ArcView Nonpoint Source Modeling interface by He (2003). It consists of six modules: (1) Soil Processor, (2) DLBRM Utility, (3) Parameter Generator, (4) Output Visualizer, (5) Statistical Analyzer, and (6) Land Use Simulator. Multiple databases of meteorology, soil, DEM, land use/cover, and hydrology and hydrography are used by the interface through the draw-down menu to derive input variables for the DLBRM (He et al. 2001; He 2003; He and Croley 2007b). The derived variables for each of the cells include: elevation, flow direction, slope, land use, Manning's coefficient (n) values, soil texture, USZ and LSZ depths, available water capacity, and, permeability, as well as daily precipitation, air temperature, and solar isolation. DLBRM outputs include, for every cell, surface runoff, ET, infiltration, percolation, interflow, deep percolation, groundwater flow, USZ, LSZ groundwater, and surface moisture storages, and lateral flows between USZ, LSZ, groundwater, and the surface (He et al. 2009). The outputs can be examined either in tabular or map format using the interface.

DLBRM input data

The upper and middle reaches of the Heihe Watershed were discretized into a grid network of 9,790 cells at 4 km2 resolution. Multiple databases of DEM (at 100 m resolution), land use/cover for the year 2000, meteorological and hydrological databases for 1978 to 2000 were provided by The Chinese Academy of Sciences (CAS) Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI). These databases were used to derive relevant input variables for the DLBRM using the AVDLBRM interface for each grid cell (Croley and He 2005; He and Croley 2007a). Since the soil database of 1999 (1:250,000) from the Gansu Province only contained soil types, we compiled both soil survey data collected by Xiao and his group (2006) and SPAW (Soil - Plant - Atmosphere – Water) Field & Pond Hydrology model (by the U.S. Department of Agriculture Agricultural Service and Natural Resources Conservation Service) to determine relevant soil attributes for each of the soil types. Such attributes include soil texture, depth of USZ and LSZ, water holding capacity (%) and permeability (cm/hr). Manning's coefficients were assigned to each cell by the hydrological response units (HRUs), which was determined according to the combination of land use, soil texture, and slope (He and Croley 2007b). Average daily river flow rates (in m^3/s) were converted into daily outflow volumes and used to conduct a systematic search of the parameter space to minimize the root mean square errors (RMSEs) between actual and simulated daily outflow volumes at the watershed outlet (Croley et al. 2005; Croley and He 2006).

Model calibration and verification

The DLBRM was calibrated over the period of 1978-1987 for each of the 9,790 cells (4-km2) at daily intervals. The calibration shows a 0.69 correlation between simulated and observed watershed outflows and a 0.072 mm/d root mean square error. The ratio of model to actual mean flow was 1.011; and the ratio of model to actual flow standard deviation was 0.68. Over a separate verification period (1990-2000), the model demonstrated a 0.71 correlation between simulated and observed watershed outflows and a 0.006 mm/d

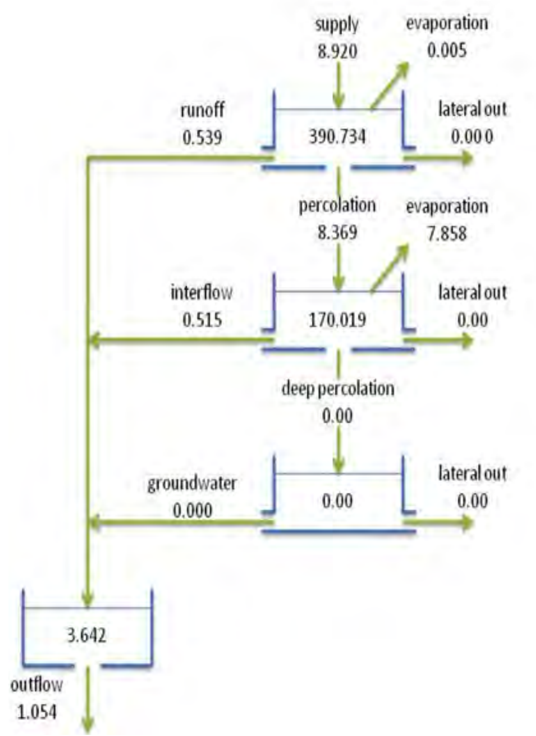
RMSE; the ratio of model to actual mean flow was 1.409; and the ratio of model to actual flow standard deviation was 0.72. The simulated annual water budget (averages of the 1990-2000) shows that annual surface net supply from both rainfall and snow melt was about 8.92 billion (10^9) m^3 (Figure3), which mainly came from Qilian Mountain in the upper reach area. The USZ stored about 391 billion m^3 of water, the largest storage among all the four storage tanks (USZ, LSZ, groundwater zone, and surface storage). Surface runoff from the USZ averaged about 0.54 billion m^3, while a much larger portion of water (8.37 billion m^3) percolated down to the LSZ. A majority (94%) of the percolated water evaporated to the atmosphere from the LSZ and the rest flowed to the stream in the form of interflow. There was hardly any deep percolation to the groundwater since the LSZ is up to 200 m deep in much of the middle reach area (Pan and Qian 2001). The average annual outflow at the outlet (Zhengyixia) of the middle reach was about 1.05 billion m^3 to the downstream (Figure3)

Discussion

The Qilian Mountain (up to 5,500 m above sea level) makes up the upper reach of the Heihe Watershed. Due to the high altitude and steep slope of the mountain area, much of the snow melt and rainfall becomes surface runoff. Once reaching the mountain outlet (Yingluoxia Station), the water quickly percolates to the deep, coarse sandy and loamy soils in the alluvial fan (up to 200 m deep) which is the main agricultural oasis in the middle reach (between the mountain outlet at Yingluoxia Station and the middle reach outlet at Zhengyixia Station) (Cheng et al. 1999). As annual precipitation in the oasis is less than 200 mm, the majority of the river flow is used to irrigate crops like spring wheat, corn and rice in the oasis, depleting river flow downstream of Zhangye City (Figure1). As the LSZ is up to a few hundred meters deep, there is hardly any deep percolation to the groundwater. Instead, a portion of the water in the LSZ flows to the river channels though interflow. This simulated phenomenon is similar to the findings by other researchers such as Cheng et al. (1999), Pan and Qian (2001), and Jia et al. (2005). Groundwater recharge is only observable in the middle reach area with groundwater level less than 5 m deep and daily precipitation more than 10 mm. Irrigation return flows first percolate to the groundwater zone and then flow to the river channel in certain middle reach areas.

The simulated average annual flow for 1990-2000 was about 1.05 x 10^9 m^3 at the middle reach outlet (at Zhengyixia Station) under a normal precipitation year (P=50%). But the annual river flow was simulated to change from 0.80 x 10^9 m^3 in 1991 (a dry year, P=75%) to 1.27 x 10^9 m^3 in 1998 (a wet year, P=20%). It appears that under normal climatic years, the amount of flow passing the middle reach outlet is slightly over 1 x 10^9 m^3, satisfying the requirement of delivering 0.95 x 10^9 m^3 downstream annually by the State Council. This amount of flow, however, only has an exceedence probability of 50 percent, meaning that the annual river flow is less than 1 x 10^9 m^3 at Zhengyixia Station 50 percent of the time. In addition, this study excluded the impacts of irrigation in the middle reach to river flow in the simulations. In reality, increased withdrawals for agricultural irrigation and urban supplies in the middle reach oasis, particularly after the 1980s, have significantly depleted the river flow downstream most of the time each year, shrinking the area of oasis downstream, damaging the aquatic ecosystem, drying up the West Juyan Lake, and causing the expansion of desert in the lower reach. It seems likely that these irrigation withdrawals are contributing to the high ratio of modeled to actual mean annual flow volumes of 1.4 achieved in the model calibration for the 1990-2000 model verification period. Implementation of the State Council's water allocation plan requires taking about 0.58 x 10^9 m^3 water out of irrigation each year in the middle reach in order to deliver 0.95 x 10^9 m^3 of water at Zhenyixia Station for rehabilitating the downstream ecosystem (Pan and Qian 2001; The City of Zhangye 2004). This goal seems achievable during normal climatic conditions and governmental entities (e.g. Cities of Zhangye and Jiuquan) in the middle reach, while coping with an annual economic loss of about $240 million, are taking a number of actions such as adjusting crop patterns, water pricing, and market transfer to deliver more water downstream. Between 2000 and 2008, for example, rice planting area was reduced by over 1,000 ha to cut down irrigation withdrawals for delivering more water downstream (The City of Zhangye 2009). But under dry years, a significantly lesser amount of flow would be available at the Zhengyixia Station, making it much more problematic to deliver the targeted 0.95 x 10^9 m^3 of water downstream.

Figure 3. Annual water budget (1990-2000 average in 10^9 m^3) of the Upper-Middle Reaches of the Heihe Watershed



Conclusions

This paper simulated the hydrology of the Heihe Watershed, the 2nd largest terminal lake in arid Northwest China. The results show that Qilian Mountain in the upper reach area is the main runoff production area for the entire Heihe Watershed. On average, surface runoff and interflow contributed 51 and 49 percent of the river flow respectively for the period of 1990 to 2000. Annually the river was simulated to discharge slightly more than 1 x 109 m3 of water from the middle reach (at Zhengyixia station) downstream under normal climatic conditions. While requiring a significant reduction in water withdrawals by water users in the middle reach, this amount seems to meet the mandate of delivering 0.95 x 109 m3 of water at Zhengyixia Station for rehabilitation of downstream ecosystems by the State Council. However, the amount of the flow at the middle reach outlet is much less under dry climatic conditions, making it much harder to deliver the required 0.95 x 109 m3 of water downstream. In addition, climate change and rapid urban expansion will further intensify the water shortage problem in the Heihe Watershed. Thus, how to develop a comprehensive water management plan to address the competing demands for water among agricultural irrigation, industrial development, urban supplies, and ecosystem protection remains a long term challenge between water users in the upper, middle, and lower reaches of the Heihe Watershed. Our future work will explore the impacts of climate change and human activities on watershed hydrology to support water resource decision making in arid and semi-arid regions of China.

Acknowledgment

Partial support for this research is provided by the National Basic Research Program of Global Change (Grant No. 2010CB951002), the International Partnership Project of the Chinese Academy of Sciences, "The Basic Research for Water Issues of Inland River Basin in Arid Region" (CXTD-Z2005-2), and Scherer Endowment Fund of Western Michigan University Department of Geography. The data set used in the study is provided by "Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China" (http://westdc.westgis.ac.cn). The assistance of Drs. Xin Li, Haiyang Xi and Luxin Zhai for data acquisition and processing is deeply appreciated.

References

» Chen, L. and Xiao, H., 2003. Heixi Mountain Soils and Their Applications. Ocean Press, Beijing. P.132

» Cheng, G.D., Chang, B.Y., and Qu, Y.G., 1999. Assessment and Rational Use of Water Resources for Coordinated Economic Development and Ecologic and Environmental Protection in the Heihe Watershed. Lanzhou Institute of Glaciology and Geocryology. The Chinese Academy of Sciences, "95" National Key Science and Technology Project Report 96-912-03-03, Lanzhou, China, 276 p.

» Croley, T. E., II, and He, C., 2005. Distributed-parameter Large Basin Runoff Model I: model development. *Journal of Hydrological Engineering* 10(3):173-181.

» Croley, T. E., II, He, C. and Lee, D. H., 2005. Distributed-parameter Large Basin Runoff Model II: application. *Journal of Hydrological Engineering* 10(3):182-191.

» Croley, T.E. II. and He, C., 2006. Watershed Surface and Subsurface Spatial Intraflows. *Journal of Hydrological Engineering*, 11(1):12-20.

» Feng, Q., Cheng, G. and Kunihiko, E., 2002. Towards sustainable development of the environmentally degraded river Heihe basin, China. *Hydrological Science Journal* 46(5): 647-658.

» Fu, G., Chen, S., Liu, C. and Shepard, D., 2004. Hydro-climatic trends of the Yellow River Basin for the last 50 years, *Climatic Change*, 65:149-178.

