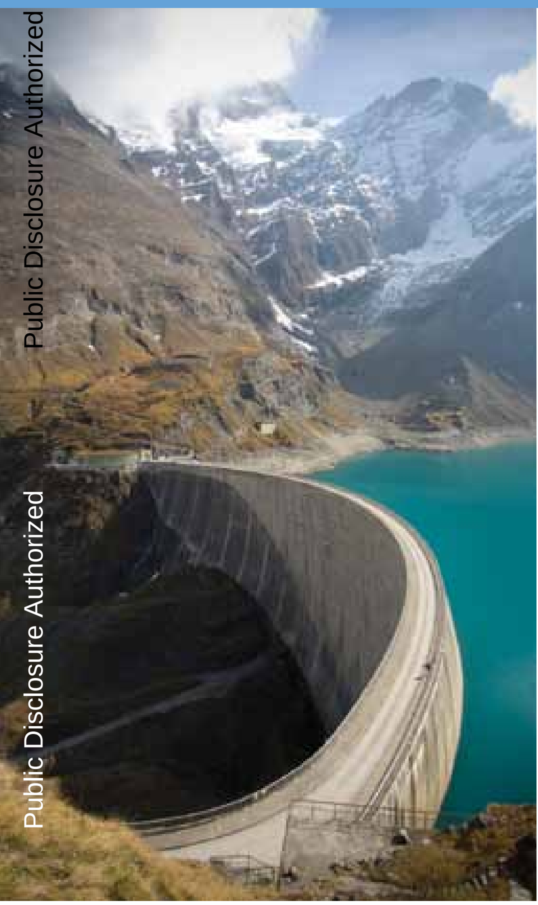
59808 v1

A REVIEW OF SELECTED HYDROLOGY TOPICS TO SUPPORT BANK OPERATIONS

HEF Technical Report 1 – June 2010



HEF
HYDROLOGY EXPERT FACILITY
AN EXPERT SUPPORT TEAM (EST)
OF THE WATER PARTNERSHIP
PROGRAM (WPP)

THE WORLD BANK

bnwpp
Bank-Netherlands
Water Partnership Program

WATER
PARTNERSHIP
PROGRAM

Acknowledgments

This document was prepared by Luis E. García and Gabrielle Puz under the direction of Abel Mejia, former Manager of the Water Anchor. The authors thank the workshop presenters, and discussants, namely, Torkil • nch Clausen, • anusz Kindler, • uan B. Valdés, Bob Meade, • effrey Richey, Peter Droogers, Ignacio Rodriguez-Iturbe, Kenneth Strzepek, Pedro Restrepo, Curt Barrett, Peter • . Kolsky, Stephen Foster, Douglas C. Olson, Nagaraja Rao Harshadeep, Winston u, Ronald N. Hoffer, Grant Milne, Bekele Debele Negewo, • ulia Bucknall, Paola Agostini, for their valuable contributions. The collaboration and participation in the workshop of NOAA, USACE, SWAT, and GW-MATE is gratefully acknowledged. Diego Rodriguez, Arno Boersma, Azamat Tashev, Meike van Ginneken, Immaculate Bampadde, Parivash Mehrdadi, Zsuzsanna P. Baldiviezo, Sanna-Leena Anneli Rautanen, Eileen Burke, Hywon Cha Kim, Doreen Kirabo, Eric Dickson, Benedicte Marie Cecile Augeard, contributed to the organization and realization of the workshop. The workshop and the publication of this report were made possible by the financial support provided by the Bank Netherlands Water Partnership Program (BNWPP) and the Water Partnership Program (WPP). Special thanks to Ashok Subramanian and the peer reviewers Matthijs Schuring, Rita Cestti and Grant Milne, who provided valuable guidance and suggestions for this report.

Disclaimer

A Review of Selected Hydrology Topics to Support Bank Operations

THE WORLD BANK

Papers from the Workshop
Hydrologic Analysis to Inform Bank Policies and Projects: Bridging the Gap
November 24–25, 2008
Washington, DC

Washington, DC, June 30, 2010

Table of Contents

Introduction

The World Bank's 2004 Water Resources Sector Strategy focused on the need for both water resources management and development in dealing with growth and poverty alleviation. Planning and design of new hydraulic infrastructure for water supply and sanitation, food production, hydropower generation, flood protection, ecosystem restoration or other such purposes require dealing with all elements in the interaction among land, water, vegetation, human intervention and climate variability and change, with an emphasis on the end-user. They also require the simultaneous consideration of technical, economic, institutional (governance), political, financial, environmental and social factors, as called for in the Bank's 1993 Water Resources Management Policy.

To provide high-level insight on the key hydrology issues involved, a group of world class experts gathered at a workshop held at World Bank Headquarters in November 2008. The workshop was organized by the Hydrology Expert Facility (HEF) of the Water Anchor. The presenters discussed advancements in key hydrologic topics that were selected for their relevance to Bank operations. The focus was on potential implications for the Bank's development assistance on water projects, programs and policies.

A wide spectrum of topics was presented for discussion in a workshop that was more exploratory than analytical. Its main purpose was to identify the interest of the Bank's water community for those topics that could jointly be moved forward by following actions aimed at further dissemination and development of specific knowledge products.

The remainder of this introduction provides a brief description of the topics and lays forth the **reasons for selecting** each of them for discussion at the workshop.

Integrated Water Resources Management

This topic was selected because of its importance in current World Bank support for the role that water plays in the development process. The concept of integrated water resources management (IWRM) was embraced by the Bank's 1993 Water Resources Management Policy Paper and the ensuing 2004 Water Resources Sector Strategy, which gave strategic directions for World Bank engagement in water. Climate changes, as well as changing conditions in river basins and watersheds, demand the development and implementation of new **integrated water resources** approaches while addressing the reality of low capacity and unfavorable local conditions. In these new approaches, the focus is on reaching the end user and achieving results in the field, stressing the importance of multisector and multistakeholder participation to address the often conflicting interests of major water uses in a basin or watershed management context. Although IWRM is a widely accepted concept, it has encountered hurdles in implementation that go beyond the conceptual phase and require additional analysis and discussion.

> The three-part paper by **Torkil Jønch-Clausen** focuses on integrated water resources management (IWRM) "beyond the conceptual phase," moving away from the rhetoric to results "on the ground." Part 1 of this paper provides a brief status update of IWRM and how its principles are actually being applied around the world. In Part 2, recent work by the author in Orissa, India, is used to illustrate how a "roadmap for IWRM" can, in fact, help a state (or country) define the relevant small steps leading towards improved water resources development and management. In Part 3 the author provides some brief personal reflections on how IWRM has evolved in the World Bank.

Water scarcity and the degradation of water quality (both surface and groundwater) are reaching alarming proportions in many parts of the world. It is often better, in economic and environmental terms, to manage existing supplies than to develop new ones. **Demand management** on a national and basin level, as well as in urban areas, has become an important component of policy making and water resources planning and management. This topic was selected to underline the importance of undertaking adequate demand management analyses in Bank water projects that focus on growth-oriented sustainable poverty alleviation, especially in water scarce areas. It is also important because of the challenges that need to be faced in this area. Increased scarcity and costs highlight the importance of increased efficiency. Challenges differ at different scales and for different users, and while water demand analysis has advanced considerably over the last decades, there are still many unresolved issues and limitations requiring more research.

> In his paper, **Janusz Kindler** synthesizes the state of the art in this area and reflects on how it can be applied to water sector policies and water projects. The author presents the fundamentals of water demand analysis and modeling approaches, and then discusses the demands of individual water users, such as households, industrial plants and irrigation systems. Special attention is given to the relatively new group of hydro-economic models and their role in water demand analyses. The paper closes with a few comments on the role of water demand analysis, its limitations, and further research needs.

Climate Variability and Change

The latest reports issued by the Intergovernmental Panel on Climate Change (IPCC) indicate that climate change will intensify the hydrological cycle, making **hydrologic extremes** like floods and droughts more frequent and of higher magnitude. As a result of their limited resources and stream-flow regulation capacity, developing countries will be disproportionately affected by the projected increased variability of precipitation and frequency of extreme events.

Most of the existing hydraulic infrastructure was designed using parameters and analytical tools established some decades ago, under different climatic and geographical conditions from those prevailing today or expected to prevail in the future. Hydraulic infrastructure design assumes stationary hydrological processes. However, if climate change follows projected scenarios, the **stationary assumption** might no longer be valid. More erratic weather is projected, including extreme variability of precipitation. Experts in the field are still debating whether climate change requires different planning criteria for dealing with climate variability, or whether climate change simply represents one more factor to consider in the usual analysis.

The selection of this topic follows the need to maintain a focus on data, even if basic hydrologic assumptions such as stationarity, are under scrutiny. The topic was also selected to stress the importance of not losing sight of the need to account for climate variability for the planning, design, and operation of water resources projects in the short and medium term, along with climate change in the long term.

> In his paper, **Juan Valdés** discusses efforts to characterize floods and droughts and refers to the state of the practice in dealing with extremes based on instrumental records and the hypothesis of stationarity. He also discusses the importance of maintaining data collection under non-stationarity conditions and using paleoclimatic data to increase the instrumental record length, the use of climate projections from the most recent runs of the global circulation models (GCMs) for hydrologic applications, and the implications of climate variability and change on the management of water resources systems.

Hydrologic Interactions

There are many hydrologic interactions. However, three were selected for this discussion because of their importance to the Bank's water-related portfolio. These interactions are erosion and sedimentation, land-water interactions, and management of evapotranspiration.

Erosion and Sedimentation. This issue was selected for discussion during the workshop because it is among the major water and soil degradation problems in many large river basins throughout the world. As more and more terrestrial materials are delivered to freshwater and coastal ecosystems, the interactions and conditions of upstream erosion and downstream sedimentation acquire renewed importance. The Bank's 2004 Water Resources Sector Strategy called for renewed attention to hydraulic infrastructure built to alleviate poverty because of its complementarities with other environmental, institutional and social measures within an IWRM approach. Proposals for the construction of reservoirs and dams are expected to increase as climate change increases water scarcity and variability. The economic life of the infrastructure will be affected by the sediment load they trap, while at the same time, downstream impacts of changing sedimentation patterns can be considerable.

The paper by **Robert H. Meade** focuses on the significance of stationarity for sediment studies in rivers and how this concept has worked against monitoring programs by implying that predictive models could substitute for actual measurements. The author uses examples from the Colorado, Amazon and other major rivers to discuss the difference between intrinsic non-stationarity and non-stationarity of measurement and purpose.

Land-water Interactions. These were specifically chosen to highlight their significance and the need for paying increased attention to integrated approaches. These interactions are particularly important because there are few instances of Bank engagement in the coastal zones. The volume and quality of water at any given point of a stream, lake or aquifer is a function of the precipitation regime as well as the geophysical characteristics of the catchments and the land-water interactions occurring in them, from the water divide to the ocean. These conditions are also changing continuously. Human intervention in watersheds and river basins is now so widespread that human activity must be considered part of the hydrological cycle and taken into account in a comprehensive manner as water moves from its source to its sink in the coastal areas.

The paper by **Jeffrey Richey** presents a "systems-level" overview of the key processes and transitions, from land to rivers to oceans and their marine fate. It summarizes the types of issues confronted in coastal-focused topic areas. The author also discusses World Bank environment and water projects as a means of identifying existing projects and their requirements. He also presents a case study of the Mekong River basin, as an example of a full suite of land-to-ocean issues. Finally, Richey's paper advances the concept of a "virtual river/coastal basin," driven by a "dynamic information framework," as a means to provide a convergence of cross-sector information.

Management of Evapotranspiration (ET). The bulk of the world's agricultural production (82 percent) continues to be rainfed (as opposed to irrigated). In developing countries, rainfed agriculture accounts for 60 percent of agricultural output. In arid and semiarid regions, water management is crucial for agricultural production. As new methodologies for efficient water use have acquired new relevance, ET has been shown to be a key component of the hydrological balance. A focus on the management of evapotranspiration is required to understand water-related issues and improve water management. The concept of ET management requires innovative tools such as remote sensing, which many believe is the only tool currently available to monitor ET over large areas.

Peter Droogers discusses the importance of focusing on evapotranspiration as the dominant water consumer. His paper discusses methodologies to support policy makers and water administrators to manage evapotranspiration. It also provides practical examples from China and Egypt. Droogers advocates the inclusion of a combination of remote sensing and simulation models in policy support tools and introduces the concept of scenario-based modeling.

Associated Changes in Climate and Land Use

This topic was chosen to discuss the links between climate change and land use and how the potential effects of these changes interact and reflect on the water resources of a region and its ecosystem, as well as how to quantify these changes. Rapid changes in land use and access to water resources have been posited to be the greatest challenges facing many regions of the world. Global climate change models also predict an increase in total rainfall and rainfall variability in some regions and decreases in others. Local climatic observations can provide reasonable predictions of the impacts of changes and feedbacks on the natural system. Information derived from these models and from hydrologic and meteorological time-series will always be needed, but it is not sufficient. Watershed geomorphology, vegetation cover, soil and land use are of increasing importance in water resources management because they are dynamically linked to climate.

In his paper, **Ignacio Rodríguez-Iturbe** posits that accounting only for changes in mean responses to climatic variability is not sufficient for a realistic evaluation of the impact of climate change on ecosystems. Changes in the dynamics of less frequent and stronger rainfall events will have larger consequences for the assimilation process and survival of vegetation. An increase in the intensity of rainfall events also leads to other types of ecohydrological consequences especially in aspects related to soil erosion. His paper also focuses on those challenges where ecohydrology will contribute decisively to the understanding needed to ameliorate and manage these effects.

Key Messages

Workshop presentations and discussions yielded several key messages about integrated water resources management, climate variability and change, hydrologic interactions and associated changes in climate and land use, which are discussed below.

Integrated Water Resources Management

- IWRM requires facing many challenges. There is a need to integrate across different spatial scales, all the way from river basin to the national level. In addition, there is a need to integrate across sectors and in terms of the environment and other cross-sector activities, which are much more difficult to handle. It is also necessary to integrate across institutional functions and responsibilities, which is probably the most challenging of all.
- There is also a need to balance the old challenges of growth, poverty, and other development issues with new emerging challenges posed by global climate change. This rebalancing must take into account global economic links as well as increasing financing needs and fixed (if not decreasing) financial resources.
- The issue of monitoring water use cannot be overemphasized. The balance between the supply of and demand for water requires the quantification of water availability and water use: How much is actually being extracted from a given source and how much is the intake for each and all of the different uses in a given watershed or river basin. However, developing countries usually lack monitoring or measurement capabilities. They also lack a system of water rights and an inventory and characterization of wastewater discharges. It is not possible to manage what is not measured; this is a most basic part of water resources management that developing countries need to address.
- The demand management approach embedded in the concept of IWRM implies that water use has to be measured to price it on a volumetric basis in order to ensure that it is being charged and that users are paying for that use. Otherwise, water charges are not going to be a factor in water use efficiency and there is not going to be any change in how much water is wasted.
- There are other issues related to efficiency that go beyond water charges. For example, improving irrigation efficiency does not necessarily mean that water is going to be saved in the basin because when water is diverted and transported, a portion of it recharges groundwater. Also, if efficiency is improved, the return flows decrease and the amount that is consumed increases.
- More attention needs to be paid to flood prevention in IWRM. Flood management is largely an afterthought in the countries with which the Bank works. Mostly, attention has been given to mitigation measures once a flood has occurred. But that is much more expensive than preventive approaches.
- Integrated water resources management links top-down and bottom-up approaches. Top-down approaches (that is, laws and policies, regulations, standards) are applied mostly in the developing world. However, bottom-up approaches require increased attention. Work actually starts in the field with the water users and uses, regulating discharges and managing water at the very local level.
- To improve the management of water resources in any given river basin, there is a need to slowly move away from the project-by-project approach and actually apply and achieve the integrated water sources management concepts. This implies the improved planning and management of water use, improved construction and operation of infrastructure, improved reliability of extreme event forecasting, and so on.
- In order to move towards using modern systems and approaches, decision support tools and systems should be employed that rely on new and innovative ways of doing things (something that was not possible just a few years ago). This will require a special and sustained effort within the Bank environment and is perhaps where the major challenge lies.

Climate Variability and Change

- Hydrologists have not spoken out about climate change as much as professionals in other fields. This may drive the Bank in some potentially unexpected ways, particularly if not enough attention is given to the effects of climate change on water resources. In this realm, the focus should be on precipitation and stream flow, rather than temperature. Shifts in precipitation will result in shorter but perhaps more intense periods of rainfall, an issue that needs to be looked at in more detail.

- The study of climate variability and change is rife with uncertainty. Thus, the use of uncertainty analysis should be encouraged to help evaluate policy and project options. In addition, models can also be a useful tool. A modeling system that meets user needs from the basin down to the sub-watershed or micro watershed level is required. However, the availability and use of models should not mean that measurement and monitoring of key variables should cease. Quite to the contrary, the uncertainties surrounding non-stationarity require that monitoring be continued and accurate records be kept for as long as possible and by any means possible.
- Models that operate at the basin/sub-basin level are needed to establish a broader context in the area of watershed management. These models could help guide watershed projects, which tend to operate more at a sub-watershed and micro-watershed level. Nevertheless, no single model can do it all. A common language is needed for seamless communication among different models so that all contribute to obtaining a better idea of the bigger picture.
- Models are useful even when their results are not entirely correct because they facilitate communication. Yet, to take full advantage of this feature, transparency in the application of models needs to be improved. Explanations about how to use the models are particularly important, as are means to communicate with users of all types, including those who may be less sophisticated in the area of modeling. Models should be easier for non-experts to understand. A step in this direction is to improve the ability to visualize results in graphical form.
- Rising awareness of the effects of climate variability and change on water resources is not only important for practitioners or policy makers. The media and society as a whole also need to become more informed about this topic.

Hydrologic Interactions

- Hydrologic interactions are complex and often difficult to take into account in a comprehensive way. In many of the places where the Bank provides assistance, data and data collection remain challenging issues. Appropriate time and effort should be devoted during project preparation for data collection and analysis. At least a year of data should be collected regardless of the project or whether it relates to hydrology, sediment or other relevant topics. Also, sufficient time should be available at this stage of project preparation for analysts to look at the trends provided by the information gathered.
- More thought should be given to the selection and relevance for analysis of extreme events. The impacts of highly improbable but possible events should be duly considered in order to identify the latest techniques to deal with them.
- The most important advances in the area of evapotranspiration are not the reexamination of the hydrologic cycle or efforts to educate policy makers so they begin to think more like hydrologists. Indeed, the most important tools in evapotranspiration are satellite technologies and other remote sensing products that many Bank clients can use. In terms of continuity and accuracy, the better approach might be a judicious mix of on-the-ground information and images from satellites and other remote sensing platforms.
- There has been a tendency to focus on environmental flows to ensure that enough water is reaching coastal wetlands and mangrove forests. However, the issue of the quality and chemical constituents of that water need to be further examined. Additional areas that require attention include watershed characteristics and sediment yields, as well as how those sediment yields may be affected by changes in basin development or land use.
- Projects are often prepared by government agencies without the benefit of all the expertise that may exist within their own jurisdictions. Agencies should be encouraged to avail themselves of this expertise. Specific efforts should be made to ensure that stakeholders are engaged with the project at an early stage. Although many developing countries may have strong legal or policy frameworks, they often lack the data, capacity, and institutions to move projects forward. This is also an area that requires strengthening. Finally, project managers should consider bringing in experts in other disciplines.

Associated Changes in Climate and Land Use

- The availability of water at a given site in a watershed or river basin depends on the amount of precipitation and of the response of the watershed or basin. However, stream flows may sometimes change because conditions other than precipitation, such as land use, have changed. Land use is an important factor that needs to be taken into consideration.

- Among other things, land use affects vegetation cover and, as a result, the dynamic relationship among climate, land use and vegetation. It is important to address forest health and changes in forest cover, as well as changes in crop selection by farmers. However, just as important is the management of water resources and future water needs focusing on how changes in precipitation and stream flow affect the water balance, and also on the interrelated changes in vegetation cover, soil moisture, and so on.
- Models and model results are needed to improve understanding and raise awareness about the interactions among water, land, vegetation, and evapotranspiration, particularly with respect to climate change.
- The temporal distribution of hydrological variables is as important as their spatial distribution. The main factor to consider in the practical application of climate change conditions to water resources management and use, to floods, to ecosystem response and so on, is not necessarily how the mean value of each variable has changed because the mean may have remained the same. It may be more important to analyze the rate of change during different seasons throughout the year, the number of rainy days and the amount of precipitation during each rainy day.

Papers

This section contains the papers that were submitted and presented at the November 2008 workshop, as prepared by the authors. Power point presentations and the presenters' biographical information are included in an accompanying CD. All views expressed are those of the authors.

1. Application of Integrated Approaches in Water Resources Management Beyond the Conceptual Phase

Torkil Jønch-Clausen
Water Policy Adviser, DHI Group

Abstract

The title of this workshop emphasizes “beyond the conceptual phase.” At this point in time that is very appropriate. Integrated water resources management (IWRM) has been a key concept driving the rhetoric, policies and strategies of countries, development banks, donor agencies and many international organizations for more than a decade. However, because it appears to be difficult to show results in the field, questions have been raised about the concept itself.

Part 1 of this paper briefly describes the current (November 2008) status of IWRM: Why was this concept developed and taken to heart by so many; what (in brief) the author understands by IWRM, and how IWRM principles are actually being applied throughout the world. Part 2 relies on recent work by the author in Orissa, India, to illustrate how a “roadmap for IWRM” can help a state (or country) define the relevant small steps necessary to improve water resources development and management. In Part 3, the author provides some brief personal reflections on how IWRM has evolved in the World Bank.

This paper builds on recent work by the author in collaboration with DHI colleagues in Denmark,[1] and the Asian Development Bank’s Technical Assistance to the State of Orissa.[2] This support is gratefully acknowledged.

Introduction

The world is facing serious water challenges, driven mainly by population and economic growth. Water is essential in achieving the Millennium Development Goals to reduce poverty, hunger, diseases, and environmental degradation. Increased investments in water are fundamental to continued economic growth, and job creation, in both rich and poor countries. In addition, many countries, but particularly developing countries with poor capacity and infrastructure, are vulnerable to the impact of climate change. Addressing their needs requires investment in appropriate adaptation measures.

In an increasing number of countries water scarcity and deteriorating water quality have been or will soon become critical factors limiting national economic development, expansion of food production and/or provision of basic health and hygiene services to the population. Extreme events such as floods and droughts add to this challenge. The current concerns about adaptation to climate change call for integrated approaches in all countries.

Improved water governance can be achieved through integrated water resources management. At the national level, IWRM provides a basis for balancing the different demands on a country’s water resources. Investments in water infrastructure, water allocation decisions, and

1. A paper entitled “IWRM in Action” was drafted in 2008 by Jan Hassing, Niels Ipsen, Torkil Jønch Clausen and Henrik Larsen, of DHI Water Environment Health and the UNEP-DHI Centre for Water and Environment, in Hørsholm, Denmark, as a special contribution to the World Water Development Report. Passages from this draft paper are quoted.
2. Orissa Integrated Irrigated Agriculture and Water Management Investment Program (OIIAWMIP), Technical Assistance for Integrated Water Resources Management (IWRM) in Orissa, supported by the Asian Development Bank and carried out in cooperation with Prof. B. Das.

water management actions and policies have an impact on a country's achievements in multiple ways. IWRM is an approach that can capitalize on the opportunities for synergies and help reconcile difficult trade-offs in the achievement of these goals. Hence, a lot of the "integration" in IWRM takes place at the basin scale, whether at the local catchment or aquifer, or at the multi-state or multi-country river basin.