» He, C., J.F. Riggs and Y.T. Kang., 1993. Integration of geographic information systems and a computer model to evaluate impacts of agricultural runoff on water quality. *Water Resources Bulletin*, 29: 891-900.

- He, C., C. Shi, C. Yang, and B.P. Agosti., 2001. A Windows-based GIS-AGNPS interface. *J. of American Water Resources Association.* 37(2):395-406.
- He, C., 2003. Integration of GIS and simulation model for watershed management. *Environmental Modeling and Software* 18(8-9):809-813.
- He, C., Cheng, S. and Luo, Y., 2005. Desiccation of the Yellow River and the South Water Northward Diversion Project. *Water International*, 30(2):261-268.
- He, C. and Croley, T.E., 2007a. Application of a Distributed Large Basin Runoff Model in the Great Lakes Basin. *Control Engineering Practice*, 15(8): 1001-1011.
- He, C. and Croley, T.E., 2007b. Integration of GIS and Visualization for Distributed Large Basin Runoff Modeling of the Great Lakes Watersheds. In: Scarpati and Jones (eds). *Environmental Change and Rational Water Use*. Orientación Gráfica Editora S.R.L., Buenos Aires, Argentina, pp. 247-260.
- He, C., C. DeMarchi, T. E. Croley, Q. Feng, and T. Hunter, 2009. Modeling the Hydrology of the Heihe Watershed in Northwestern China. *Journal of Glaciology and Geocryology*, 31 (3):410-421.
- Huang, Q. and Zhao, X., 2004. Factors affecting runoff change in the upper reaches of the Yellow River, *Progress in Natural Science*, 14(9):811-816.
- Jia, Y., Wang, H., Nin, G., yang, D., Wang, J., and Qin, Q., 2005. Principles and Applications of Distributed Watershed Hydrologicalal Models. Water Resources Pressing, Beijing, China. 283 p.
- Micklin, P.P., 1994. The Aral Sea Problem. *Proc. of Instn. Civ. Engrs Civ. Engng*. 102:114-121.
- Pan, Q.M. and Qian, S.L., 2001. *Water Resources in the Heihe Watershed*. The Yellow River Press. Zhengzhou, P.R. China. 144 p.
- Reynolds, J.F., Smith, D.M.S., Lambin, E.F. et al., 2007. Global Desertification: Building a Science for Dryland Development. *Science* 316 (2007):847-851. 10.1126/science.1131634.
- The City of Zhangye, 2004. Research and Implementation of Water Saving Programs in the City of Zhangye - Technical Report. Zhangye, Gansu Province, China.
- The City of Zhangye, 2009. Annual Statistics. Zhangye, Gansu Province, China.
- U.N. World Water Development Report, 2003. *Water for People, Water for Life.* UNESCO Publishing and Berghahn Books.
- Xiao, H., 2006. Analysis of types and mechanical composition of soil samples (unpublished data). The Chinese Academy of Sciences Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou, China.
- Yang, D., Li, C., Hu, H., Lei, Z., Yang, S., Kusuda , T., Koike, T., and Musiake, K., 2004. Analysis of water resources variability in the Yellow River of China during the last half century using historical data, *Water Resources Research*, 40, W06502.

The influence of international water governance on water management in Zambia.

Jonathan M. Kampata

Department of Water Affairs, P.o Box 50288. Lusaka. Zambia
E-mail: jkampata@yahoo.com

Abstract

Zambia's water policy and institutional framework has been influenced over the years by the resolutions and adaptation of numerous international conferences and instruments. The turning point was in 1991 when the country initiated water sector reforms that were largely influenced by the Dublin principles and Agenda 21. A National Water Policy was adopted by government in 1994 that took on board the Dublin principles. The paper analyses how this changed water resources management in Zambia. Zambia and the rest of the Southern African Development Community (SADC) countries were also influenced by the 1997 United Nations Convention on the Law of Non-Navigational Uses of International Watercourses. In response to this Zambia has participated in the development of protocols/ agreements and institutional framework to manage its international waters. The paper will outline the river basin institutional and legal frameworks that have been developed for the Lake Tanganyika River basin and the Zambezi River Basin. Finally the paper addresses the influence of the 2002 Johannesburg World Summit on Sustainable Development which among others called for countries to develop Integrated Water Resources Management and Water Efficiency (IWRM/WE) plans of which Zambia produced one in 2008 and is currently implementing it within the framework of the national development plan.

Keywords:
water sector reforms, international waters, water policy, institutional framework

Introduction

International concerns about water resources management have led to the global consensus on the need to adopt a new approach to managing water resources. This new agenda calls for a comprehensive water resources management framework that integrates social, economic and environmental considerations (African Development Bank, 2000). A water governance system to manage such a framework is needed

According to UNDP (2010) Water governance addresses among other things:

- Principles such as equity and efficiency in water resource and services allocation and distribution, water administration based on catchments, the need for integrated water management approaches and the need to balance water use between socio-economic activities and ecosystems.
- The formulation, establishment and implementation of water policies, legislation and institutions.
- Clarification of the roles of government, civil society and the private sector and their responsibilities regarding ownership, management and administration of water resources and services.

In many countries, the recognition of the need for integrated water resources management has stimulated efforts to organize water governance according to hydrologically defined boundaries, e.g. as integrated river basin and catchment based management. Specific river basin or catchment management organizations have been created and written into legal and administrative frameworks governing water management not only in Europe and North America but also in many developing countries (Ravnborg and Funder, 2009).

The scale of management however presents a particular problem. For operational reasons it is desirable to decentralize water management to the level of hydrological boundaries, i.e. basins and sub-basins, but these boundaries seldom coincide with the administrative boundaries (African Development Bank, 2000). International Water Governance paradigms

A number of landmark events have shaped most of the current paradigms and the consensus on norms regarding water resources and water services management. The chronology of events building up to the current consensus most often includes the UN Conference on the Human Environment (Stockholm, 1972); the UN Conference on Water (Mar del Plata, 1977); the International Conference on Water and Environment (Dublin, 1992); The United Nations Framework Convention on Climate change (1992); the UN Conference on Environment and Development (Rio de Janeiro, 1992); the United Nations Convention on the Law of Non-Navigational Uses of International Watercourses (1997), the World Water Forums (Marrakech 1997; The Hague, 2000; Kyoto, 2003; Mexico, 2001; Istanbul, 2009); revised Protocol on Shared Watercourses in the Southern African Development Community (2000); the Millennium Development Goals (2000); the World Summit on Sustainable Development (Johannesburg, 2002) and The Convention on Sustainable Management of Lake Tanganyika (2003).

The central message of these is a holistic / sustainable approach to management of water. The Dublin Principles specifically revolves around the recognition that (i) water is a finite and vulnerable resource, essential to sustain life, development and the environment(ecological principle); (ii) that water development and management should be based on a participatory and gender sensitive approach involving all users, planners and policy makers at all levels (institutional principle); and (iii) that water has an economic value in all its competing uses, and should be recognised as an economic (and social) good; or social, economic and environmental resource.

The above consensus on norms has found expression in "vision" documents including the World Water Vision (2000); the Africa Water Vision (2000); and the Southern Africa Water Vision (2000). The Southern Africa Water Vision calls for, "equitable and sustainable utilisation of water for social and environmental justice, regional integration and economic benefit for present and future generations".

In Africa, more recent developments have included the African Ministerial Conference on Water (AMCOW) initiative under the auspices of the New Partnership for African Development (NEPAD). NEPAD recognises the important role of water in development and endorses the Africa Water Vision and supports the implementation of Integrated Water Resources Management (IWRM) best-practice principles (management at the river basin level, management at the lowest appropriate level, demand-driven approaches, ownership and participation by all stakeholders). Zambia has signed and ratified several of these international instruments that directly relate to water and environment sectors.

The body of collective wisdom, knowledge and experience is therefore quite well developed and there is consensus on many issues. Integrated Water Resources Management suggests an approach that embodies the Dublin Principles. In practice, the principles translate among others into management at the river basin level while embracing the 3 E's (equity, efficiency and environmental sustainability). Translating these good intentions into tangible actions at the national and local levels is a challenging task. The challenges notwithstanding, there is increased recognition that the world faces an impending water crisis and that, that crisis is a crisis of governance – water governance (Water Resources Action Programme, 2003).

Key water resources management issues in Zambia

Zambia is situated in southern Africa and covers an area of 752,614 km^2. The country is located between the upper reaches of both the Zambezi and Congo rivers leads to the interpretation that all rivers in Zambia are considered international waters. About 75% of Zambia's territory fall within the Zambezi basin and the remaining 25% within the Congo Basin (Republic of Zambia 2007). The annual average renewable surface water resources are about 86,852 Mm3 per year and 57,500 Mm3 of groundwater. This results in a total renewable water resource base of around 144,000 Mm3. Water use in 1995 was estimated at about 5% of the total renewable water resource (Ministry of Energy and Water Development, 1995). This level of use is relatively low and a sign of low economic output despite the huge potential available to utilise the nation's water resources for social and economic use.

Some of the key challenges are the uneven distribution of water resources across the country and high climatic variability (resulting in frequent floods and droughts) made worse by the emerging climate change phenomenon, coupled with degrading water quality are increasingly undermining the important role of water in the country's economic development. There are significant spatial and strong seasonal variations across the country which results in areas having localised water stress or scarcity.

Water quality is an increasing concern, particularly in the Kafue River. Kafue provides water to the main economic water consuming sectors in the country: mining, agriculture and industry. Additionally, Kafue also supplies water to over 40% of the population.

Currently Zambia's water resources infrastructure is poorly developed. Growth in water demand, that has to be met by increased Water Resources Infrastructure Development, is expected to come mainly from Government's strong policy focus on (MEWD, 2008):

- The agriculture sector, particularly irrigated agriculture where Government's vision is to increase from the present 155 000 ha to 400 000 ha under irrigation by 2030.
- Development of hydro power stations as a priority in order to meet the growing electricity demand that is necessary to sustain the economic growth. The country's hydropower resource potential stands at an estimated 6,000 MW (megawatts) while the present installed capacity is 1,876 MW. The planned projects, amounting to over 1,500 MW have been identified for development.

The above issues call for a proactive integrated approach in the management of the water resources. With effective WRM, potential exists to increase water availability, especially for hydro-power, industrial and agriculture use, in a sustainable way.

Situation in Zambia before the sector reforms

Before the start of the water sector reforms in 1993, the sector was characterised by a diffusion of institutions dealing with various aspects of water and sanitation often on ad-hoc basis resulting in poor sector coordination and performance. The formulation and adoption of a National Water Policy (NWP) in 1994, to provide a framework for future coordinated development of the sector, therefore, marked an important milestone in the development of the sector.

The key problems the water sector faced at the start of the reforms included: lack of a comprehensive water sector policy or strategy to guide sector organizations; unclear roles and responsibilities for the water sector players; deteriorating infrastructure and lack of new investments; erratic and insufficient funding; increasing pollution of water resources; lack of a comprehensive legal framework for managing water resources; low stakeholder involvement and ownership among others (MEWD, 1994, NWASCO 2004; GRZ 2008) and inadequate required skills at central and decentralised levels.

The water sector reforms

1994 National Water Policy

The aim of the 1994 National Water Policy (NWP) was "to promote sustainable water resources development with a view to facilitate an equitable provision of adequate quantity and quality of water for all competing groups of users at acceptable costs and ensuring security of supply under varying conditions".