Like any other reform, IWRM is a process that could take several decades. In France, the process was started with the establishment of basin agencies in 1968. Other important milestones were a revised water law in 1992, which was amended to comply with the European Union's Water Framework Directive in 2003. In Spain, maturing of the process has lasted close to 80 years. Other countries, such as India, have started to respond to these kinds of challenges in a number of ways. A National Water Policy was adopted in India in 2002 (updating the first version of 1987) that is strongly inspired by IWRM. In Orissa, India, the process of reforming and developing the water sector started in 2008. This case illustrates the realities of trying to "introduce IWRM on the ground."

Part 1 – Integrated Approaches in Water Resources Management: Theory and Practice

Water Resources and Key Global Development Issues

In addition to satisfying basic human needs for domestic water supplies and basic sanitation (particularly in developing countries), increasing and acute water challenges in the world relate to energy, food and the environment. Increased investments in water infrastructure and management are required to sustain this development, especially in the face of considerable increases in electricity consumption[3] for both domestic and industrial needs. A new focus on the production of biofuels, and the significant acceleration in hydropower production are also part of the solution. In an effort to meet the main food challenge of reducing hunger among the poorest people of the world, economic growth and increasing welfare for large parts of the population, have implied changes towards more water consuming diets that add to current agricultural water requirements. In other words, the current energy and food crises are intricately related to water. Moreover, other sectors are placing increasing demands on water resources. This includes the growing industrial and mining sectors of developing countries, as well as tourism and navigation. This added pressure is being placed on the already stressed and vulnerable water resources, raising the question of whether the ecosystems on which biodiversity and the livelihoods of millions of poor people depend can be sustained. Protecting the environment calls for massive investments in wastewater treatment and pollution reduction, along with maintenance of environmental flows for downstream ecosystems.

Water Resources and the Millennium Development Goals

The main challenges for developing countries are addressing such basic societal issues as poverty, hunger, education, gender equality, health, and environmental sustainability, as expressed in the Millennium Development Goals (MDGs). Adequate water availability and quality, and thus prudent water resources management, are important contributions to achieving these goals.

Water is basic to food production, and hence clearly a factor in reducing poverty and hunger. The productivity of irrigated agriculture is particularly dependent on rational and wise water resources management. Moreover, activities surrounding agricultural production help create jobs for the poor. Water related diseases (such as diarrheal diseases, malaria, bilharzias, and cholera) are among the most common causes of death in developing countries, and the poorest segments of the population often bear the heaviest burden, not least the women who carry the daily responsibility for the health of their families. Natural resources and ecosystems face increasing degradation as a result of unsustainable exploitation, often for short-term gains. Degraded ecosystems can no longer retain their productivity and provide essential goods and services to sustain biodiversity and livelihoods.

3. Annual growth in Asia has been between 5 and 8 percent.

Countries Experience Serious Water Governance Issues

The recognition of the need to redress the effects of weak water governance structures has convinced many countries that a new water management framework is needed. Other common critical issues are listed below.

- Awareness of water issues, as well as the political priority given to them, are limited.
- Institutions are often rooted in a centralized culture with supply-driven management and fragmented and subsector approaches to water management. Few water managers view water holistically.
- Local governments lack the capacity to manage the different demands and pressures placed on water resources.
- Inappropriate pricing structures, and hence limited cost recovery, result in the inefficient operation and maintenance of water systems, as well as in the misallocation and loss of water.
- Investments in the water sector are low and do not get sufficient attention in national budgeting discussions.
- Information and data to support sound water management are generally lacking.
- Economic, social, and environmental criteria for the approval of policies, plans, and projects are most often few and inadequate.

Towards Integrated Water Resources Management

Improved water governance can be achieved through the integrated management of water resources. The Global Water Partnership (2000) defines it as:

> A process that promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

IWRM is a comprehensive approach to the development and management of water, addressing its management both as a resource and, in establishing the framework for the provision of water services, as a political process that involves conflicts of interest that must be mediated. Effective water governance is crucial for the implementation of IWRM.

The concept of IWRM was already recognized in Agenda 21 (the UN Conference on Environment and Development, which took place in Rio in 1992) and is to a large extent based on the four Dublin Principles developed earlier that year.[4] Inspired by the Dublin Principles, the World Bank developed its Water Resources Management Policy in 1993. Ten year later, in 2002, the Plan of Implementation adopted at the World Summit on Sustainable Development in Johannesburg (WSSD) called for countries to "develop Integrated Water Resources Management and Water Efficiency Plans by 2005." These plans were to be milestones in cyclic and long-term national water strategy processes, and progress in their development and implementation has been measured regularly at the World Water Forums (the most recent for this paper took place in Mexico in 2006) and by the Commission for Sustainable Development (CSD, most recently in 2008).

IWRM is not a scientific theory, which needs to be proved or disproved by scholars, but a simple framework to understand water in its larger economic, political and societal contexts. IWRM has proven to be a flexible approach to water management that is adaptable to diverse local and national contexts. This requires policy makers to make judgments about which set of suggestions and reform measures, management tools or institutional arrangements are most appropriate given the particular cultural, social, political, economic and environmental circumstances they are facing.

One of the great strengths of IWRM and its principles and concepts is that it has given the water community a common language, which is applicable over a wide range of levels from the local to the national and regional. This allows

4. The UN Conference on Water and Development, which was held in Dublin in January 1992, produced the four Dublin Principles: (1) the holistic principle; (2) the participatory principle; (3) the gender principle; (4) and the economic principle. These provided an important mindset for water resources development and management. The World Bank's 1993 Policy Paper redefined these principles to three: the *ecological*, the *institutional* and the *instrument* principles.

an exchange of knowledge and lessons learned across borders, across regions and at the local level. It also makes it possible for decision makers and managers to agree and monitor policies and targets for improving the management of water resources.

IWRM Processes Focus on the Critical Water Resources Issues of Any Country

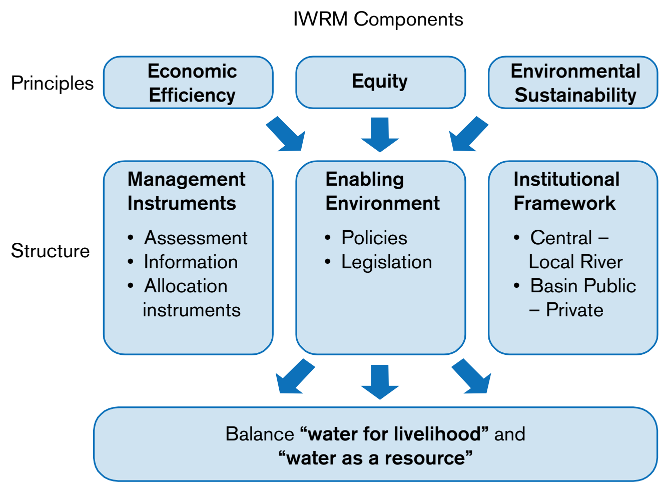
The role of IWRM and the shape it takes will vary depending on each particular country's stage of development. The implementation of IWRM in developing countries, countries in transition and developed countries will differ widely, as will the specific benefits that each will derive. For developing countries, water resources management may be seen as a factor in addressing poverty, hunger, health problems, and environmental degradation, including the particular challenge of providing better livelihoods for women. Countries in transition may see IWRM as a rational approach to improving management of the resource to promote and sustain continued economic development. Developed countries may find valuable inspiration in IWRM processes and may choose to design their own variety, as in the case of the EU Water Framework Directive.

For all countries the current concerns about adaptation to climate change call for integrated approaches.[5]

The Three Pillars of IWRM

Implementing an IWRM process is basically a question of getting the "three pillars" right. That is, (1) moving towards an enabling environment of appropriate policies, strategies, and legislation for the sustainable development and management of water resources; (2) putting in place the institutional framework through which to implement the policies, strategies and legislation; and (3) setting up the management instruments required by these institutions to do their job. The three pillars are illustrated in Figure 1 below. The Global Water Partnership (GWP) has developed a tool box to expand upon this framework and illustrate

Figure 1. The Three Pillars of Integrated Water Resources Management



concepts and useful approaches through specific tools ("good practices"), as well as relevant references and case studies of IWRM experience.

Roles of the Actors

Governments play a key role in the implementation of IWRM as regulators and controllers in the water sector with its associated infrastructure. Private actors may be involved in the provision of water services. Governments need to promote improvements in the public sector, regulate private sector involvement, and make decisions about market mechanisms. Governments working with civil society must raise awareness of the importance of improved water resources management among policy makers and the general public. Dialogues will take place among the many stakeholders involved, including government, civil society and the private sector. Good water governance requires the involvement of all relevant national (and if appropriate also regional/trans-boundary) stakeholders in the dialogue during the development and implementation of an IWRM framework that acknowledges the needs and rights of all stakeholders, including poor and vulnerable populations who depend on water for their livelihoods.

5. Global Water Partnership notes that "if mitigation is about energy, adaptation is about water," and that adaptation to climate change calls for IWRM approaches (www.gwpforum.org). The IPCC's 4th Assessment Report from 2007 (Working Group 2) in its chapter on freshwater states that "it can be expected that the paradigm of Integrated Water Resources Management will be increasingly followed around the world…which will move water, as a resource and a habitat, into the centre of policy making. This is likely to decrease the vulnerability of freshwater systems to climate change."

Cross-sector and Multistakeholder Integration

A critically important element of IWRM is the integration of various sectoral views and interests in the development and implementation of the IWRM framework (see Figure 2). Integration should take place within:

- The natural system, with its critical importance for resource availability and quality, and
- The human system, which fundamentally determines the resource use, waste production and pollution of the resource, and which must also set the development priorities and control the associated infrastructure.

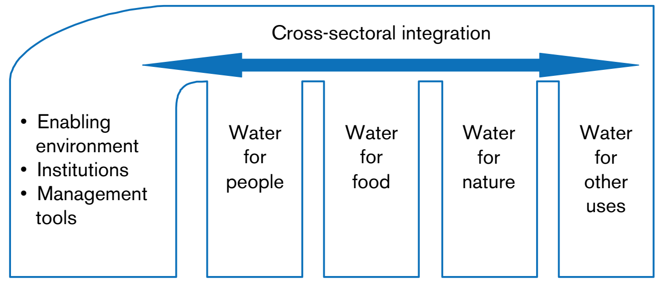
For instance, within the natural system it concerns the integration of land and water management, as well as interests related to surface and groundwater, and upstream and downstream water, recognizing the full hydrologic cycle with respect to both quantity and quality.

Recognizing that most of the important decisions affecting water resources are actually made in other sectors (agriculture, energy, and so on), integration within the human system relates, in particular, to the cross-sector integration of policies and strategies among all relevant stakeholders in the decision-making processes. It is about mainstreaming water in the national economy, rather than looking at water as a separate "sector." Formal mechanisms and means of cooperation and information exchange need to be established to secure the coordination of water management efforts across water related sectors and throughout entire water basins. These coordination mechanisms should be created at the highest political level and put in place in all relevant levels of water management.

It is equally important that IWRM should build on and be consistent with existing government policies and national or sectoral development plans and/or budgets and be consistent with these. The links between IWRM and national and sectoral plans and processes must be clearly understood and taken into account during the planning stage.

Water is *everybody's business,* and although governments have a key role to play, good IWRM is a question of

Figure 2. IWRM and Its Relationship to Subsectors



Source: Global Water Partnership (2000).
Note: In its 2004 Water Resources Sector Strategy, the World Bank has adopted this figure, but added additional sectors and redefined the three pillars of IWRM to four: Institutional Framework, Development and Management of Infrastructure, Management Instruments, and Political Economy of Water.

ensuring dialogue and the sharing of interests among the multiple stakeholders involved in and affected by water resources development and management.

The Water Basin Is the Basic Planning and Management Unit

Water follows its own boundaries: the river or lake basin, or the groundwater aquifer. Analyses and discussions of water allocation between the needs of users and ecosystems make sense only when addressed at the basin level. Hence, a lot of the "integration" in IWRM takes place at the basin (whether at the local catchment or aquifer) or at the multi-state or multi-country river basin. Many countries understood this and organized their water management at the basin level many years ago.[6] Other countries are only now setting up river and lake basin management structures. The EU Water Framework Directive has made basin level management law for an entire region.

The daily competition for water happens at the local level, and needs to be addressed in the context of the river basin. Competition for water changes over time and as a result of development, and the agricultural sector is often the prime stage where this competition takes place. In many countries of the developing world there is a strong tradition of "agriculture takes all" (often at negligible to zero cost). Economic growth and the emerging prominence

6. The Spanish river basin management structure recently celebrated its 75th anniversary. The first Mekong River basin structures were established in the 1950s.

of other economic sectors are challenging that tradition. Typical conflicts requiring dialogue, trade-offs, and good management to balance water uses in a river basin are:

- Conflicts between irrigated agriculture and a growing industrial sector.
- Conflicts between irrigated agriculture and burgeoning cities.
- Conflicts among hydropower, irrigation, and flood control interests in the planning and operation of dams and reservoirs.
- Ensuring that sufficient water is available for environmental needs, including for vulnerable ecosystems and the people whose livelihood depends on them (environmental flows).

Upstream/downstream issues are particularly important in IWRM at the basin level. Drainage from agricultural land has increased salinity almost tenfold in the Colorado River/Rio Grande in recent years, resulting in production losses in the billions of dollars (not accounting for the decline in ecosystem functions). Another example is the Syr Darya and Amu Darya river basins in Central Asia, where large-scale cotton growing, farming, and domestic use in downstream areas, and power generation in upstream areas compete for access to water. Poor management has led to the shrinkage of the Aral Sea (both in volume and surface area) and a worsening of its ecological status at the downstream end of the basins. The importance of cooperation across international boundaries is also exemplified by the Mekong River Commission, through which the four lower riparian countries (Laos, Cambodia, Vietnam, and Thailand) attempt to coordinate the development of the basin. An IWRM strategy is guiding the preparation of a basin development plan.

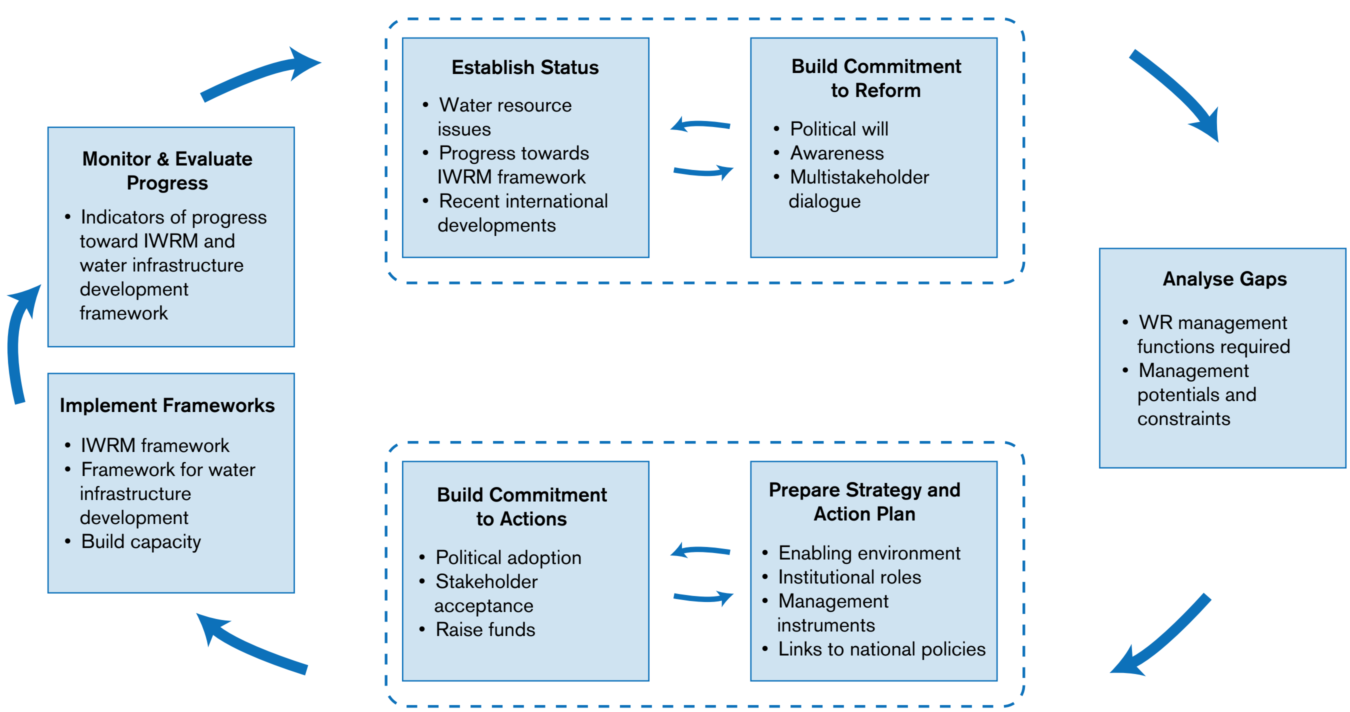
IWRM Is a Never-ending Process

As shown in Figure 3, IWRM is a cyclical process; that is, circumstances and priorities change over time and require continued adjustments and development. The cycle starts with planning processes and continues into implementation of the frameworks and action plans, and monitoring of progress. IWRM plans are just one step or milestone in the process of improved water resources management.

Changing the Way of Thinking

IWRM processes are now established or being established in major parts of the world. At the 4th World Water Forum

Figure 3. The Integrated Water Resources Management Cycle



in Mexico (2006) it was reported that out of 95 countries surveyed, 74 percent either had IWRM plans/strategies in place or had initiated a process for formulating them. Many of these are not “just water plans” The IWRM plans for Malawi and Zambia, for example, flow directly from the national economic development plans, and were prepared jointly with the ministries responsible for economic planning. The table in Annex 1 lists 42 countries that by 2008 had adopted integrated water resources management and explicitly used the term in their official documents. While the existence of these documents alone is not proof that IWRM is working in these countries, they are essential for helping to create and support an enabling environment for water reform.

The UNEP-DHI Centre on Water and Environment (previously known as the UCC-Water) carried out a survey in 2007 (with the support of Danida and UNEP) to gain a more detailed understanding of the extent to which government institutions have adopted IWRM. The survey covered 58 countries in Africa, Central Asia, South East Asia, Latin America, and the Caribbean. The respondents were typically senior government officials. One of the indicators used was the institutional capacity for maintaining various functions basic to IWRM, including policy formulation, water allocation, and water demand management. The results of the survey are shown in Figure 4. It appears that the best developed capacities (that is, highest scores) are in policy formulation, drafting of laws, and cooperation on shared watercourses. Cost recovery of expenses for water resources management and capacity for water demand management were among the areas with the lowest scores.

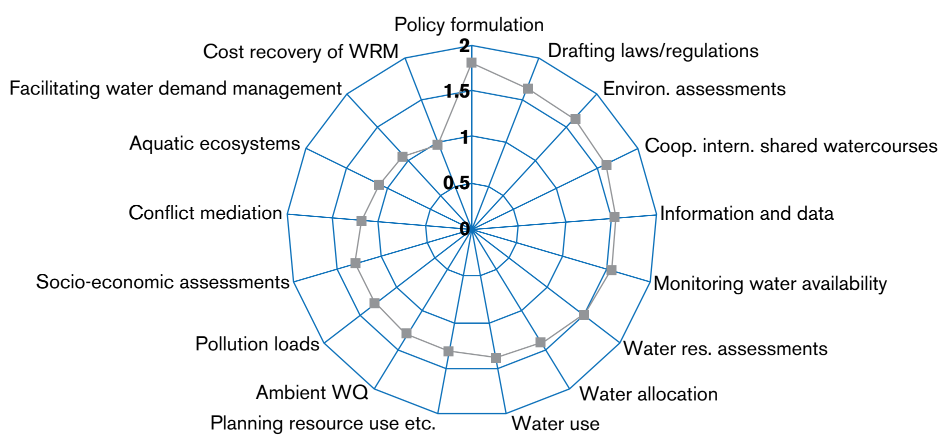
The results of the survey showed an expected pattern. Experience tells us that countries focus first on creating the enabling environment for reforming the water sector, including developing adequate policies, laws, and regulations. New policies and laws pave the way for new institutions, establish institutional roles, and help develop the capacities for carrying out these roles. Once institutions are in place, new management instruments and capabilities can be developed to implement IWRM.

Another important indicator of progress towards IWRM is the number of countries whose water legislation includes IWRM principles (see Figure 5).

The figure shows that *stakeholder participation* is the highest scoring indicator, followed by *user pays*, and *river basin management*. These results (as well as other survey results) indicate that many countries acknowledge the usefulness of IWRM principles and associated management approaches, and use them as guidance to advance water resources management. However, they also show that capacity is not always commensurate with the priorities set out in legislation. The high priority given in legislation to the *user pays* principle is not reflected in the capacity to ensure that water resources management costs are recovered.

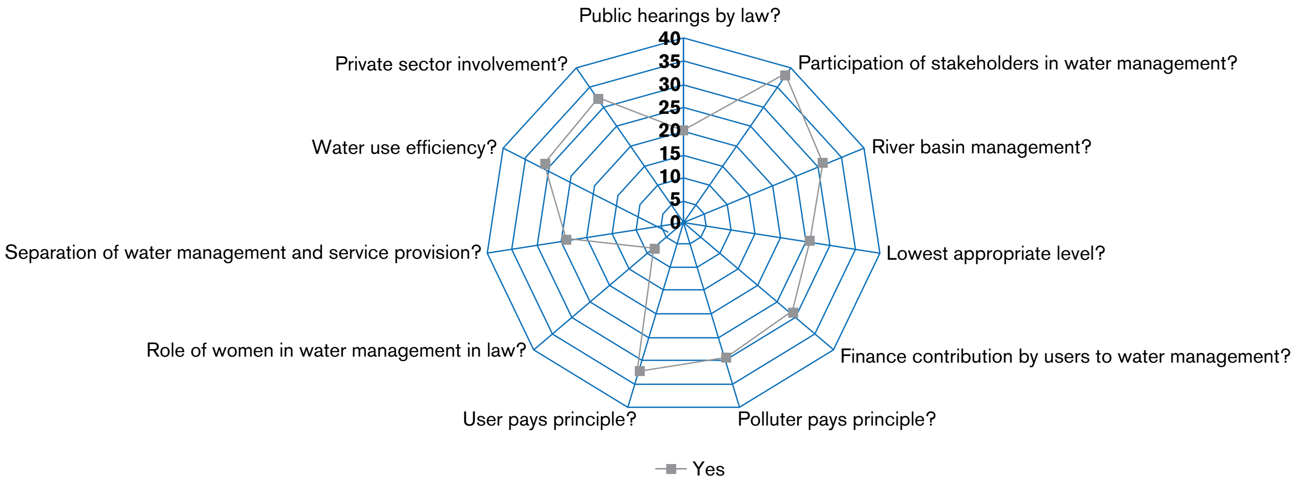
Since 2002 the UN organizations dealing with water (UN-Water) have coordinated and monitored global progress

Figure 4. Institutional Capacity for Carrying Out Various IWRM-inspired Functions



The ratings that the respondents were asked to give were: 0 = function not established, 1 = function has many gaps in quality and coverage, 2 = function has some gaps in quality and coverage, 3 = function operates at realistic goal levels.