One of the key policy measures adopted was: Promoting water resources development through an integrated approach. The NWP also contained the seven sector principles which have been the basis for implementation of the water sector reforms. These principles are:

- Separation of water resources and executive functions from water supply and sanitation (WSS);
- Separation of regulatory and executive functions within the water supply and sanitation sector;
- Devolution of authority to local authorities and private enterprises;
- Achievement of full cost recovery for the water supply and sanitation services (capital recovery, operation and maintenance) through user charges in the long run;
- Human resources development leading to effective institutions;
- Technology appropriate to local conditions; and
- Increased Government Republic of Zambia (GRZ) spending priority and budget spending to the sector;

2010 National Water Policy

A revised National Water Policy was adopted by Government in February 2010. The 1994 Water Policy was revised in order to comprehensively cover all sectors since water is a cross-cutting issue and all sectors impact or are impacted by water resources in a number of ways. The revised National Water Policy reinforces integrated water resource management as the guiding principle. It embraces modern principles of water resources management and endeavours to deal with the daunting challenges of poverty reduction, takes into account the Decentralisation Policy of Government, seeks to address cross-sectoral interests in the water sector with particular focus on water resources planning, development, management and utilization and addresses specific sector and cross-sectoral issues such as Agriculture, Energy, Water Supply and Sanitation, Gender, HIV-Aids, land use, wet land conservation, climate-change and conflict management. The policy acknowledges being shaped by a number of international landmark events and instruments which include those outlined in Section 2 above.

The Vision of the revised National Water Policy, 2010 is: "To optimally harness water resources for the efficient and sustainable utilization of this natural resource to enhance economic productivity and reduce poverty."

Other policies

The National Policy on Environment addresses issues of conflict of interest, harmonisation of strategies and rationalisation of legislation that concern the use and management of environment of all sectors. The policy promotes the National Environmental Action Plan (NEAP) as the key instrument for national environmental planning and implementation. The current NEAP developed in 1994 adopted two notable strategies for the water sector namely, that integrated river basin management be adopted with the watershed area as a unit of management and; that emphasis should be placed on water resources development while ensuring sustainable use of the resource. Thus policy harmonization is being seen among such key policies which improve implementation of water resources management measures.

Legal framework

Water resources management is governed by the 1948 Water Act cap 198. Some key weaknesses of this act are that water allocation is made at a central level, inadequate stakeholder involvement, and ground water and international waters are not regulated.

This is a violation of best practices of water management as well as IWRM principles which requires that water be management holistically.

In view of this, under the Water Sector Reforms the Government of Zambia, through the Water Resources Action Programme (WRAP), has developed a proposal for a new legal and institutional framework for IWRM. The proposal is laid out in the Water Resources Management Bill, 2010. The proposed legislation has been developed through a comprehensive stakeholder consultation process and takes into account the principles of IWRM.

Some key highlights of the Water Resources Management Bill, 2010 include:

- Providing for the establishment of a decentralised system at (river basin level) of water resources management that includes local level institutions representative of the water users in an area(catchment, sub-catchment, water user levels)
- To provide for the regulation of groundwater on an equal basis with surface water
- To establish an appropriate set of fees, levies and/or raw water tariff structure, reflecting that water beyond basic needs usage is to be treated as an economic good
- To ensure that the new Act covers international watercourses (including shared lakes) and the regulation of water thereof; also provide for the domestication of international treaties(e.g. SADC Protocol, UN Convention) that Zambia has ratified thereby providing the basis for the international protocols to which Zambia is a signatory to legally come into effect
- Water resources are clearly dealt with as a social and economic good
- Financing of water resources infrastructure will be enhanced by establishment of a water resources development trust fund and promotion of public private partnerships

The Bill is in the final stage of being prepared for presentation to parliament.

Institutional framework

The key change in the institutional framework has been the realisation of the principle of "Separation of regulatory and executive functions within the water supply and sanitation sector". The National Water Supply and Sanitation Council (NWASCO), as an independent regulator for urban water services, has been established under the Water Supply and Sanitation Act, No 28 of 1997. Its establishment has seen an improvement in Urban WSS.

International river basin management

Zambia's territory being entirely in international shared river basins (the Congo (25%) and Zambezi (75%) necessitates the country to be active in the management of international waters. This is important in order to achieve sustainable management of its water resources as downstream and upstream waters including shared aquifers affect the availability, and use of water in Zambia and its neighbours.

A major achievement has been being party to the Zambezi River Authority (established under the Zambezi River Act, 1987), the revised SADC protocol on shared watercourses and the Lake Tanganyika Convention. In addition Zambia actively participated in the development of the proposed Zambezi Water Course Commission and Zambezi River Basin Strategy. Further capacity is being built by administrative establishment of an International Water Management unit in DWA. In addition the revised Water Policy 2010 and the proposed WRM Bill take into account measures to enhance international water management.

Integrated Water Resources Management and Water Efficiency (IWRM/WE) plans

One of the targets agreed by Heads of State at the 2002 World Summit on Sustainable Development (WSSD) held in Johannesburg, South Africa, was that "nations should prepare National Integrated Water Resources Management and Water Efficiency Plans (IWRM/WE Plans) by 2005". It was acknowledged that to achieve the Millennium Development Goals (MDGs) sustainable water resources management was key especially to eradicating extreme poverty and hunger, ensuring environmental sustainability and improving health conditions.

In 2004, the Zambian Government through the Ministry of Energy and Water Development, with facilitation of the Zambia Water Partnership, began implementation of the Partnership for African Water Development Project (PAWD). The Zambia IWRM/WE Implementation Plan was launched in 2008. Support was provided by the Canadian International Development Agency through the Global Water Partnership (GWP). GWP South Africa provided guidance, technical support and capacity building during the process.

One key achievement of the process was that Water issues were integrated into the National Development Plan in Zambia. The water sector has been identified as a key sector contributing to national development while ten IWRM related programmes in the plan had been included in the fifth National Development Plan (NDP) (2006-2010) as well as the upcoming sixth NDP (2011 to 2015). The IWRM/WE Plan was used as a guiding document for any external support as well as for planning of interventions by various stakeholders. This contributed in improving coordination and collaboration in the sector.

The National Development Plan

Zambia is currently developing the sixth NDP 2011-2015. The river basin approach has been found to be ideal for water resources planning, demand management, infrastructure development, financing and climate change adaptation. It is a primary vehicle for transformation leading to investments in multi-purpose dams to support the development of agricultural farm blocks and the growth of mining, industry, tourism, and the electricity sectors. One of the proposed key strategies of the sixth NDP under the Water Sector is:

Implementation of Integrated Water Resources Management, including mainstreaming cross-cutting issues and mitigation of Climate Change impacts. Development of Catchment Management Plans will be central to successful implementation of NDP programs.

Conclusion

In the light challenges facing the water resources management in Zambia and the global paradigms of integrated water resources management, the Government of Zambia put in place a reform process to improve the management of water resources following the best practice of integrated water resources management. Various international water governance measures from the various conferences and instruments has influenced the development of Zambia's water governance system as evidenced from the Water Policy development and its provision, the institutional framework and the proposed water resources management Bill.

References

- Ravnborg, H. M., Funder, M., 2009. The challenge of local water governance – insights from the Competing for Water programme. Paper presented at the Danida Technical Seminar on Water and Sanitation, Livingstone, September 29 – October 2, 2009
- Republic of Zambia, 2007. National Adaptation Programme of Action on Climate Change. Ministry of Toursim, Environment and Natural Resources
- Ministry of Energy and Water Development, 1994. National Water Policy.
- Ministry of Energy and Water Development, 2008. Proposed Zambia National Strategy for Water Resources Pricing and Financing. Final Report
- Ministry of Energy and Water Development, 2010. Sixth National Development Plan, 2010 – 2015 Draft Water Chapter
- Ministry of Energy and Water Development, 2010. National Water Policy (Revised)
- UNDP, 2010. Water Governance Facility (WGF). Available online: http://www.watergovernance.org/whatiswatergovernance
- Water Resources Action Programme, 2003. WRAP National Consultative Forum. An Overview of the emerging framework for the use, development and management of water resources in Zambia. Ministry of Energy and Water Development.
- Zambia Joint (GRZ/ Cooperating Partners) Annual Water Sector Review. Final Mission Report, September 2009 and June 2010

Multilateral environmental agreements – a catalyst for interlinkages in river basin management? A case study of Pahang river basin, Malaysia

Jing Lee

Institute of Environment and Development, University of Malaysia, 43600 Selangor, Bangi, Malaysia. PhD Candidate, Dundee IHP-HELP Centre for Water Law, Policy and Science (under the auspices of UNESCO), Peters Building, University of Dundee, DD1 4HN, Scotland, UK

E-mail: leejing@ukm.my; j.y.lee@dundee.ac.uk

Abstract

Holistic governance of river basins advocates for the wise use of freshwater resources, propounding the need to implement integrated water resources management (IWRM) practices in the utilisation and management of freshwater resources. The drainage basin approach underlying the concept of IWRM necessitates recognising the interdependence of all living and nonliving resources in the terrestrial and aquatic ecosystems within watersheds. Development generally entails freshwater resources degradation. Land conversion, water abstractions and overexploitation of natural resources for the satisfaction of developmental needs, as well as the pollution caused by such activities, are factors identified as the causes of degradation. Contemporary approaches to water resources management, based on an improved knowledge of hydrology and interdependency within physical and social systems, promote the incorporation of an ecosystem approach in river basin governance. Several Multilateral Environmental Agreements (MEAs) imposed similar obligations on the Contracting Parties to use specific components of the environment sustainably and wisely, in a manner similar to the IWRM approach. However, the need for a more integrated legal response has been repetitively raised, which led to establishing various formal cooperative arrangements and other institutional connections between MEAs. For instance, the Convention on Biological Diversity (CBD) is working together with other conventions, including the Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention) in the promotion of interinstitutional interlinkages. The collaboration initiative of these convention bodies to collaborate is known as interlinkages. The Malaysian government, by acting in conformity with the environmental protection obligations imposed under the CBD and the Ramsar Convention through implementation of domestic legislation, has positive effects on river basin. The case study of Pahang River Basin (PRB) is a good example to demonstrate the influence of international environmental regime on river basin governance. The interactions between the CBD regime and the Wetland regime have acted as a catalyst in promoting the integrated management of Pahang River Basin.

Keywords

Multilateral Environmental Agreements (MEAs), environment protection, Integrated Water Resources Management (IWRM)

Introduction

Issues related to water scarcity have generated much debate and discussion on heightening awareness on water security concerns and the increasing need to manage our freshwater resources. The importance of freshwater resources as an essential component of the global hydrosphere and biosphere is reaffirmed in the international environmental law regime (Chapter 18, paragraph 1, Agenda 21). The essential link between freshwater resources and the terrestrial ecosystem therein drawn in paragraph 1 provides the foundation for the integrated management of water resources that includes considerations related to the impact of land uses and other modifications of the terrestrial ecosystem on freshwater-related resources. The paper looks at hownterlinkages at the level of Multilateral Environmental Agreements (MEAs) in the conservation and protection of environment influence the integrated management of water resources in Malaysia. It also highlights the need to adopt an ecosystem approach, which is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way, in water resource management (Guerrero, 2008).

The paper initially looks at the obligations to protect and sustainably use natural resources as stated under the relevant MEAs and the general policies that purport to implement these obligations. It then proceeds to identify the obligations stipulated by the relevant domestic legislations in force for the conservation of ecosystems and their implementation by taking into consideration the general guideline provided in the National Policies and the MEAs. Subsequently, the discussion turns to whether the Pahang Water Resources Enactment 2007, recently drafted for the control of water resources in the State of Pahang, provides the necessary aperture, as well as a supportive legal framework for interlinkages stemming from obligations imposed under MEAs through the prism of the integrated water resources management (IWRM) paradigm. The paper will conclude that the interlinkages proposed by the MEAs create an enabling environment for the integration of land, water and living resources in the sustainable and equitable utilisation of natural resources in the country, acting as a catalyst for the implementation of an integrated development and management of its river basins. Finally, the paper reflects on the recent implementation of the Pahang-Selangor Interstate Raw Water Transfer System (2006-2010) project.