Figure 5. Inclusion of IWRM Principles in Respondent's Water Law



The scale shows number of water laws where the item has been included.

towards IWRM and Water Efficiency Plans. At the CSD-16 in 2008 UN-Water reported on the latest status of IWRM planning work.[7]

Implementation Takes Time and Requires Trade-offs

Implementing the IWRM concept has many challenges. Some of these challenges revolve around integration and the degree to which it can be achieved given that water resources are used by many sectors and many institutions are engaged in water management. Thus, the first step is coordination, but many real world factors, such as need, funding, resources, human capacity, institutional barriers, and many others, establish the operational limits and determine how far integration can be taken.

Like any other reform, IWRM is a process that could take several decades before all its most important principles are implemented. While change may happen gradually, a trigger is often required. Examples of triggering events include a severe drought in Zimbabwe resulting in a 15 percent decline in GDP in one year; a major chemical spill on the Rhine River, which led to trans-boundary cooperation; anoxic conditions resulting in dead lobsters in Danish coastal waters in 1987, which led to the development of a succession of major national Aquatic Action Plans; severe floods causing unnecessarily high losses of lives and property because of poor preparedness; or simply greater social pressure caused by poor management of increasingly scarce water. Climate change may add to the list.

In France, the process was started with the establishment of basin agencies in 1968. The country's water law was revised in 1992 and amended again in 2003 to bring it into line with the EU's Water Framework Directive. In Spain, it has taken almost 80 years for the process to mature. As expected, weak institutional capacity in developing countries has yielded slower progress towards IWRM. Other factors also limit the speed with which developing countries are able to implement integrated water resources management. There is a high degree of informality in the water sector of many developing countries, particularly in rural areas, where people rely on self-supply and local water institutions are based on customary laws and practices. Moreover, the ability of national governments to enforce regulations is limited and laws, prices, and policies often fail to function as intended. In contrast, the water sector in developed countries is more formalized and a large proportion is under direct regulatory supervision. The chance of success for IWRM at the national level goes hand in hand with the development of national governance structures. At the local level, IWRM principles will still guide water resources management, but initiatives and actions are often taken by the communities on their own accord.

7. This status reporting is based on surveys made by UN-DESA (2007), UCC-Water (2007), GWP (2006) and AfDB (2007).

Implementation of IWRM requires tough trade-offs among sometimes conflicting objectives. Changing a water law typically involves changing an indirect power balance in relation to water among different interest groups.[8] Changing water allocation in order to achieve a better overall societal use of the resource will typically yield both winners and losers; that is, users who get more and users who get less water. In some countries (as, for example, the large "irrigation countries" of Asia), large water users are influential but often use water inefficiently. In such cases, implementation of IWRM may require delicate, time-consuming. and difficult negotiations and trade-offs, as well as a shift in the mindset of farmers.

Box 1. Management Issues at Increasing Levels of Water Scarcity: The Turn of the Water Screw

The crucial scarcity in dealing with water may not be the scarcity of the natural resource—water—but the scarcity of social resources needed to adapt to water scarcity. The significance of this is made clear by considering how water managers can deal with increasing scarcity over time.

(1) At the first turn of the water screw, the remedy is to get more water. This goal is predominantly accomplished by water storage and transfer in time and space.

(2) At the second turn the effort is redirected towards efficiency measures, predominantly end use efficiency. The goal is to get more benefit per drop.

(3) The last turn of the water screw is reallocation of water rights. This requires profound changes in national policies, since achieving allocation efficiency could mean the withdrawal of water rights of irrigation schemes that generate a low value per unit of water. The food needed by growing populations will then have to be imported and paid for by the industry and services sectors. This will require large-scale social restructuring and entails risks of tension and conflicts, within countries and between sectors and population groups with different stakes in the new socioeconomic environment.

Based on FAO (2000) and Yevjevich (1995) as cited by Snellen and Schrevel (2004).

Top-down and Bottom-up Processes Go Hand-in-hand

It has been shown that central influence on the management of water resources tends to be dictated by the degree of scarcity (either because of lack of water as such or because the water available is of poor quality). It may not seem to matter how one deals with a resource that is plentiful and of good quality vis-à-vis its demand and environmental needs. In economic terms one might say that water has no or little value (little or zero opportunity cost). However, as scarcity increases so does competition and, as a result, the value of water rises. Governments need to regulate water use to ensure that it is not wasted on low value uses, but it is used instead in the ways that yield the greatest social benefits. Until that happens, local initiatives and ownership are essential in the majority of cases where water demands are relatively small. Large-scale use will continue to be under central regulation.

As alluded to in the box above, bottom-up water resources management processes can thrive in situations where there is abundant water relative to demands. Once that is no longer the case, the enabling environment and institutional changes called for in IWRM will have to be put into practice. The clear specification of institutional roles will describe how authority and responsibility are to be shared among local levels, basin levels, and the central government. In 2000, South Africa reached a degree of water scarcity (and inequality in access to water) that necessitated reallocation measures. The response was a "compulsory licensing" process. Existing water rights were revoked and previous owners need to reapply for their allocation. In addition, water licenses were made time-bound and land ownership and water licenses were no longer connected.

8. Water laws are not developed overnight. Vietnam's current water law took 22 drafts over 8 years and now needs to be revised.

Conclusion to Part 1

The world has come a long way in recognizing the need for a new approach to water resources management since the Dublin Principles and the Rio Summit in 1992. This new approach was articulated in the 1990s as "IWRM," and adopted ten years later by the World Summit (WSSD) in Johannesburg in a call for all countries to develop "IWRM and water efficiency plans." This has been a long process of building popular awareness and political will to start developing and managing water as a resource that is fundamental to economic growth, poverty reduction, and social equity, as well as environmental sustainability. The evidence is clear. Countries, particularly the developing countries, are adopting IWRM principles in their policies, strategies, and legal framework for water resources management, while trying to change water management practices accordingly. The statistics and examples shown above and in the Annex attest to that.

Unfortunately, however, the drivers of this development at the international level are impatient, and in spite of rhetoric about "small steps," "picking the low hanging fruits first," and so on, are demanding here-and-now evidence of the direct link between the IWRM concept and visible impacts on the ground.[9] As a consequence, some major international actors now shy away from referring to IWRM.[10] This is unfortunate. After years of building up an understanding about this concept, and with most developing countries explicitly referring to IWRM in their policies, strategies, and laws, we are left to wonder why those who championed these sensible principles are now shying away from them (the same question could be asked about the concept *sustainable development*).

The foregoing, together with the case study presented below, attempt to show that the principles of IWRM are as valid as ever, not least in the current age of concerns about climate change. However, additional patience and small steps in the right direction are required. Although particular events, or serious water stress and scarcity can speed up the process, evidence is accumulating that small steps are, in fact, being taken throughout the world.

Part 2: The Orissa Case: Implementing IWRM in Small Steps

Recent work by the author in Orissa, India (2008), illustrates the realities of trying to introduce IWRM "on the ground." Orissa is in the process of reforming and developing its water sector with significant assistance from the World Bank and the Asian Development Bank (ADB), among other institutions. Both banks are providing irrigation development support in the context of river basin management, each focusing on a pilot river basin (the World Bank in the Mahanadi River basin and ADB in Baitarani River basin). ADB support has an additional component of introducing IWRM in the state. Working with a national specialist, the author has undertaken a preliminary ADB technical assistance project to propose a "roadmap for IWRM" in Orissa. Follow-up technical assistance was being formulated in close collaboration between the state government, the World Bank, and ADB to continue this activity.

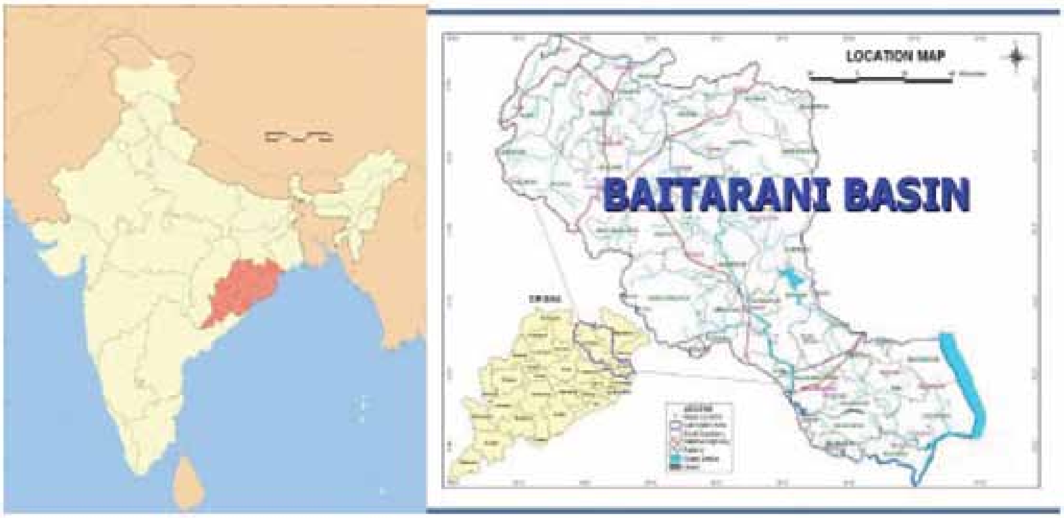
A quick overview of the *why, what*, and *how* of the proposed IWRM roadmap for Orissa is presented below.

Water Challenges Facing Orissa

Orissa must adapt to increasing water challenges. Although the state is, on average, well endowed with water resources (3,300 m^3/yr/cap, well above the UN "stress limit" of 1,700 m^3/yr/cap), the average does not reflect the strong seasonality of water (almost 80 percent of rainfall occurs in the three monsoon months), nor does it reflect anticipated declines in per capita water availability because of population growth, increased economic development demands, and increased water consumption in upstream states leading to decreasing inflows to Orissa (upstream sources currently accounts for about 30 percent of total water availability). The combination of these factors will lead to an estimated reduction in water availability of 30 percent by 2050 (to approximately 2,200 m^3/yr/cap, a low level in a monsoon climate). At the same time, some basins suffer from poor water quality because of inadequate treatment of

9. In October 2008, the author visited a Vietnamese province facing serious water problems and devoted to improved water management. However, as they expressed it, "we have 1.2 water professionals in the provincial administration per 1 million inhabitants in the province." So much for ambitions about speed!
10. The Fifth World Water Forum held in Istanbul in 2009 had 6 themes and 22 topics, none of which mention IWRM explicitly. In previous WWF in The Hague, Kyoto and Mexico, IWRM was the major theme, and the one attracting most contributions.

Figure 6. Maps of Orissa and Baitarani Basin



municipal and industrial effluents, leading to environmental degradation. In addition, serious water logging attributable to lack of drainage creates problems in the lower part of most basins.[11]

Climate change may further accelerate water problems in Orissa. The 4th Assessment report of the International Panel on Climate Change (IPCC, 2007) predicts a "projected decrease in winter precipitation on the Indian subcontinent," and "intense rain occurring during few days, which implies increased frequency of flooding during monsoons." In the coastal areas these impacts will be compounded by sea level rise.

This general situation is becoming very competitive as demand for water from a variety of users and sectors increases, particularly in the dry season. While agriculture (mainly irrigation) currently accounts for 93 percent of all water use in the state, and domestic and industrial use account for just 4 percent and 3 percent, respectively, this pattern will change. Increased urbanization will lead to increased domestic and commercial water needs, and water demand for industrial uses will continue to increase rapidly. Moreover, demand is also increasing in other economic sectors, such as fisheries, energy, and recreation and tourism. Fast economic growth, particularly in commerce and industry, have already raised demand, and mining activities have increased surface and groundwater pollution.

The environment as well as the valuable coastal ecosystems in lower Baitarani/Brahmani and Mahanadi have a serious stake in these developments and depend on the maintenance of critical flows (environmental flows) and pollution control.