Introduction to Pahang river basin

The Pahang River is situated in Lubok Paku, an area of remarkable environmental value and biological diversity, with a catchment area covering approximately 25,600km2. The main stem of the Pahang River flows over 440 km, making it the longest river in Peninsular Malaysia. The Pahang River originates from Mt. Tahan within the Taman Negara National Park at an altitude of 2,187m and discharges into the South China Sea. The annual rainfall in the basin is 2,170 mm and the mean river flow measured at Lubok Paku is 596 m3/s. (Yasuto Tachikawa et al, 2004). The virgin forest in Taman Negara National Park at the source of Pahang River is approximately 130 million years old and covers an area of 4,343 km2. The Pahang Taman Negara National Park is governed under the Taman Negara Enactment (Pahang) No. 2, 1939. Tasek (*Lake*) Bera is located at the midstream of Pahang River. It is 34.6 km long and 25.3 km wide, draining northward to join the main stem of Pahang River via the Bera River. It is a designated Ramsar site since November 1994 and the management of the Lake is in accordance with the provisions of the Ramsar Convention 1971. The total area of this Ramsar Site is 31,120 ha, of which 6,800 ha are wetlands. The buffer zone for this site is 77,380 ha.

Conservation and sustainable utilisation of natural resources under the relevant multilateral environmental agreements

The Convention on Biological Diversity (CBD) and the Ramsar Convention on Wetlands (Ramsar Convention) adopt an ecosystem approach. The obligations related to the conservation and protection of biodiversity and ecosystems imposed by these MEAs may contribute to safeguard the provision of ecosystem services, such as water supply, water purification and flood regulation (Millennium Ecosystem Assessment, 2005). The commitments undertaken by Malaysia in the observance of CBD and the Ramsar Convention have lead to various efforts in the conservation of natural resources as well as biodiversity. Conservation in Malaysia increasingly follows an ecosystem approach that is crosssectoral in nature. The evolution of environmental policy in support of the country's aspirations towards sustainable development has greatly influenced the legal framework and institutional structure of environmental governance at national level (Hezri et al, 2006).

The need to harmonise the relevant legislations and regulations for the effective conservation and sustainable use of biodiversity has been identified in order to fulfil obligations under both Conventions. The National Policy on Biological Diversity (1998) had been drafted in order to guide the implementation of CBD in Malaysia. Apart from that, the National Policy on the Environment (2002) and the National Forestry Policy (1992) are also instrumental in strengthening the institutional base and enhance cooperation and understanding between the federal and state governments especially with respect to development and management of the forestry sector. Wetlands are given special attention in the biodiversity conservation effort whereby the National Wetlands Policy 2004 is specifically drafted to ensure the conservation and wise use of the wetlands in meeting the commitments of the country to the Ramsar Convention (Fourth National Report to the Convention on Biodiversity, 2009).

Article 8 of the CBD requires contracting parties to establish in-situ conservation sites, constituted by a system of protected areas where special measures need to be taken to conserve biological diversity. The Fourth National Report for CBD demonstrated that in-situ conservation of natural habitats in Malaysia existed in various forms, including permanent reserved forests, national and state parks, wildlife sanctuary and reserves, and conservation areas designated under the United Nations Educational, Scientific and Cultural Organisation (UNESCO) World Heritage Site (Natural List), Association of Southeast Asian Nations (ASEAN) Heritage Sites, and Ramsar Sites. Taman Negara National Park, which is the catchment of the Pahang River, is designated under the ASEAN Heritage Site while Lake Bera, is a designated Ramsar site. Designation of natural habitats, especially permanent reserved forests, conservation areas, or national parks was stated in the Fourth National Report as evidence of Malaysia's compliance to the CBD.

As a signatory to the Ramsar Convention, Malaysia is required under Article 2 to designate wetland site to be included in the List of Wetlands of International Importance (hereinafter referred to as 'the List'). Malaysia is committed to promote conservation of wetlands and waterfowl through the formulation and implementation of planning that promote the conservation of the listed wetlands, and the wise use of other wetlands in the territory, even though they are not included in the List (Article 3 and 4 of Ramsar Convention). Tasek Bera is the first wetland to be included in the List. It is situated within the Tasek Bern Forest Reserve and is proposed to be gazetted under the National Forestry Act 1984 as a Permanent Reserved Forest (Azmi Sharon, 2002). It has a monitoring scheme to detect on site ecological changes (National Report of Malaysia for COP7, 19 December 1998). Tasek Bera is divided into three management zones based on the sensitivity of the area towards external disturbances. Only limited access is allowed into the large undisturbed natural areas of the Specialized Management Zone, the Sustainable Utilization Zone and the Buffer Zone.

The Ramsar Convention advocates the use of the Strategic Framework and Guidelines for the Future Development of the List of Wetlands of International importance of the Convention on Wetlands, 2008. This Strategic Framework and Guidelines goes a step further in promoting interaction of other environmental regimes, as shown in its list of indicators for reporting on the wise use of wetlands. In Strategy 1.2, Indicator Question 1.2.2 requires the country to report on whether the National Wetland Policy incorporate targets and actions established in the World Summit on Sustainable Development 2002. Strategy 1.4 establishes the linkage between wetlands and freshwater resource where the country is requested to report on the integration status of the conservation and wise use of wetlands in planning activities at all levels. The levels for integration include territorial management, groundwater management, catchment/river basin management, coastal and marine zone planning, and the response to climate change (National Report on the Implementation of the Ramsar Convention on Wetland, 2008).

A crosssectoral approach in water resources planning and management is adopted whereby reference to the impact of the national implementation of other MEAs such as the Kyoto Protocol on the conservation and wise use of wetlands, is raised in Indicator Question 1.4.4. Apart from that, Goal 3 of the Strategic Framework raises the need for collaboration with other institutions, including that of other MEAs (Indicator questions 3.1.1, National Report on the Implementation of the Ramsar Convention on Wetlands, 2008).

The efforts taken by Malaysia in compliance with CBD and the Ramsar Convention have resulted in the establishment of an enabling environment for integrating the conservation and sustainable utilisation of national natural resources. The synergistic interlinkages created by these MEAs have a positive influence on the application of an integrated water resources management approach at the river basin level.

Domestic legislation for conservation and sustainable utilisation of natural resources

The management of protected areas - be it in the form of national park, wildlife reserves or permanent forest reserves - are guided by the country's observation of its international obligations. In furtherance to that, several national policies are issued in order to harmonise and coordinate the implementation of the existing laws, which are sectoral and fragmented, for the effective conservation and utilisation of natural resources. As mentioned before, forests and wetlands play an important role in the sustainability and vitality of a river basin. The relevant domestic legislations on the conservation and sustainable utilisation of natural resources, in particularly national and state level legislations relating to the management of protected areas, will greatly affect the development and management of the PRB, for both the Taman Negara National Park (catchment) and Tasek Bera (tributary) are situated within the Basin. Hence, conservation and protection of the National Park and Tasek Bera will definitely have a positive effect on the PRB as a wholeensure the environment sustainability of the Basin.

The analysis on the interaction of international environmental regimes takes another step further by looking at how the environmental protection commitments are executed via relevant state level legislations. The relevant domestic legislations identified are the National Forestry Act 1984, adopted by the Pahang State Assembly as the Pahang State Forestry Enactment 1985 (Amended 1994), the Protection of Wildlife Act 1972, and Taman Negara (Pahang Enactment 1939, No. 2) (Pakhriazad et al, 2009). These legislations provide for the power of the state to declare a biodiversity rich, or ecologically sensitive area as a protected area and to be managed as such.

Part III, Chapter 1 of the National Forestry Act 1984 laid out the power of the State Authority to declare a land to be permanent reserved forest (Section 7, National Forestry Act 1984). The State Director of Forestry has the power, subjected to the approval of the State Authority, to classify forests as permanent reserve forest according to certain criteria of uses, inter alia, forest permanently reserved for water catchment (Section 10(1)(e), National Forestry Act 1984). The National Forest Policy 1992 guides the implementation of the Forestry Act, while the sustainable use of the forest is subjected to the principles of Sustainable Forest Management. (Pahang Forestry Department, undated).

The Taman Negara National Park (Pahang) Enactment 1939 explicitly dedicated to set aside and reserve, in perpetuity trust, the State Park for the purposes of the protection and preservation of indigenous fauna and flora of Malaya and of preservation of objects and places of aesthetic historical or scientific interest (Section 3, Taman Negara National Park (Pahang) Enactment 1939). Apart from vesting the Sultan of Pahang and the Trustees with the power to administer the State Park, the Enactment also provides for restriction in the use or occupation of any land within the State Park subject to the conditions imposed on the permit or lease (Section 5, Taman Negara National Park (Pahang) Enactment 1939).

The protection of wildlife necessitates the protection of the habitat and sanctuaries of the wildlife. Hence, it is important to take note of the legislations that cater for the protection of wildlife, since the protection of wildlife indirectly requires the preservation of its habitat. The preservation of wildlife habitat leads to the protection of the environment, especially the protection and preservation of freshwater ecosystems, which is crucial to the sustainable supply of freshwater. Part IV of the Protection of Wildlife Act 1972 provides for the declaration of wildlife reserves and sanctuaries by the Ruler of the State of Pahang (Section 47, Protection of Wildlife Act 1972). The management of these reserves are subjected to permits and licence that imposed the necessary conditions thereon on the access to these reserves.

All these legislations provide the appropriate vehicle for the implementation and execution of conservation and sustainable utilisation of natural resources as obliged by Malaysia's commitment towards the MEAs. It has been noted that the constitutional position where the state has jurisdiction over land and forest while national parks are under the concurrent jurisdiction of the federal and the state government has caused a lack of uniformity of laws (Pakhriazad et al, 2009). The lack of uniformity of law can also be due to the fragmentation and congestion of laws. They are caused by the multitude of relevant legislations that are sectoral in nature, with different objectives and aims, but applicable to the same subject matter.

However, it is heartening to note that Malaysia's commitment to these MEAs has acted as the catalyst for the harmonisation of the multitude of applicable laws on environmental protection in the country. The adoption of a crosssectoral approach and the coordination of institutional and legislative mechanisms advocated through the interlinkages efforts undertaken at the institution level of these MEAs, guided by the national policies in place, have assisted Malaysia to remedy the difficulties encountered in the implementation of the existing national laws. By virtue of the synergistic interlinkages catalyzed by Malaysia's observation of its international obligations, the challenges on integration or mainstreaming of environmental concerns into the overall developmental goals of the country can be viewed in a more favourable light.

Legal framework for integrated management of Pahang river basin

Water is the linking factor that strings all components of the environment together. Any modifications or changes to the ecosystem in the drainage basin will ultimately affect both the water quality and quantity. The interdependence of water and its related ecosystems, such as forests and wetlands exemplifies the importance of managing ecosystems in their entirety to protect the ecology as well as the ecological services they provide, which is vital in ensuring water resources sustainability. This brings on the justification for the need to manage river basin in an integrated manner (Blumenfeld et al, 2009). The adoption of the drainage basin approach underlying the integrated water resources management (IWRM) process has been promoted throughout Malaysia. At the Federal level, the National Water Resources Council (NWRC) was established in order to effect a more comprehensive management of water resources (Malaysian Water Partnership, 2001). States are encouraged to draft their own water resources enactment for the better management and protection of their water resources that applies the IWRM process.

Pahang State Authority had taken up the challenge and had drafted the Pahang Water Resources Enactment 2007 (hereinafter referred to as 'the Pahang Enactment'). It vested the State Authority with the overall responsibility for the control of water resources and abstraction of raw water in the State of Pahang, and other incidental power to execute such responsibility (Preamble and Section 3, Pahang Water Resources Enactment 2007). The State Authority may declare any lake or water resource or any part thereof, or its surroundings to be a catchment area and the Enactment provides for the power to regulate the catchment areas to prevent pollution, contamination or siltation of any river or reservoir in the catchment areas. (Sections 6 and 7, Pahang Water Resources Enactment 2007) The State Authority is entitled to appoint a public officer to be the Director of Water Resources. The Director shall have the duty to exercise regulatory functions in respect of water resources and raw water, including the planning and development of strategies, standards and procedures relating to the control, management, conservation and utilisation of water resources and raw water (Sections 10 and 11, Pahang Water Resources Enactment 2007).

Although the Pahang Enactment adequately establishes a framework for the management of water resources in the Pahang State, it falls short of providing a comprehensive legislative framework for the integrated management of water resources. The control and management of the water resource rest solely on the Director of Water Resources appointed by the State Authority, without providing a platform for participation by other stakeholders. A legislative act specifically provided for the control of water resources is the most effective mechanism to coordinate and harmonise all stakeholders' interest and to promote integration. The lack of this platform that promotes an integrated approach in the Pahang Enactment deemed a missed opportunity to enhance the positive efforts undertaken by the various relevant national institutions in their implementation of obligations under the MEAs. The continuity of the efforts taken under Malaysia's compliance with the MEAs discussed above will be better incorporated into the management of the basin if the participatory approach, crucial to the IWRM process, is enshrined in law.

It is suggested that the contemporaneous Kedah Water Resources Enactment 2007 (hereinafter referred to as 'the Kedah Enactment') on the management and control of water resources in the State of Kedah is a better legislative model that complements the interlinkages created by the MEAs, and transfers the synergies created to the management of river basin through an IWRM approach. The Preamble of the Kedah Enactment expressly provides for the integrated management of the use, development and protection of water resources in the State of Kedah. The scope of the Kedah Enactment is expansive where the interpretation section of the Kedah Enactment defines 'river basin' as "any river and the land area it drains", to include activities on land that the river drains (Section 3, Kedah Water Resources Enactment 2007). Protection of the river basin is found in Part VII for the declaration of river reserves or water conservation areas (Sections 34 and 36, Kedah Water Resources Enactment 2007). The institutional arrangements envisaged in the Kedah Enactment adopts an integrated approach whereby the membership of the Water Resources Board, of which the Water Resources Director is accountable to, consist of the Head of State, State Legal Advisor, State Finance Officer, the Water Director himself, and representatives from various relevant governmental departments (Section 5, Kedah Water Resources Enactment 2007). The IWRM process is further strengthened in the Kedah Enactment where public participation, in the form of comments and objections on any river basin plan, or licensing of any significant activities, is expressly provided in Section 21 of the Kedah Enactment.

Conclusion

The PRB is an interesting case study to demonstrate how the interlinkages and synergistic relationship established through the compliance of international environmental obligations can be translated into actual action on the ground through an IWRM process properly supported by the appropriate legal framework operational on the river basin level. Malaysia's endeavour in meeting its international environmental obligations especially the CBD and the Ramsar Convention, have spearheaded the adoption of a crosssectoral approach in addressing environmental concerns in the country. Its international commitments compel Malaysia to implement measures that embrace the protection and conservation of the environment.

Due to the physical unity of the environment in a drainage basin, any modifications or changes to the environment will necessarily have an impact on water resources. The provisional services provided by the ecosystems, in particularly the provision of freshwater, will be greatly enhanced through the preservation and protection of the environment - its biodiversity and its ecosystems. The international environmental regimes, most notably, the body of MEAs established, present a legal reading of the IWRM approach, which provide for a comprehensive and adaptive legal framework for intersectoral and interinstitutional coordination (Boisson de Chazournes, 2010).

It is unfortunate that Pahang State does not adopt a more IWRM oriented approach in the drafting of its Water Resources Enactment, despite the advantages gained on the conservation and environmental protection front by the Malaysia's observance of conservation obligations imposed by these MEAs. These advantages will be better captured and more readily translated into action at the river basin level if the appropriate legal framework for the management and development of river basin is in place. However, notwithstanding the lack of supportive water resources legislation at the state level, recent research had looked at the necessary institutional framework crucial to the implementation of IWRM process in the Pahang River Basin (Tan et al, 2009).

In conclusion, although Malaysia has the sovereign right to exploit its own resources pursuant to its developmental policies, as a signatory to the Rio Declaration 1992, it is obliged to recognise environmental protection as an integral part of the development process (Principles 2, 3 and 4, Rio Declaration 1992). The institutional and governance interlinkages proposed by the MEAs of which Malaysia had committed itself, create an enabling environment for the integration of land, water and living resources in the sustainable and equitable utilisation of natural resources in the country. The observation by Malaysia of its conservation obligations under the MEAs as discussed above provides the necessary stepping-stone for the implementation of an integrated development and management of its river basins. Most importantly, a supportive legislative framework operational at the river basin level that enforces the interlinkages created through the implementation of the MEAs, is crucial to realise the maximum benefits derived from these interlinkages in the comprehensive management of water resources that safeguard the equitable and sustainable use of water.Further thought for reflection

The Federal Government of Malaysia had decided to execute the Pahang-Selangor Raw Water Transfer Project in order to address the problem of water shortage in the Federal Territories. The project entails the construction of dams and the impoundment in Hulu Selangor (in the State of Selangor) of a total surface area of 600 ha with a total catchment area of 19,700 ha, including nearly a thousand hectares of low montane forest (CAP, 1999). The construction of the Kelau Dam with a reservoir area of 24 km^2 at the Pahang end will inundate the Lakum Forest Reserve, which is rich in biological diversity (Raja Zainal Abidin, 2004; Imhof, 2003). Despite serious threats identified through the Detailed Environmental Impact Assessment (DEIA) conducted, they are deemed insufficient to deter the implementation of the project. The inclination to adopt an engineering solution (which modifies and destroys the environment) in resolving water shortages is alarming. An ecocentric outlook that favours conservation should prevail over maximum utilisation of natural resources for short term economic or developmental gains.

References

- A. A. Hezri and Mohd. Nordin Hasan, 2006. Towards Sustainable Development? The Evolution of Environmental Policy in Malaysia. Natural Resources Forum 30 37 – 50.
- Aviva Imhof (editor), 2003. Development Disasters. Japanese-funded Dam Projects in Asia. A publication of Rivers Watch East and Southeast Asia (RWESA), International Rivers Network and Friends of the Earth Japan 29 – 34. Available online: http://www.internationalrivers.org/files/030309.irnjbic.pdf
- Azmi Sharom, 2002. Malaysian Environmental Law: Ten Years after Rio, Singapore Journal of International and Comparative Law 6 855-890.
- Consumer Association of Penang, 1999. Comments on the Detailed Environmental Impact Assessment Study for the Proposed Development of the Sungai Selangor Dam in Hulu Selangor. Available online: http://www.magickriver.net/doecap.htm
- Eduardo Guerrero, 2008. Ecosystem Approach to Integrated Water Resources Management, EcoBytes, Commission on Ecosystem Management (CEM), International Union for Conservation of Nature (IUCN), 1(April). Available online: http://cmsdata.iucn.org/downloads/ecobytesapril2008_1.pdf
- H.Z. Pakhriazad, I. Hasmadi, H.M.K. Aida, Kamaruzaman Jusoff, 2009. Historical and Current Legislations of Taman Negara National Park Peninsular Malaysia. 2(1) Journal of Politics and Law 44-49.
- Laurence Boisson de Chazournes, 2010. Environmental Protection and Access to Water: The Challenges Ahead, 22 September 2010, Delft, the Netherlands. Available online: http://www.hydrology.nl/images/docs/ihp/nl/21_Sep_2010/Environmental_protection_and_access_to_water_Boisson_de_Chazournes.pdf
- Malaysian Water Partnership, Malaysia's Water Vision: The Way Forward. in Le Huu Ti and Thierry Facon, The FAO-ESCAP Pilot Project on National Water Visions. From Vision to Action: A Synthesis of Experiences in Southeast Asia, 2001. FAO/ESCAP, 25 – 41. Available online: ftp://ftp.fao.org/docrep/fao/004/AB776E/AB776E00.pdf
- Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Available online: http://www.maweb.org/documents/document.356.aspx.pdf
- Ministry of Natural Resources and Environment, Malaysia, 2009. Fourth National Report to the Convention on Biological Diversity.
- Ministry of Natural Resources and Environment, Malaysia, 2008. National Report on the implementation of the Ramsar Convention on Wetlands. National Reports to be submitted to the 10th Meeting of the Conference of the Contracting Parties, Republic of Korea, 28 October – 4 November 2008. Available online: http://www.ramsar.org/pdf/cop10/cop10_nr_malaysia.pdf
- Ministry of Science, Technology and the Environment, 1998. National Report of Malaysia for COP7, Ramsar Convention, 19 December 1998. Available online: http://www.ramsar.org/cda/en/ramsar-documents-natl-rpts-cop7-national-report-of-18141/main/ramsar/1-31-121-280%5E18141_4000_0__
- Pahang State Forestry Department (undated) Executive Summary, updated 18 October 2010. Available online: http://forestry.pahang.gov.my/v2/index.php?option=com_content&view=article&id=91:executive-summary&catid=35:berita&Itemid=136
- Raja Dato' Zaharaton Raja Zainal Abidin, 2004. Water Resources Management in Malaysia – The Way Forward, Presentation for the 2004 Asia Water Conference, 20 – 31 March 2004, Kuala Lumpur. Available online: http://www.epu.gov.my/html/themes/epu/images/common/pdf/papers/txtspeech.pdf
- S. Blumenfeld, C. Lu, T. Christophersen and D. Coates, 2009. Water, Wetlands and Forests. A Review of Ecological, Economic and Policy Linkages. CBD Technical Series No. 47. Available online: http://www.cbd.int/doc/publications/cbd-ts-47-en.pdf
- Tan Kok Weng and Mazlin Bin Mokhtar, 2009. An Appropriate Institutional Framework Towards Integrated Water Resources Management in Pahang River Basin, Malaysia. 27(4) European Journal of Scientific Research 536-547.
- Yasuto Tachikawa, Ross James, Keizrul Abdullah and Mohd. Nor bin Mohd. Desa (Eds), 2004. Catalogue of Rivers for Southeast Asia and The Pacific - Volume V. Available online: http://flood.dpri.kyoto-u.ac.jp/ihp_rsc/riverCatalogue/Vol_05/7_Malaysia-5.pdf

Asymmetry and accountability deficits in water governance as inhibitors of effective water resource management

Mike Muller

Global Water Partnership -TEC; Visiting Adjunct Professor, Graduate School of Public and Development Management, Witwatersrand University, Johannesburg South Africa; Commissioner, National Planning Commission, South Africa

E-mail: mikemuller1949@gmail.com

Abstract

Water resources are amongst the most difficult of the natural resources in which to establish management regimes that are effective in meeting the needs of human communities while sustaining the natural environment at an acceptable level.

Water users usually have a local, basin or, occasionally inter-basin perspective on the resource and focus their engagement at this level. National government intervention in water-stressed countries to address over-arching dimensions of water resource management and manage transboundary issues is often limited. While some countries have strong sectoral institutions, in many others, water management and use is regulated by a proliferation of local and regional organizations.

On the other hand, environmental interest groups with specific, limited goals are often organized on a global level with a mandate and resources to intervene at all levels in pursuit of specific interests. As a result, it is suggested that they play a disproportionate role in policy debates, particularly in poor countries through their impact on the funding priorities of donors and

It is suggested that this has seriously skewed global water policy and practice in two ways. Firstly, it has given primacy to the protection of the aquatic environment at the expense of social needs and economic imperatives. Secondly, it has distorted the institutional arrangements to reflect its partial objectives as demonstrated by donor emphasis on river basin management institutions.

One consequence of this asymmetry is that water resource policy initiatives, particularly in poorer developing countries have often been disconnected from the immediate development needs of their societies. Another outcome has paradoxically been to weaken environmental performance since regulations introduced through unaccountable organizations which do not reflect local priorities and resources cannot effectively be imposed and are often ignored.

It is suggested that, to the extent that water resource matters are regulated at a global level, institutional approaches are needed that actively seek to balance the interests of different social, economic and environmental stakeholders and in particular to ensure that there is effective accountability to the societies concerned.

Introduction

Water resources are amongst the most difficult of the natural resources in which to establish management regimes that are effective in meeting the needs of human communities while sustaining the natural environment at an acceptable level.

The complex social and environmental dimensions of water resources together with the diverse nature and behaviour of the renewable resource means that simple economic instruments have only limited value in ensuring that its management achieves the objectives of communities and countries.

This complexity has attracted theoretical interest, most recently recognised by the award of the Nobel Prize in economics to Elinor Ostrom for her work on "common pool resources", such as water, and their management, whose significance will be elaborated on below.