IWRM in India

India has responded to these challenges in a number of ways. A National Water Policy was adopted in 2002 (updating the 1987 version), which draws strongly from IWRM principles, and makes explicit reference to *multi-sectoral*, *multi-disciplinary* and *participatory* water management. In line with IWRM approaches, it also calls for water resources development and management to be planned for a "hydrological unit such as a drainage basin as a whole or for a sub-basin." Several Indian states have responded to the National Water Policy by developing state water plans, and also by moving towards the establishment of appropriate river basin organizations (RBOs). One state, Maharashtra, has even created a quasi-judicial Water Resources Regulatory Authority to determine, regulate, and

11. This information is drawn from the Orissa State Water Plan of 2004, which in turn was developed on the basis of 11 river basin plans. While figures for the present situation are credible, the projected figures appear to be, at most, indicative.

enforce the distribution of water entitlements, along with a water tariff system for various categories of water use.

Water in India is basically a state matter. While the central government plays an important role in setting overall policy directions, controlling and approving major water projects, and addressing interstate water issues, IWRM needs to be developed at the state level.

Legislation concerning water remains fragmented, and most states rely on old irrigation acts and pieces of legislation in a range of other acts. No comprehensive "water acts," per se, exist in India. Although a Groundwater Model Act has been proposed by the central government, few states have adopted it, leaving groundwater largely uncontrolled. "Modern" legislation to support IWRM approaches needs to be developed.

Orissa has taken the lead in developing an IWRM process. A multi-sector state water resources board was formed in 1993, chaired by the chief secretary and including ten principal secretaries as members; a state water policy was first formulated in 1994; and a state water plan was developed in 2004. This plan calls for "a legal framework to ensure that water-related matters are appropriately dealt with in the context of IWRM." Building on these, a revised Orissa State Water Policy was adopted in March 2007 that reiterates the importance of IWRM and river basin management by, for example, calling for "macro-level multi-sector river basin plans" to be "ground-truthed through the river basin organizations." The Orissa Department of Water Resources (DOWR) is taking the steps listed below to better respond to the requirements of IWRM.

- DOWR is creating an IWRM directorate headed by an engineer-in-chief, and including the Orissa Water Planning Organization headed by a chief engineer. Although still in the same department, this may be seen as an important first step towards separating water resources management from service provision functions. Potentially, it is also an important first step to create a multi-disciplinary environment within the DOWR, with professionals deputed form other line departments to address broader water issues.
- The Department is also setting up and *piloting* river basin organizations operating through a council made up of key stakeholders, and a board that includes government representatives from different sectors. A resolution on this was issued by the Orissa state government (OSG) in February 2007, specifying the functions of the RBOs and the composition of the council and board.

With a growing population and economy, as well as prospects of a general decrease in water resources caused by upstream development and climate change, Orissa can no longer rely on a traditional fragmented water resources management system. Key issues to be addressed through IWRM include:

- *Drinking water and domestic use* (human and animal consumption). This includes water supply for rural and urban areas, and basic water use for livestock. The sector consumes relatively little water on average, but rapid urbanization will increase urban water demand significantly (a threefold increase by 2040 is estimated). Plans include reducing current water losses of 40 to 50 percent in urban distribution systems to a target of 15 percent in the future.
- *Ecologic requirements.* These are currently treated as a fixed proportion (roughly estimated at 30 percent of natural flows) for environmental flows to the ecosystems (as per the 2004 State Water Plan), including the two Ramsar sites in Orissa. Knowledge about these requirements (including sustaining the livelihoods of poor people who depend on these ecosystems) and approaches to address them through environmental flow methods are currently low.
- *Irrigation (and drainage), agriculture and other related activities, including fisheries*. Irrigation is currently generally taking place during the monsoon season without water scarcity (apart from some dry spells in "bad years"), but the demand for water for irrigation in non-monsoon seasons (*Rabi*) still represents the dominant water demand compared with other sectors. Improved management of the irrigation and drainage systems, water conservation, and improving the efficiency and productivity of water used for irrigation (and associated drainage) are high priorities and hold potential for accommodating an increase in agricultural production without adversely affecting other use sectors. Lack of proper drainage systems and overuse of water for irrigation cause serious water logging problems and soil salinization in some areas, including the Mahanadi and Brahmani systems.

- *Hydropower*. Hydropower presently accounts for 55 percent of the energy production in the state. The desired hydro-thermal mix is 60 percent hydropower to 40 percent thermal. In the future, more than 90 percent of the thermal power may be exported to other states with little benefit for Orissa. The view of the sector is, therefore, that power production should not compromise requirements for flood control and water use requirements for other sectors.
- *Industries, including agroindustries, mining and commerce*. The state expects industry in Orissa to grow from the present 19 percent of state GDP to 30 percent to 35 percent of state GDP over the next 10 years. Industrial water use is the single most important "competing use" to agriculture in Orissa, and conflicts with the irrigation sector are already occurring. Industries and mines, as well as urban areas, are serious contributors to surface and groundwater pollution.
- *Navigation* and other uses such *as recreation* and *tourism*.

In addition to satisfying the demands of these primary water users a number of water management issues call for IWRM approaches, such as:

- *Inter-state water sharing*. Orissa receives some 30 percent of its water from upstream states. With increasing development and water abstraction in these states, discussions about water sharing arrangements are becoming increasingly serious.
- *Storage capacity*. Orissa is subject to strong seasonality of rainfall, losing the majority of the monsoon flows to the sea. In spite of this, Orissa has only 45 m^3/cap in storage capacity, against some 200 m^3/cap for India (and 5,000 m^3/cap for the United States and Australia). Obviously, additional surface water storage capabilities will help increase the availability of water during the dry season and reduce water losses. However, before engaging in large-scale dam building for this purpose other, more cost efficient options should be considered first. These options include improved management of the existing surface water dam and canal systems; improving drainage to bring presently waterlogged lands into production; building small storage tanks, ponds, and rainwater harvesting structures in the upper catchments; and recharging the groundwater aquifers.
- *Water quality management*. Very little urban wastewater is currently being treated in Orissa. Industries are required to treat their wastewater, but enforcement is uncertain. Apart from a few places, groundwater pollution is not (yet) a problem.
- *Groundwater management*. While surface water use is controlled by the state, groundwater use is largely uncontrolled and represents an important source of "self-supply." Groundwater accounts for the majority of domestic use, and some 14 percent of irrigation use, but only 25 percent of the state's total potential groundwater is being used. However, overdrafts cause localized lowering of water tables. The state has considered developing a groundwater act, but given the limited scale of overdraft problems, it has decided not to do so yet. No mechanisms for managing the conjunctive use of surface water and groundwater exist.
- *Extreme events* such as intense rainfall, floods and droughts visit the state regularly and cause human and economic losses. While infrastructure such as dams and levees may mitigate some of the effects of floods, a number of "softer," non-structural management solutions are called for to increase preparedness and reduce losses.
- *Watershed management* in upstream catchments holds the key to local land and water management with both local and basin benefits. Land use management and practices (including forest management) are key to controlling run-off and upper basin recharge. Clearly, this calls for the integration of land, forest, and water management.
- *Salinity intrusion* in coastal river reaches and deltas cause problems that, in many cases, can be addressed only in a basin context. Adequate regulatory measures are required to stop the overexploitation of coastal aquifers.

Key Constraints to Developing IWRM in Orissa

In many ways, introducing IWRM is paramount to demanding a paradigm shift in water management, from relying solely on a traditional top-down supply oriented approach (building new infrastructure to meet demand) to combining this with a bottom-up demand management approach that builds on extensive user participation. Such a fundamental change takes time, and will only come about through small steps in the right direction.

As explained below, there are several constraints to the introduction of IWRM in Orissa.

- Except for extreme events (floods, droughts), stakeholders *lack awareness and information* about the long-term water situation and the opportunities to change it. Unless information is made publicly available and easily accessible, an informed dialogue among stakeholders (the general public, government officials, politicians, civil society, and so on) cannot take place.
- *Irrigation is the dominant water user* and farmers are the most important stakeholders. Changing the "Irrigation Department" to the "Water Department" does not change that perception overnight. It takes time to change the culture and staff composition of the DOWR so that a better balance can be struck in the attention given to all water users and issues.
- There is a *history of compartmentalized administrative functioning* that has led to a lack of coordination and dialogue mechanisms between sectors and users. At the local level, the water users associations (*Pani Panchyats*) provide a mechanism for dialogue among farmers, but similar mechanisms do not exist for other sectors/users.
- There is a *general political and administrative wariness* about involving non-official and non-political stakeholders and user representatives in decision-making processes. There is also a reluctance to share power with them.
- *Surface water and groundwater management are separated*, as is responsibility for managing water quantity (DOWR) and water quality (Pollution Board).
- *Supply management* rather than demand management is the dominant paradigm. The traditional response to meeting demand is to plan and build new infrastructure to increase supply, rather than look for ways of adjusting demand.
- Orissa *lacks of water entitlements and tariff systems* to ensure proper water allocation and cost recovery. Although the state water policy stipulates the full recovery of operation and maintenance costs from users, a long tradition of underpriced water for irrigation may be very difficult to change. Similarly, pricing mechanisms for industrial water use needs urgent attention.
- There is a *large degree of self-supply in the informal sector*; that is, people access surface water and groundwater sources directly through private tube wells or from ponds, for example. These activities remain outside the reach of the government. Related to this are the special challenges involved in managing water resources and providing services in tribal areas
- *The state lacks the capacity, at all levels, to address IWRM issues.* This is the case within the water sector itself, as well as in other sectors and in line ministries, in district administrations, blocks and *Gram Panchayats* and *Pani Panchayats*.
- Finally, there is a *lack of reliable and comprehensive data* to support informed decisions.

Priority IWRM Issues: First Step

Orissa has taken important steps towards introducing IWRM at the policy and resolution level, but this is not a sufficient condition for action. The challenge now is to translate these intentions into actions. While the DOWR remains focused on irrigation, the multisector dialogue among water dependent sectors has yet to be put into operation, and stakeholders have not yet been properly incorporated into the planning and decision processes.

A new water resources management approach system that follows IWRM principles needs to be developed. In the prevailing climate of limited awareness and capacity for IWRM not all aspects of it can be addressed simultaneously. Prioritization—first steps first—is required. The two single most important IWRM functions that needed to be introduced in Orissa:

- *Informed* dialogues across sectors of the government, and among stakeholders at all levels.
- Creation of an *accepted* system of water allocation and tariffs, backed by legislation and institutional change.

For the dialogues to be *informed* and for changes to be *accepted*, immediate efforts are required to create:

- awareness about water issues and a participatory framework to address them,
- a hydrological and environmental knowledge base to support this, and
- capacity building at all levels, and among all stakeholder groups.

The IWRM Roadmap for Orissa, described below, proposes 12 actions to deliver on these priorities.

Informed Dialogues Across Government Sectors and Stakeholders

Putting IWRM processes into action requires initiatives at four levels: (1) the local level, from the villages to the RBOs; (2) the basin/RBO level; (3) the state level; and (4) the interstate/union level.

The Local Level

The local level in water resources management goes all the way from the villages through the *Gram Panchayats*, blocks and districts/*Zilla Parishads* to the river basin/RBO level. Only the irrigation sector has developed structures for stakeholder participation in water management at this level. However, since water is an important factor in overall economic and social development, issues concerning water are also being addressed in other sectors. The potential for using these forums to promote the principles of IWRM, including discussions of allocation among users, needs to be explored.

The Basin Level

The function and composition of river basin organizations as stipulated in the DOWR's February 2007 resolution are as follows: "The objective of RBO is to ensure IWRM in the basin. RBO is an organization of all stakeholders department in the basin and will bring coordination of their activities with a view to resolving conflicts and avoid duplication among them" According to the 2007 State Water Policy "the (river basin) plans prepared by the OWPO will be ground-truthed through RBOs" and "placed for approval of the State level Water Resource Board" The interaction between the local level and the river basin level remains a serious challenge. In particular, it remains unclear how the views and voices of stakeholders at lower levels will be represented in the basin level council, and how all water users, as well as those affected by water, get to the table. Pilot projects for the implementation of river basin organizations are currently being undertaken in Rushikulya (DOWR), Mahanadi (with World Bank support) and Baitarani (with ADB support). Developing these RBOs from theory to practice while respecting the diversity of each basin and its problems, requires extensive dialogues and stakeholder consultations.