But this complex set of relations also opens opportunities for countries to promote their economic interests and interest groups their sectoral agendas. The work of Drezner (2008) is helpful in understanding the realpolitik that underlies patterns of international regulation, of which global water governance is a small and underdeveloped part. Drezner's analytical framework suggests that it could be expected that global systems of water governance would be used to promote the interests of richer societies and the empirical evidence is that this is what is occurring.

Such asymmetric power relations and institutional arrangements may lead to decisions that ignore the preferences of poorer societies, are inherently undemocratic, weaken accountability and may have other perverse outcomes. The implications of these issues and possible responses to them need to be understood if effective systems of global water governance are to be established in the limited areas in which they could make a useful contribution to achieving social goals.

Objectives, instruments and scale of WRM activities

It is important to understand the range of objectives of water management. At its most passive, this is simply to give effect to existing property and social entitlements through a framework of law. At its most active, it is to use water resources as an instrument through which to achieve social and economic goals, which may include the protection of the natural environment.

This is not the place for an exhaustive articulation of what activities may constitute water resources management (WRM) in different contexts. For the purpose of this analysis, it is simply noted that WRM covers a wide range of activities and instruments, including the monitoring of the changing quantity and quality of the resource in time and space to the planning, development and operation of infrastructure to modify this behaviour and the establishment and administration of allocation of water use rights.

These different activities are often realised at different scales, often by different institutions and the institutional configuration may change over time. The institutions may be formally in the "water sector" or may be the water-using branches of the institutions of other sectors. The financial requirements of WRM are also met in different ways in different contexts. Particularly in those cases where water stress is not yet apparent, the extent of sectoral coordination may be limited.

Polycentric nature of water resource management

Ostrom drew attention to the complex overlaps between the physical systems within which water resources and found and used and the social and economic systems within which such water use activities occur and are governed.

River basins are important units of analysis in assessing physical water availability and conditions. However water users often work with very different spatial perspectives. They may operate within the jurisdiction of a local or state government which sets effluent quality standards or simply as a member of a group of farmers who share access to a canal.

While national governments in water-stressed countries may address over-arching dimensions of water resource management and manage trans-boundary issues, many dimensions of water management and use are regulated by a proliferation of more or less formal local and regional organizations.

Ostrom noted that shared resources are often effectively managed, despite the challenges of the commons, when groups of users with common interests are enabled (or at least allowed) to work out their own local governance arrangements. In these circumstances, they are more likely to be aware of the long-term benefits of a shared approach to protect the interests of the community of which they are a part. However she also recognised that such local governance must be supported and, by implication, that the interfaces with other user groups must be carefully managed.

She suggested that this complexity needs to be recognised and celebrated rather than subjected to efforts to simplify it; indeed, anyone who provides a panacea for the management of common pool resources would certainly be wrong and their recommendations would probably be damaging, she warned.

In this paper, it is argued that those who promote a normative approach to water resource management, and particularly single focus institutional approaches, are likely to fall into this category.

Regulation as a form of global politics

A separate set of issues relates to the nature of global regulation as a vehicle to give expression to global politics as outlined by Drezner ("All Politics is Global"). Drezner identifies the interests which drive different power blocs in their negotiations around international regulation in areas as diverse as trade, finance, public health and environmental issues. An overriding concern is often a desire for regulatory consistency, for competitive and related reasons, since otherwise economic benefits will flow to the areas whose regulatory regimes are less demanding.

The dilemma arises when there are good motivations for differences in regulatory approach but where these are inconvenient for one of the global political powers (Drezner identifies primarily the USA, the EU and China in this category).

The EU has perhaps gone furthest to place environmental protection as the core focus of water resource management through the Water Framework Directive (2000) although US legislation in areas such as endangered species protection has created similar (though less well structured) instruments which are used to achieve similar goals.

While these measures may represent the democratically determined preferences in the countries concerned (a separate debate), they still impose a considerable burden on those economies, compared with countries with less onerous standards. It is thus not surprising that EU and the USA should take the lead in seeking to enforce global environmental protection, not just to reduce their competitive burdens but also to take advantage of the business opportunities that are offered through the imposition of higher standards.

It would be in keeping with Drezner's thesis that Europe and the US should lead in the promotion of more restrictive environmental standards in their dealings with poorer countries, both through their bilateral programmes and through their positions in the multilateral domain. And it is relevant that, in the related though infinitely better analysed domain of climate-related regulation, it is China and to a lesser extent India and related countries that are objecting to, or simply ignoring, a form of regulation that requires them to shoulder equally a burden whose origin lies elsewhere.

Finally, Drezner notes that International Non Governmental Organizations (NGOs) play an important "front" role for more conventional expressions of national interest by powerful nations who "will be happy to exploit the advocacy functions of NGOs and facilitate their role as proselytisers, promoting the merits of regulatory coordination to recalcitrant members of the periphery". Again, this experience has resonance in the context of global water governance debates.

Environmental protection – one objective of WRM

Ostrom's thesis is that the complexity of water resource management is best managed by a constellation of different groups at different scales and addressing different sets of WRM functions or challenges. The interactions between these groups themselves require institutions that are able to support and enable them as well as to articulate between them; these are often and most effectively national governments.

However, environmental interest groups have specific, limited goals, essentially, the conservation of biodiversity and the natural environment more generally. In the water domain, this translates to reducing to a minimum the human impact on the water environment. As Dr. Claude Martin, former Director General of WWF put it:

"Our objectives have never been clearer – slow climate change, reduce toxins in the environment, protect our oceans and fresh waters, stop deforestation, and save species."[1]

[1] *Cited in WWF in the new Millennium, URL: http://wwf.panda.org/who_we_are/history/millennium/ (Accessed January 31, 2012)*

These interest groups are often organized at a global level with a mandate and resources to intervene at all levels in pursuit of their specific interests. And this, it is suggested, is antithetical to the concept of polycentric governance because it can easily lead to the promotion of arrangements that suit the single objective rather than the overall complex of activities that constitute WRM, for pragmatic, clearly justifiable reasons in terms of the specific interests that are being promoted. In the case of environmental protection, this can lead to the physical river catchment being glorified as the primary unit of focus for the management of water resources rather than recognising the importance of polycentric management.

Moreover, the environmental goals are amongst the few that can obviously and operationally be pursued at a global level, since economic and social goals will usually be mediated by the sectors concerned – thus the driver for more effective water use for agriculture may be reform in agricultural trade while basic service provision depends more on development finance, decentralisation policies and local politics than access to water resources.

For this reason, it is suggested that the environmental policy goals receive disproportionate and asymmetric attention in global water policy debates, particularly in poor countries, through their impact on the funding priorities of donors and development finance institutions (DFIs) and that this distorts global water governance to the detriment of better water resource management in the interests of sustainable social and economic development.

Distorted polycentrism, assymetric priorities and accountability deficits

It is suggested that the unitary environmental focus has seriously skewed global water policy and practice in three ways.

- Firstly, it has given primacy to the protection of the aquatic environment at the expense of social needs and economic imperatives.
- Secondly, it has distorted the institutional arrangements to reflect its partial objectives as demonstrated by donor emphasis on river basin management institutions.
- Thirdly, it has deliberately sought to constrain the other centres of governance by attempts to impose overriding principles such as full participation and full prior consent to actions that impact on the resource.

What these three dimensions have in common is that, in each, a limited set of preferences is being enforced through apparently sensible and ethical proposals. Certainly, the natural environment is important, but so too is human life. Similarly, river basin organizations can obviously play a useful role in water management but they are by no means the only – or even the most successful - institutions for managing water. And were the principles of "prior consent" to be applied in comparable areas of endeavour such as transport, energy and urban development, they would paralyse the social and economic life of complex societies. This is why even the USA has a doctrine of "eminent domain" that allows the state to override individual concerns in the wider public interest.

Fundamental to all three of what are considered here to be distortions of water policy is the intent to interpose an external set of priorities into local decision-making which has the immediate and deliberate effect of reducing the accountability of local institutions

Empirical evidence

Is there any empirical evidence to suggest that social preferences, and therefore societal standards, are different in poorer and richer countries?

It is suggested that the evidence is extensive as illustrated by a current dilemma in South Africa. Two systems have been established to monitor local government performance in the water services field. The Blue Drop survey (DWA 2010a) records the extent to which municipalities comply with drinking water standards; the Green Drop (DWA 2010b) reports their compliance with wastewater treatment standards.

The methodologies can be questioned, but they use the same underlying approach and the results can be considered to be reflective of the situation. Significantly, whereas reported compliance in Blue Drop is high with high participation levels, reported compliance in Green Drop is much lower; even more significant is the fact that participation rates is below 50% - the majority of municipalities simply do not believe that wastewater treatment is important enough to engage with.

The evidence, hardly surprising in a country in which there is still extensive poverty and many people do not have access to adequate sanitation, suggests that drinking water provision has a much higher priority than wastewater treatment, despite the fact that the latter is well known (through extensive media reports and commentary) to be causing substantial pollution and environmental damage.

Further empirical evidence that damage is done by an exclusive focus on the environment comes from the much delayed Bujagali dam in Uganda. The five year delay in meeting the country's electric needs in the first five years of is widely recognised to have contributed to slower economic growth and growing unemployment and poverty[2]. There is in turn a demonstrable link between poverty and child mortality – it is estimated by the author that 10 000 additional child deaths a year were caused by these delays, which are a direct reflection of externally imposed environmental policies.

And is there empirical evidence that this distortion is the result of deliberate, structured campaigns? Perhaps the best documented case is that of efforts to prevent the World Bank from lending money to countries for dam construction. This case, which has been well documented, demonstrates not just the intent of the lobbyists but the intersection of their interests with the national interests of rich country governments.

Paradoxical consequences

One consequence of this asymmetry and associated accountability deficits is that water resource policy initiatives, particularly in poorer developing countries have often been disconnected from the immediate development needs of their societies. Another outcome has paradoxically been to weaken environmental performance since regulations introduced through unaccountable organizations which do not reflect local priorities and resources cannot effectively be imposed and are often ignored.

So, while large dam construction was effectively blockaded by environmental interests, through their lobbying of DFIs and aid agencies, as soon as alternative sources of funding became available (notably from the BRIC countries, which have themselves largely ignored the anti-dam campaigns), the barriers dropped and projects went ahead. But because of the unrealistic demands that had been made

[2] cf. International Monetary Fund Uganda (2006) Article IV: Consultation and staff report for the Article IV Consultation, Washington.

through channels such as the World Commission on Dams (for instance, for "prior full informed consent" a condition that effectively enables projects to be permanently blocked), the opportunity to constructively engage in the project design and implementation process was lost.

And it is notable that, belatedly, bilateral agencies are scrambling to reassert a role in this important area, suddenly discovering the self-evident truth that storage is important for water management, that hydropower is a valuable and practical form of renewable energy and that the blockade on dam projects has significantly reduced the development of renewable alternatives to energy generation from fossil fuel sources[3].

Yet, again, the empirical evidence is that concern about domestic environmental impacts could most usefully be addressed by assisting countries to achieve a level of economic prosperity. The river which flows through Sweden's capital Stockholm has been reclaimed from what was a putrid sewer in less than a century. More recently, Seoul in South Korea has celebrated its rising economic status by demolishing an urban freeway in the process of reclaiming its local river. Although there will continue to be much debate(Mc Granahan, 2008), there is evidence to support the thesis illustrated by the "environmental Kuznets curve" that environmental impacts increase and then decrease with growing incomes and that this reflects the democratic preferences of the societies concerned (Dasgupta et al., 2002).

Conclusions

It is suggested that, to the extent that water resource matters are regulated at a global level, institutional approaches are needed that actively seek to balance the interests of different social, economic and environmental stakeholders and in particular to ensure that there is effective accountability to the societies concerned. This applies just as much to those activities which may constitute global water governance as it does to the interaction between a few neighbours on a canal.

Such approaches would recognise that environmental preferences, as with social and economic preferences, must be informed by local and national considerations even where there may be overarching matters of global strategic concern.

In this context, the focus on river basins as the unique locus of water resource management only makes sense from an environmental policy perspective. Social and economic policy will draw the net both wider and in a more restricted form.

Similarly, the emphasis on full prior informed consent to any action at all the local scales is often merely a device to inhibit if not obstruct actions designed to address issues at a wider scale.

The challenge for global governance is to reflect on all three dimensions of water resource management and not be constrained by the narrow objectives of a single, albeit important, interest group. That is necessary not just for effective WRM but to respect the underlying principles of democratic decision-making, at the appropriate levels, that should underpin our management of public affairs.

References

» Dasgupta S, Laplante B, Hua Wang and Wheeler D, 2002. Confronting the Environmental Kuznets Curve, Journal of Economic Perspectives, 16, (1): pp. 147–168.

» Department for International Development, Water Storage and Hydropower, 2009. Supporting Growth, Resilience and Low Carbon Development, London.

» Drezner, 2008. All politics is global. Princeton University Press, New Jersey.

» DWA (Department of Water Affairs), 2010a. Blue drop report V.1. South African drinking water quality management performance, Pretoria.

» DWA (Department of Water Affairs), 2010a. Green drop report V.1. South African waste water quality management performance, Pretoria.

» McGranahan, G., 2007. Urban transitions and the spatial displacement of environmental burdens. In: Scaling Urban Environmental Challenges From Local To Global And Back. Marcotullio, P.J., McGranahan, G., Earthscan, London.

[3] *cf. Department for International Development, Water Storage and Hydropower (2009) Supporting Growth, Resilience and Low Carbon Development, London.*

Legitimate stakeholders?

Worldwide we see the rise of non-state, multi-stakeholder organizations setting norms and standards for socially and environmentally responsible conduct. A multi-stakeholder organization builds on the idea of assembling actors from diverse societal spheres into one rule-setting process, thereby combining their resources, competences and experiences. These processes are also a way of including competing interests into negotiations and deliberations about their different concerns.

Any person, group, or organization that is directly or indirectly affected by an organization's actions, objectives, and policies can be considered as stakeholder. Traditionally, firms only addressed the needs and wishes of investors, employees, suppliers, and customers. Some modern approaches promote a broad, self-organizing system including all interested parties, governmental bodies, political groups, trade unions, communities from which the business draws its resources, and the public at large. In other words, those who identify themselves to be stakeholders are stakeholders.

Confronted with the resulting complexity, defining the specific stakeholders as well as the conditions under which the parties should be treated as stakeholders remains a first-order theoretical and practical challenge, based on aspects of power, legitimacy and urgency.

Stakeholders are not equally affected. Rather, powerful and different stakeholders are entitled to different consideration. A company's customers are legally entitled to fair trading practices but do not enjoy the same protection as the company's employees. In contrast, some government actors possess the authority to impose their will in the process. For example, in the International Commission for the Protection of the Rhine the plenary assembly decides on recognition as stakeholder on the basis of a set of criteria. However, in the case of the construction of the new railway station of the German town of Stuttgart, enough citizens of the federal state considered themselves as stakeholders to topple the state government over the issue and force a full plebiscite.

The more regulatory competence and authority is conferred upon formal and informal institutions and actors beyond the nation-state, the more relevant are questions of how to ensure the legitimacy of the multi-stakeholder systems that are created or strengthened. Legitimacy derives from accountability, and many private organizations gain legitimacy through their members or donors, or from the environmental good they seek to protect. In some environmental areas where governments fail to agree on effective international rules, non-state actors are even taking the lead role. But the disparities in representation between stakeholder groups raise the need to understand the democratic quality of multi-stakeholder organizations.

Finally, setting environmental and social norms and standards ultimately involves conflicts about access to and allocation of goods — raising questions about justice, fairness, and equity. The urgency or criticality of the stakeholder's claims is often diametrically opposed to the power of a stakeholder group. This phenomenon gains special relevance in environmental contexts involving potential long-term systemic risks to ecosystems, human health or livelihoods.

In conclusion, multi-stakeholder interaction and dialogue are claimed to be good for both democratic (legitimacy) and instrumental/practical reasons (combining ideas, knowledge, and other resources), for example in environmental policymaking. However, crucial questions remain regarding the sources of accountability and legitimacy in multi-stakeholder organizations, the effects for the performance of governance systems, and the appropriate institutional designs that guarantee a balance of interests and perspectives.

Integrated river basin management and its limitations

Since the 1992 Dublin and Rio de Janeiro conferences, the river basin approach to the management of water resources has become more and more established. The European Water Framework Directive (WFD) (2000) binds all EU-Member States to this approach in order to achieve its ambitious goals. Von Keitz and Kessler (2008) put this approach to test and highlighted several shortcomings of the river basin management approach as unique basis for Integrated Water Resources Management (IWRM).

From a hydrological perspective a river basin represents an independent unit from which all surface run-off flows into the sea at a single river mouth. The situation, however, is not as unequivocal when considering groundwater. A river catchment does not correspond either with a clearly delimited natural geographical unit or ecosystem or with an underlying aquifer. Problems were already encountered in the initial characterization of the water body in the WFD; this was also the case for the delimitation of water bodies and the economic analysis. With its typology of rivers and lakes, the WFD includes aspects with no relation to the river basin itself. Rivers of the same type can occur in different river basins. At the same time the water supply of a big city may come from different river basins which are not interlinked by the same integrated water basin management.

The situation is similar for pollution caused for instance by agriculture or urban areas, especially non-point pollution, which does not follow river basin limits; solutions for the problems related to these activities should rather be formulated at regional, national or European level than at the river basin level. Substantial functional problems arise when strictly applying the river basin approach in the case of groundwater, inter-basin water transfers, with the cross-media approach (soil, air, water) and within the administration.

IWRM is usually carried out at river basin scale. It does not only focus on the internal integration (water quantity and water quality), but also implies an external integration with the different water related interests/functions of the water including the ecological function. This integrated water management also includes the participation of different stakeholders and interest groups.

The management of the water takes place in an institutional setting. In some cases the boundaries of the authorities dealing with water management coincide with the water basin boundaries; however other authorities on physical planning or agriculture management are totally different. Boundaries of cities and provinces almost never comply with hydrological boundaries.

It is therefore good to realize that river basin management, IWRM and the definition of river basins are very useful as a philosophy, but not always as a template. Good integrated water resources management goes beyond basin borders!

Reference

» S. von Keitz and P. Kessler, 2008. Grenzen des Flussgebietsmanagement, Korrespondenz Wasserwirtschaft, 1: 354 - 360.

Water security

While the main paradigms in water resources governance and management are sustainability recently policy statements refer more frequently to "water security". In a recent article, Cook and Bakker (2011) analyzed the emergence of this term in academic literature. Certainly not necessarily a contradiction to the previous concepts, the term water security however indicates additional emphasis, including a potentially stronger political focus. Water security is clearly user oriented. People are the usual referent of water security and not the resource itself. Though even human water security implies more than adequate quantity and quality of drinking water. Water is withdrawn from the natural hydrological cycle or used in-stream to serve municipalities, industries, energy generation and transport as well as agriculture, which is the largest among the water use sectors on the global scale. Water security, in conformity with the principle of integration, is closely related to other "securities", first and foremost those of energy and food. Irrigation alone is accounting for over 70% of water withdrawn from rivers, lakes and aquifers. The links between water and food security are hence obvious. However, the demand for water in agriculture is increasing as the demand for food increases, while the demands for water for industrial and energy purposes are also increasing. Through the role of water as a major production factor in agriculture the food crop versus energy crop dilemma accentuates competition for water and indicates how complex the links among different aspects of security can become. In 2011 an important international multiple stakeholder conference was held to explore the water, energy and food security nexus with regard to finding sustainable solutions for a green economy (Bonn2011 Conference).

The aspirations for "security" with regard to water depend on a set of features: a functioning hydrological cycle, reliable engineering schemes, as well as legal system and effective governance, all formulated and coordinated to manage water (more) wisely. These features must take full account of the importance of the above described interdependence. An additional challenge of the security concept is that provision of water and its management and governance cannot be squeezed into a single 'water sector'. Water resources management has to respond to all substantial processes shaping our societies, economies and environment. Hitherto the role of ecosystem services and biodiversity received little attention in the engineering community. Even the influential "McKinsey Report" (2009), makes no mention of biodiversity and hardly any of ecosystems or ecosystem services.

The importance of water extends far beyond its significance for humans. Both aquatic and terrestrial ecosystems and the biodiversity they sustain depend upon provision of adequate quantities and quality of water. Meeting the needs of humans will have major implications for the supply of water required by ecosystems. Thus even human water security has more than one dimension. For example, the traditional development paradigm, particularly in dry regions, is to consider unused freshwater as 'wasted' water despite its role in sustaining rivers, inland and coastal wetlands as it flows to the sea. The potential for conflicts between water security of humans versus that of biodiversity has been discussed recently by Vörösmarty et al (2010) who had undertaken a global analysis of the magnitude of relative threats to water security based on a combination of 23 factors which may stress the water system. Many of the places where humans are currently experiencing water security are also those where freshwater biodiversity faces the greatest threat. By investing in water technology and infrastructure, developed countries could achieve adequate human water security, though frequently at the expense of aquatic biodiversity for which there were few or no counterpart adjustments. This approach reflects the "traditional" water management strategy, exercised quite widely all over the world. It is to tolerate degradation of the supporting ecosystems and then applying costly remediation strategies, if at all. As already indicated, long term water security is closely linked to sustainability.

In many parts of the world this fundamental competition for the resource exists and in the future will intensify. New approaches, aiming to satisfy human demands while securing biodiversity and ecosystem services at the same time, are urgently needed. Compromises are unavoidable. Water professionals should be able to find these and highlight the inherent tradeoffs. Professionals should be able to mediate the search for sustainable consensus solutions within multiple stakeholder contexts rather than leaving the public debate to ideologically motivated actors.

It is not conceivable that the present one billion people who suffer hunger and further two billion people on inadequate diet and the increasing population (an expected additional three billion by 2050) can be provided healthy nutrition without increasing water use in agriculture (both irrigated and rainfed), though the emphasis should be on water efficiency increases. Stabilizing the food production close to the consumers implies that more attention is paid to issues such as rural livelihoods and local level water management. It has as by-product, a potentially regulated urbanization. Thus addressing rural development issues could help reducing the rural exodus and ultimately would even help cities to cope with the water security challenges they face. The recent increase of energy crops might help improving rural income but competition with food crops has to be addressed to avoid declining food security on the expense of improving energy security.

While the specter of water scarcity has often been invoked, much less has been done to improve or encourage water use efficiency (especially in the irrigation sector) and this is a matter that needs urgent attention. As a global average, at least half of the water withdrawn for irrigation does not reach the crops it is intended for. Water use efficiency also implies protection of water quality. Rapid industrial development without applying state-of-the-art treatment and recycling of process and cooling water pollute the natural water cycle, destroys ecosystems and deteriorates human health. Further it renders water unusable for other purposes and hence aggravates water scarcity. These potentially vicious cycles show that water security is neither one-dimensional, nor can it be conceived without explicitly accounting for the intricacies of the hydrological cycle.

The present emphasis on energy crops will likely sharpen the conflict between energy and food security. The demand for cooling water, steam and the thermal pollution of recipient water bodies will remain high. Yet an improving trajectory is expected to occur, both by closing industrial water cycles and improving efficiencies. Hydropower remains an important contributor to the energy mix. Its chief function will be to provide peak energy and energy storage to stabilize the security of continuous electricity supply.

The anti-hydropower attitude of the last decades prevented the development of this renewable energy potential in several developing countries thus delaying their economic betterment. What was argued as an environmental agenda kept those countries to rely on expensive exported fossil fuel. No doubt that irreversible loss of biodiversity and vital ecosystem functions could accompany upstream reservoir constructions and modification of flow regimes to generate electricity. Policies are needed to be developed and put into practice to mitigate these potentially negative impacts. Unique riverine ecosystems should be saved from the negative effects of indiscriminate dam building. However the world cannot afford to ban this renewable energy source. It has to be recognized that even "green" energy generation might have negative impacts on environment and consensus based compromises will have to be developed.