The State Level

Currently, the institutional structure for integrated water resources management in Orissa is limited to the State Water Resources Board (SWRB), which is not very active. The state is also exploring the possibility of setting up a regulatory authority. While the institutional set-up of other states cannot easily be translated to Orissa because of differing geography and economic conditions, the experience of other states can provide inspiration and serve as a starting point.[12] State authorities will have to identify the structures best suited to the water conditions and challenges of Orissa. In addition, the appropriate state level structure for IWRM, and the enabling legislation will need to be discussed and designed in close coordination with the development of the RBO (and lower) structures to ensure that *bottom-up* and *top-down* processes form a coherent whole.

Central Government and Interstate Levels

While water is a state matter and the state government will play the main role in the development of IWRM in Orissa, the central government also plays a role in state water resources management through the Department of Water Resources and the Central Water Commission, as well as a number of acts (such as the Environmental Act). In addition, projects receiving financial support from the central government as well as the environmental impact assessments of major projects require central government approval. Orissa will also have to consider establishing and possibly institutionalizing agreements with upstream states in order to come to water sharing arrangements.

An Accepted System of Water Allocation and Charging

One of the most important and difficult to address constraints is that of the lack of properly functioning water allocation and charging systems. There is still far to go in Orissa to achieve the stated policy goal of full recovery of operation and maintenance (O&M) costs. In irrigated agriculture, which is the main water user in the state, cost recovery in surface water systems (canals) remains low. During the wet (*Kharif*) season, users are charged some 250 rupees per hectare (class i), which is only

12. An example is the Maharashtra Water Resources Regulatory Authority, which operates jointly with a state water council and water board.

about 30 percent of actual O&M costs. While charges during the dry (*Rabi*) season differ according to the crop, they are also much lower than actual costs. In contrast, farmers who depend on lift irrigation (from groundwater or surface water) do pay their actual energy costs. For example, growers of high value crops pay between 5,000 and 10,000 rupees per hectare during the *Rabi* season, indicating that there is, in fact, a willingness and ability to pay full costs.

Water in Orissa's urban areas is also underpriced, resulting in poor and unreliable service and a public financial deficit. This need not be so. Examples abound of Indian cities where full cost recovery is taking place, and even some that are making a profit. Cost recovery need not be a burden for the urban poor who can be supplied at less than full cost through cross subsidies from commercial and industrial users.

The current allocation system for surface water can best be characterized as an *evolving status quo.* That is, the current system respects existing traditional rights while "new water" from dams and other such water infrastructure projects is being allocated on a project-by-project basis. The extent to which such allocations are based on considerations of the actual cost of providing water to new users, and their willingness to cover those costs, are not clear.

No groundwater system currently exists and there is a high degree of self-supply from this source for both domestic and agricultural use.

An improved system of water allocation and charging in Orissa has two main requirements, as discussed below.

- Moving towards *financial sustainability* by improving cost recovery. The goals set in the State Water Policy (SWP) include "participation of the beneficiaries in the capital cost in suitable proportions," "differential water rates for different categories of uses," and "cost of operation and management will be fully recovered from the beneficiaries." The SWP further requires the application of the principle of "polluters must pay" to meet the expenses of maintaining water quality. As described above, in order for this to happen, the prices paid by farmers who irrigate their fields must be raised to more realistic levels. It appears that there actually is a willingness and ability to pay more realistic water tariffs; however, this would require a change of the society's mindset from reliance on the government as provider to taking individual responsibility. The establishment of realistic prices that are closer to the full-cost price should be within reach in urban areas, particularly since the willingness to pay of commercial and industrial users substantially exceeds the full cost.
- Creating *incentives*, through an improved water allocation and charging system, *to improve water use efficiency*, mainly in agriculture (through volumetric pricing), but also in urban systems.

Several different models to make the improvements necessary in the allocation of water may be conceived. There is a spectrum of approaches running from a "minimum" to a "maximum" approach, as described below.

- Under a so-called *minimum solution*, the state government would take steps to improve the existing system by gradually raising the prices of surface water to comply with the SWP. At the same time, appropriate dialogue structures would be created among sectors and with stakeholder to help improve the decision-making process.
- A *maximum solution* would involve taking bold steps towards the implementation of a modern system of water allocation and charging. Attempts would be made to put in place mutually attractive sharing arrangements (win-win) among industries, urban areas and irrigated agriculture. A system could be envisaged by which water is allocated through entitlements to various user groups, which are then allowed to negotiate and trade among themselves. The state government could look to the legislation that created the Maharashtra Water Resource Regulatory Authority (2005), which makes provision for the establishment of such a system, as an example of how one could be created in Orissa. Such new arrangements will require extensive consultation and the dissemination of information to raise awareness in rural communities. It needs to be explained to local residents and policy makers that when prices reflect water's true economic value in an accurate and transparent manner, everyone benefits.

A Roadmap for IWRM in Orissa: The Purpose

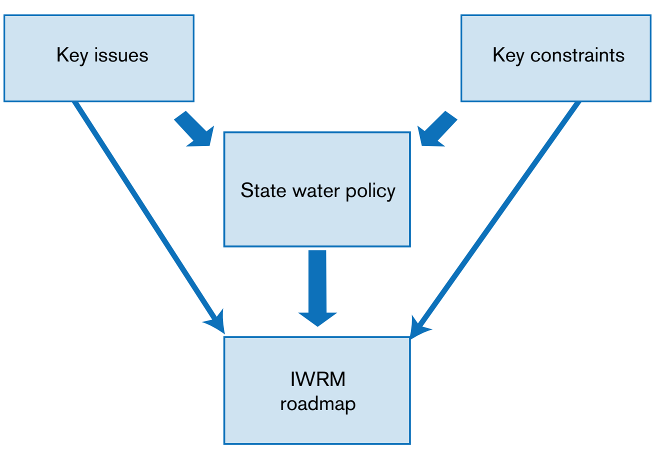
The purpose of the IWRM Roadmap is to launch a stepwise process to introduce and implement IWRM in Orissa by proposing a set of actions that can be realistically implemented within the proposed time frame. An important assumption is that external assistance will be provided to the Orissa state government in areas where there is no or very limited capacity.

Overall Criteria for the Roadmap

The point of departure is the State Water Policy adopted in 2007. This implies moving from policy goals to the establishment of a timeline of prioritized actions (*operationalizing the water policy)*. Addressing the key issues and priorities of the state as reflected in its water policy should be considered essential. However, there are other key issues and constraints that are not specifically included in the policy document and have to be addressed as the proposed actions unfold.

Figure 7 illustrates the approach for the development of the IWRM Roadmap, showing that it is strongly linked to the state's water policy but also includes additional links to key issues and constraints that may not be part of the policy. All the proposed actions are referenced against relevant articles in the State Water Policy.

Figure 7. The Basis for Developing the IWRM Roadmap



Priority Actions to Create an Enabling Environment

- *Action 1:* Develop a revised State Water Plan (or an IWRM Plan) by using the IWRM Roadmap to establish a prioritized plan with costs and timelines to implement the state's water policy.
- *Action 2:* Review the legal framework for water resources management in order to develop recommendations for updating and harmonizing water related legislation as well as develop a Water Act for Orissa.

Priority Actions Addressing Institutional Development

- *Action 3:* Review existing institutional mechanisms for water resources management at the highest state level. Revitalize the state's Water Resources Board and consider the creation of a state water resources council.
- *Action 4:* Consider the creation of a regulatory authority for water resources whose mandate would include establishing and enforcing the a*llocation* of water entitlements for various categories of use, as well as establishing a system of water tariffs, including criteria for water charging at the basin and state level.
- *Action 5*: Develop the river basin organization structure as stipulated in the state water policy. The initial focus should be on creating operational forums for intersector dialogue and stakeholder participation at the basin level and below (district, block, village), starting with selected pilot basins.
- *Action 6*: Develop capacity within the DOWR to respond to the requirements of implementing the IWRM Roadmap, initially through an interdepartmental and multidisciplinary IWRM Directorate and the Orissa Water Planning Organization (OWPO).
- *Action 7*: Develop institutional and human capacity to respond to the requirements of implementing the state water policy through an IWRM approach, at the state, basin, and local levels.
- *Action 8*: Develop a multi-stakeholder Orissa Water Partnership.

Priority Actions Addressing Management Instruments

- *Action 9*: Develop an awareness, advocacy, and education program for IWRM.
- *Action 10:* Develop a water allocation system based on a system of water rights/entitlements associated with differential water rates/tariffs for different uses, as well as a system of pollution charges.
- *Action 11*: Develop a hydrological information system for collecting, processing, archiving, and disseminating water-related data.
- *Action12:* Develop a system to address the environmental flow requirements for the state's ecosystems.

Concluding Remarks on Part 2

This case illustrates the relevance of the basic principles of IWRM to Orissa. Of particular importance are the governance dimensions in IWRM; namely, emphasis on multisector and multi-stakeholder dialogue and coordination at all levels, and the focus on the river basin as the natural unit for managing water and balancing its uses. Both dimensions are essential to address current water problems in the state. The state of Orissa has realized this and has adopted IWRM principles in its policies and strategies, inspired by similar decisions by the government of India, and by encouraging examples from other Indian states.

However, Orissa faces the challenge of implementing these policies and strategies in a situation of severely limited financial and human resources, and against the backdrop of old traditions where water development is synonymous with irrigation development. Moreover, the state has a relatively large informal sector that remains outside of the government's reach. A pragmatic approach with small steps in the right direction is the only realistic way forward.

Part 3: Reflections on the World Bank and Integrated Water Resources Management

In 1993, the World Bank issued a Water Resources Management Policy Paper that reflected the broad global consensus forged at the Dublin Conference and Rio Earth Summit that took place in 1992. The policy paper is strongly inspired by the *Dublin Principles,* which the Bank summarizes into three: the *ecological*, the *institutional*, and the *instrument principles*. A review by the Bank's Operations Evaluation Department (undertaken some 10 years later) concluded that "while the 1993 Policy Paper remained relevant and appropriate, the major challenge was the developing of context-specific, prioritized, sequenced, realistic and patient approaches to implementation (World Bank 2004)."

The Bank' s Water Resources Sector Strategy of 2004 reflects IWRM thinking, and includes the "comb" developed by the Global Water Partnership to illustrate IWRM. However, it mentions IWRM only by stating that "the main management challenge is not a vision of integrated water resources management but a pragmatic but principled approach." It goes on to say further that "there is some concern that this sequenced and prioritized approach means abandoning the idea of integrated water resources management, which was a core principle of the 1993 Policy Paper. This is not the idea. As noted earlier, even the world's most developed countries are a long way from integrated water resources management, and progress has been slow and incremental. The goal of the Strategy is not to dismiss the goal of integrated water resources management, but to define practical, implementable and, therefore, sequenced and prioritized actions that can lead to that end."

Bank statements in the Water Resources Sector strategy echo fully the views and experiences of the author as described in Parts 1 and 2 of this paper, although it is regrettable that the Bank apparently has become hesitant to refer explicitly to IWRM. As argued, when a large number of the Bank's client countries explicitly adopt this terminology (after being strongly encouraged to do so by the international community, including the Bank, in the 1990s), why not continue to use this *common language* while patiently focusing on the small steps? A shift in Bank rhetoric took place in the early 2000s with renewed focus on the rising tide theory ("a rising tide raises all boats") and on Bank support for the development of water infrastructure, as well as an expressed willingness to take the necessary risks. As the Bank refocused on the *development* aspect, the softer *governance* aspects, including the IWRM terminology, apparently had to take second place. That is unnecessary. Nothing in the IWRM concept contradicts the need for infrastructure development;[13] the argument is not about *if* but *how* to develop water infrastructure. This may sound like academic splitting hairs, but when confronted with leaders in the developing countries who are committed to their own IWRM-inspired policies and strategies, terminology sometimes does matter.