There is another dimension of the water and energy security nexus. Providing and purifying water is very energy intensive. Withdrawing water from the natural environment and distributing to users implies pumping. In arid areas with saline ground water or in coastal zones desalinization offers an option to meet water demands. While technology improvements led to lower costs, the energy consumed for desalinization is still high. In the foreseeable future desalinization is unlikely to be a viable approach of water security with the exception of securing direct human consumption and use. Traditional sewage treatment fails to eliminate molecular scale and dissolved pollutants. Microfiltration and membrane technology imply high energy demand. Water resources management means also energy consumption with increasing trend.

References

» Bonn2011 Conference, 2012. URL: www.water-energy-food.org

» Cook, C., Bakker, K., 2012. Water Security: Debating an emerging paradigm. Global Environmental Change 22(1), pp. 94-102

» Hoff, H., 2011. Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. 51p, Stockholm Environment Institute, Stockholm

» Vörösmarty, C.J. et al, 2010. Global threats to human water security and river biodiversity. Nature I. 467 (7315), pp. 555-561.

» 2030 Water Resources Group (McKinsey), 2009. Charting Our Water Future: Economic frameworks to inform decision-making. URL: http://www.2030waterresourcesgroup.com/water_full/Charting_Our_Water_Future_Final.pdf

» GWSP IPO, 2011. Water Security: Challenges for Science and Policy – Interconnected problems of a changing world call for sustainable solutions.

Glossary and list of acronyms

ACRU	Agricultural Catchments Research Unit, agro-hydrological model (for further information see: University of KwaZulu-Natal)
AfDB	African Development Bank
alfalfa	also lucerne, perennial forage crop
AMMA	African Monsoon Multidisciplinary Analyses
AQUACROP	crop-model to simulate yield response to water, developed by FAO (for further information see: FAO)
ASCE	American Society of Civil Engineers
ASEAN	Association of Southeast Asian Nations
AVHRR	Advanced Very High Resolution Radiometer (space-borne sensor on board of the NOAA polar orbiting platforms)
AWBM	Annual Water Balance Method
BCW	Beaver Creek Watershed
Bern CC	climate/carbon cycle model with coupled ocean, atmosphere and terrestrial biosphere components
Blue water	technical term usually referring to the water available in surface and saturated ground water bodies
BMBF	Bundesministerium für Bildung und Forschung, German Federal Ministry of Education and Research
BMP	Best Management Practice
BOD	biological oxygen demand, biochemical oxygen demand
BOKU	University of Natural Resources and Life Sciences, Vienna
BRIC	grouping acronym for the countries of Brazil, Russia, India and China – since 2010 called BRICS, including South Africa
BW	blue water
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute
CAS	Chinese Academy of Science
CBD	Convention on Biological Diversity (international legally binding treaty on the conservation of biological diversity, for further information see: http://www.cbd.int)
CCR	Central Commission for Navigation on the Rhine
CC-WaterS	research project: Climate Change and Water Supply
CESR	Center for Environmental Systems Research, University of Kassel
CFC	chloro-fluorocarbons
CFI	Canadian Fertilizer Institute
CFT	crop functional types (generalised crop prototypes designed to capture the multitude of structures and functions of crops as used in the LPJmL, for further information see: Bondeau A, Smith P, Zaehle S, Schaphoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Müller C, Reichstein M, Smith B (2007): Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13)
Cote d'Ivoire	Ivory Coast
CP	Circulation Pattern
CROPWAT	software for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data, developed by FAO (for further information see: FAO)
CRU	Climatic Research Unit
CRW	Cline River Watershed
CWP	crop water productivity
DAAD	Deutscher Akademischer Austauschdienst, German Academic Exchange Service
DFI	Development finance institution
DLBRM	Distributed Large Basin Runoff Model, developed by NOAA (for further information see: NOAA)
DPSIR	Driving forces, Pressures, States, Impacts and Responses (causal framework for describing the interactions between society and the causal framework for describing the interactions between society and the environment adopted by the European Environment Agencyfor further information see: EEA)
ECAFE	United Nations Economic Commission for Asia and the Far East
ECHAM	European Centre Hamburg Model (atmospheric GCM developed by the MPI-M, for further information see: MPI-M)
ECOWAS	Economic Community Of West African States
EEA	European Environment Agency
EIA	environmental impact assessment
ENSO	El Niño-Southern Oscillation (a quasi-periodic climate pattern that occurs across the tropical Pacific Ocean roughly every five years)
ESCAP	United Nations Economic and Social Commission for Asia and the Pacific

ESI	Environmental Sustainability Index
ESSP	Earth System Science Partnership
ET	evapotranspiration
ETo	reference evapotranspiration (from a well-watered crop)
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FDI	foreign direct investment
FRIEND	Flow Regimes from International Experimental and Network Data (international research programme of UNESCO IHP to set up regional networks for analyzing hydrological data)
GCCM	Global Climate Change Model
GCM	Global Circulation Model, also General Circulation Model (mathematical model of the general circulation of a planetary atmosphere or ocean)
GDP	Gross Domestic Product
GEF	Global Environment Facility (international financial organization to address global environmental issues)
GEO	Group on Earth Observations (voluntary partnership of governments and international organizations for collaboration in Earth observation)
GEOSS	Global Earth Observation System of Systems (interconnects the Earth observation systems that are owned and maintained by the member governments and participating organizations of GEO, for further information see: GEOSS)
GIS	geographic information system
GLOWA	Globaler Wandel des Wasserkreislaufes, Global Change in the Hydrological Cycle (research project supported by BMBF for the development of simulation-tools to realize a sustainable water management under global change conditions)
GLOWA IMPETUS	Integratives Management Projekt für einen effizienten und tragfähigen Umgang mit Süßwasser in Westafrika, An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa
GNI	Gross National Income
Green water	technical term usually referring to the water captured in the vadose zone and plants, being returned to the atmosphere via evaporation and transpiration
GW	green water
GWP	Global Water Partnership
GWSP	Global Water System Project
GWSP IPO	Global Water System Project International Project Office, hosted by ZEF
GZ	groundwater zone
HDI	Human Development Index
HHH region	Huang-Huai-Hai region in China
HRU	hydrological response unit
IAWR	International Association of Waterworks in the Rhine Basin
IBWT	Inter-basin water transfer
ICPDR	International Commission for the Protection of the Danube River
ICPR	International Commission for the Protection of the Rhine
IEEE	Institute of Electrical and Electronics Engineers
IMPETUS	see GLOWA IMPETUS
IMS	information management system
IO	input-output
IPCC	Intergovernmental Panel on Climate Change
IPCC SRES	IPCC Special Report Emission Scenarios
ITCZ	Inter Tropical Convergence Zone
IWRM	Integrated Water Resources Management
Kolkhoz	collective farm in the former Soviet Union, plural kolkhozy
Lat	latitude
LEGOS	Laboratoire d'études en géophysique et océanographie spatiales
Lon	longitude
LPJmL	Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model (simulates vegetation composition and distribution, stocks and land-atmosphere exchange flows of carbon and water for both natural and agricultural ecosystems, for further information see: PIK)
LSZ	lower soil zone
LWSB	Lake Winnipeg Stewardship Board
MAD	Moroccan dirham
MAFRI	Manitoba Agriculture, Food and Rural Initiatives
MAP	mean annual precipitation
MDGs	Millennium Development Goals (eight international development goals that the UN member states and several international organizations agreed to achieve by the year 2015)
MEA	Multilateral Environmental Agreement
MENA	Middle East and North Africa
MODIS	Moderate Resolution Imaging Spectroradiometer (scientific instrument to measure electromagnetic radiation, launched by NASA)
MPI-M	Max Planck Institute for Meteorology
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
MW	Megawatt
NASA	US National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NDVI	Normalized Difference Vegetation Index
NERC CEH	National Environment Research Council - Centre for Ecology and Hydrology
NGO	non-governmental organization

NHS	National Hydrological Service
NLWIS	National Land Water Information System
NOAA	National Oceanic and Atmospheric Administration
NMC	National Mekong Committee
NVWI	Net virtual water import
NWRC	National Water Resources Council
OCHA	UN Office for the Coordination of Humanitarian Affairs
OECD	Organization for Economic Cooperation and Development
PCIC	Pacific Climate Impacts Consortium
PDM	Project Depletion Method
PDO	Pacific Decadal Oscillation (pattern of Pacific climate variability that shifts phases on at least inter-decadal time scale)
PESERA	Pan-European Soil Erosion Risk Assessment
PIK	Potsdam-Institut für Klimafolgenforschung, Potsdam Institute for Climate Impact Research, Germany
POP	persistent organic pollutant
PPWB	Prairie Provinces Water Board
PRB	Pahang River Basin
Ramsar	"The Convention on Wetlands of International Importance, especially as Waterfowl Habitat", named after the location of adoption in Iran (for further information see: www.ramsar.org)
RAP	Rhine Action Programme
RBO	river basin organization
RCM	Regional Climate Model
REMO	Regional Model (tool for climate modelling and weather forecasting on a regional scale for further information see: REMO)
RMSE	root mean square error
RWHT	rainwater harvesting techniques
SCENES	Water Scenarios for Europe and for Neighbouring State, EU funded research project
schistosomiasis	sickness of bilharzia, bilharziosis or snail fever
SEI	Stockholm Environment Institute
Simulium damnosum	black fly spreading river blindness (onchocerciasis)
Sovkhoz	state farm in the former Soviet Union, plural sovkhozy
SSA	sub-Saharan Africa
SWAT	Soil and Water Assessment Tool; (river basin scale model developed to quantify the impact of land management practices in large, complex watersheds; for further information see: SWAT)
SWE	snow water equivalent
SYKE	Finnish Environment Institute
TARWR	Total Actual Renewable Water Resources
Tindana	Ghanaian term for traditional leader, also referred to as earth priest
Trypanosomiasis	sleeping sickness
UFZ	Helmholtz-Zentrum für Umweltforschung, Helmholtz Centre for Environmental Research, located in Magdeburg and Leipzig, Germany
UK	United Kingdom of Great Britain and Northern Ireland
UN	United Nations
UNDAC	United Nations Disaster Assessment and Coordination
UNDP	United Nations Development Programme
UNECA	United Nations Economic Commission for Africa
UNEP	United Nations Environment Programme
UNEP GEF	see GEF
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNESCO IHE	UNESCO Institute for Water Education
UNESCO IHP	UNESCO International Hydrological Programme (intergovernmental programme of the UN system devoted to water research, water resources management, education, and capacity building)
UN Water	interagency mechanism for coordination and coherence among all UN organizations that work on freshwater and sanitation
UNCSD	United Nations Commission on Sustainable Development
UNSRB	Upper North Saskatchewan River Basin
US	United States of America
USGS	United States Geological Service
USLE	Universal Soil Loss Equation (mathematical model used to describe and predict soil erosion processes)
USSR	Union of Soviet Socialist Republics
USZ	upper soil zone
vadose zone	"unsaturated soil", extends from the top of the ground surface to the beginning of the groundwater table
Virtual water	water required in the production process of goods and services
VRA	Volta River Authority
WATCH	Water and Global Change Project
Water footprint	volume of water used to produce the goods and services consumed by people
WaterGAP	Water - Global Analysis and Prognosis (global water resources and water use model developed by the CESR for further information see: CESR)
WBI	Wellbeing Index
WDM	Water Demand Management
WEAP	Water Evaluation And Planning System (decision support system for integrated water resources management and policy analysis, developed by SEI for further information see: www.weap21.org)

WFD	EU Water Framework Directive, European Union legislation which commits member states to achieve good qualitative and quantitative status of all water bodies by 2015
WHYCOS	World Hydrological Cycle Observing System
WMO	World Meteorological Organisation
WorldQual	large-scale water quality model
WRC	Water Resources Commission of Ghana, also: South African Water Research Commission
WRM	Water Resources Management
WUA	Water User Association
WWAP	World Water Assessment Programme of UN Water, hosted by UNESCO
WWDR	World Water Development Report, coordinated by WWAP
ZAR	South African Rand
ZEF	Zentrum für Entwicklungsforschung, Center for Development Research, University of Bonn