The Bank's 1993 Policy Paper and 2004 Sector Strategy are well-articulated documents, which, in their arguments and recommendations, constitute a strong support for improving water resource development and management in accordance with the principles of IWRM. The challenge in practical implementation is two-fold. At the policy level and in the dialogue with top decision makers, the challenge is to discuss the role of water in all sectors of the economy (notably agriculture and energy), not just within the "water sector" as is most often the case. This applies not only to the Bank's dialogue with country stakeholders, but also internally among the Bank's staff and managers. At the basin/local level, a major challenge is to build the bridge between IWRM ideals and principles on the one hand, and the realities of old traditions, little awareness, little political will, and low capacity, on the other. At this level the serious issues of competing demands for water need to be addressed urgently, often in the absence of necessary data and information, in the absence water allocation and regulation mechanisms, and in the absence of well-defined dialogue mechanisms among stakeholders to address them. At both levels no quick fixes are possible, and Bank staff and managers are challenged to be patient and take small steps as expressed in the policy and strategy documents.

References

Asian Development Bank. 2008.). Orissa Integrated Irrigated Agriculture and Water Management Investment Program (OIIAWMIP), Technical Assistance for Integrated Water Resources Management (IWRM) in Orissa. Manila.

Global Water Partnership. 2000. Integrated Water Resources Management, GWP Technical Committee (TEC) Background Paper No. 4.

Hassing, Jan, Niels Ipsen, Torkil-Jønch Clausen, and Henrik Larsen. 2009. "Integrated Water Resources Management in Action". Jointly prepared by DHI Water Policy and the UNEP-DHI Centre for Water and Environment. United Nations World Water Assessment Programme, Side Publications Series, Dialogue Paper. Paris: UNESCO.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland. Chapter on freshwater.

Orissa, India (2004). Orissa State Water Plan.

UN Conference on Water and Development. 1992. Dublin Principles. Dublin: January.

Various surveys made by UN-DESA (2007), UCC-Water (2007), GWP (2006) and AfDB (2007).

World Bank. 1993. Water Resources Management Policy Paper. Washington, DC.

World Bank. 2004. Water Resources Sector Strategy. Washington, DC.

Annex – Examples of countries having adopted IWRM as a key concept, Roadmaps, Strategies, Policies, Laws, Plans etc. with Explicit Reference to "IWRM"

The table below provides examples of some 40 countries that have found IWRM a useful framework for management of water resources and have included it as a pivotal concept. The concept has been included in key government documents that guide and regulate the use, conservation, and protection of a nation's water resources and implementation at local level. The table is not exhaustive.

13. In fact, the Global Water Partnership defines the "M" in IWRM as "development and management" (Global Water Partnership 2000).

Country	Evidence of the continued adoption and explicit use of IWRM
Algeria	• National Plan for Water – Ministry of Water Resources (2003) • National Water Law – Government of Algeria (2005) • Action Plan for implementation of an IWRM Framework – Ministry of Water Resources (draft 2006–7]
Angola	• IWRM and Water Efficiency Roadmap – Ministry of Water & Energy (draft 2007)
Argentina	• IWRM Roadmap – Sub-secretariat of Water Resources (2007)
Armenia	• Water Code – Government of Armenia (2002) • National Water Policy – Government of Armenia (2005) • National Water Programme – Government of Armenia (draft 200:)
Botswana	• IWRM Strategy and Action Plan – Ministry of Minerals, Energy and Water Resources (2006)
Brazil	• National Water Policy (Law No 9433) – Government of Brazil (1997) • National Water Resources Plan – Ministry of Environment [SRH/MMA), National Water Council • (CNRH) & National Water Agency (ANA) (2007)
Burkina Faso	• Decree No. 2003-220: Action Plan for IWRM in Burkina Faso (PAGIRE) – Ministry of Agriculture, Hydraulics & Fishing Resources (2003) • Burkina Faso Water Vision – Ministry of Agriculture, Hydraulics & Fishing Resources (2000) • Water Law No. 002-2001 – Government of Burkina Faso (2001)
Cambodia	• Integrated Water Resources Management (IWRM 2005) and Roadmap of Cambodia Resources Management and Conservation (2006) • Water Law – Royal Government of Cambodia (Sept. 2006)
China	• China Water Law – Government of China 2002
Colombia	• National Development Plan 2006–10 – National Planting Department (2006)
Costa Rica	• National Strategy for Integrated Water Resources Management – Government of Costa Rica (2006) • National IWRM Action Plan – Government of Costa Rica (2006) • National Water Law (No. 14585) – Government of Costa Rica (draft 2006)
Cote d'Ivoire	• IWRM Roadmap 2007–2015 – Ministry of Environment Water & Forestry (2007)
Egypt	• National Water Resources Plan – Ministry of Water Resources and Irrigation (2004)
Eritrea	• Integrated Water Resource Management and Water Efficiency Plan (IWRM/WE) – Ministry of Land Water & Environment (draft 2007)
Ghana	• IWRM Component Support programme (2004–2008) – Water Resources Commission (2004) • Water Resources Policy – Water Resources Commission (draft 2005)
Grenada	• Simultaneous preparation of IWRM Roadmap and National Water Policy – Water Policy Steering
Honduras	• IWRM Action Plan – Honduras Water Platform (2006)
Indonesia	• National Water Law No 7/2004 – Government of Indonesia (2004) • IWRM Roadmap – Directorate General Water Resources of Ministry of Public Works (2006)
India	• National IWRM Committee – Government of India 1999
Kazakhstan	• IWRM National Roadmap including proposed project outlines – Speed-up of the IWRM 2005 objectives implementation in Central Asia – Government of Kazakhstan (2006)
Kenya	• Water Act 2002 - Government of Kenya (2002) • National Water Policy on Water Resources Management and Development (Sessional Paper No. 1 of 1999) – Ministry of Water and Irrigation • Integrated Water Resources Management and Water Efficiency Plan for Kenya – Ministry of Water and Irrigation (draft 2007)
Kyrgyzstan	• IWRM National Roadmap including proposed project outlines – Speed-up of the IWRM 2005 objectives implementation in Central Asia – Government of Kyrgyzstan (2006)
Lao PDR	• Policy on Water and Water Resources – Government of Lao PDR (draft 2000) • The Law on Water and Water Resources – Government of Lao PDR (1996) • IWRM National Roadmap – Water Resources Coordination Committee Secretariat (2206)

(*continued*)

Country	Evidence of the continued adoption and explicit use of IWRM (*continued*)
Lesotho	• Roadmap to completing integrated Water resources management and water efficiency planning in Lesotho – Ministry of Natural Resources, Water Commission (April 2007)
Liberia	• Liberia IWRM Roadmap – Ministry of lands, Mines and Energy (draft 2007) • National Water Policy – Ministry of Lands, Mines and Energy (draft 2007)
Malawi	• National Water Policy – Ministry of Irrigation and Water Development (2005) • Water Resources Act No. 15 of 1999 with later amendments. Government of Malawi • Integrated Water Resources Management/Water Efficiency (IWRM/WE) Plan for Malawi – Ministry Irrigation and Water Development (draft 2007)
Malaysia	• 9th Malaysia Plan- Economic Planting Unit – Prime Minister's Department (2005) • National Study for the Effective Implementation of IWRM in Malaysia – Ministry of Natural Resources and Environment (2006) • Our Vision for Water in the 21st Century – Ministry of Natural Resources and Environment (2000)
Mauritania	• IWRM Action Plan – National Council for Water (2007) • National Development Policy for Water & Efficiency – Ministries of Water, Energy & Environment (1998) • National Water Act (Article 3) – Government of Mauritania (2005)
Morocco	• Master Plans of Integrated Water Resources Development for Rivet Basin – Ministry of Land, Water and Environment (2001) • National Water Plan – Ministry of Land, Water and Environment (2006) • Decree no 2-05-1594 – Development and Revision of Master Plans & National Plans for Integrated Water Resources Management – Government of Morocco
Mozambique	• National Water Resource Strategy – Department of Water Affairs & Forestry (2004) • IWRM Plan – National Directorate of Water Affairs (draft 2007)
Namibia	• National Water Policy White Paper – Government of Namibia (2000) • Water Resources Management Act – Government of Namibia (2004) • Integrated Water Resources Management Strategy and Action Plan – Ministry of Agriculture, Water and Rural Development (2006)
Nicaragua	• General law on National Waters – Government of Nicaragua (2007) • Environmental Action Plan – Ministry of Environment (1994) • IWRM Action Plan – Ministry of Environment (1996)
Philippines	• Medium Term Philippine Development Plan (2004-2-10) – Government of Philippines (2004) • Clean Water Act – Government of Philippines (2004) • Integrated Water Resources Management (IWRM) Plan Framework – National Water Resources Board (2007)
Swaziland	• Water Policy – Ministry of Natural Resources and Energy (draft 2007) • IWRM and Water Efficiency Plan – Water Resources Branch (draft 2007) • Water Act (2003) – Government of Swaziland
Tajikistan	• IWRM National Roadmap Including Proposed Project Outlines: Speed-up of the IWRM 2005 Objectives Implementation in Central Asia – Government of Tajikistan (2006)
Tanzania	• National Water Sector Development Programme 2006–2025 – Ministry of Water (2006) • IWRM Strategy and Action Plan – Ministry of Water (2004) • National Water Policy-Ministry of Water (2002) • National Water Law based on revised Water Act no. 42 of 1974 – Government of Tanzania (draft 2007)
Thailand	• National Water Law/Code – Government of Thailand (draft 2007) • National Water Policy – Ministry of Natural Resources and Environment (2000) • IWRM National Roadmap – Department of Water Resources (2007)
Togo	• National Water Policy – Directorate of Water and Sewerage (draft 2007) • National Water Law – Directorate of Water and Sewerage (draft 2007) • IWRM Roadmap – Directorate of Water and Sewerage (draft 2007)
Turkmenistan	• IWRM National Roadmap Including Proposed Project Outlines – Speed-up of the IWRM 2005 Objectives Implementation in Central Asia – Government of Turkmenistan (2006)

(*continued*)

Country	Evidence of the continued adoption and explicit use of IWRM (*continued*)
Uganda	• A National Water Policy -Ministry of Water, Lands and Environment (1999) • National Water Action Plan – Water Resources Management Department (1994) • Water Resources Management Reform Strategy – Water Resources Management Department (2005) • National Water Quality Management Strategy – Ministry of Water and Environment (2006)
Uzbekistan	• IWRM National Roadmap Including Proposed Project Outlines – Speed-up of the IWRM 2005 Objectives Implementation in Central Asia – Government of Uzbekistan (2006)
Zambia	• IWRM and Water Efficiency Plan – Ministry of Energy and Water Development (2008) • The Revised National Water Policy – Ministry of Energy and Taler Development (2007) • Water Resources Management Bill – Ministry of Energy and Water Development (draft 2007) • National Development Plan – Ministry of Energy and Water Development (2007)

2. Water Demand Management

Janusz Kindler
Warsaw University of Technology, Poland

Abstract

The purpose of this paper is to synthesize the state of the art in the area of water demand management and to reflect on how this knowledge can be applied to policies and projects in the water sector. The paper first presents some fundamentals of water demand analysis and modeling approaches, and then discusses the water demands of individual water-use activities, such as household, industrial plants and irrigation systems. The results of empirical studies show that, in most cases, residential water demand is inelastic, that is, it does not respond to price changes. The aggregated water-use activities are represented in the paper by urban agglomerations. In discussing different analytic tools, special attention is given to the IWR-MAIN Water Demand Analysis model. Water demand management at the level of the river basin is seen as part of the water resources allocation problem involving both the supply and demand sides of the water balance equation. Special attention is given to the relatively new group of hydro-economic models and their role in water demand analyses. At the national level, practically all studies and statistics refer to national water use rather than water demand. The paper closes with a few comments on the role of water demand analysis, its limitations, and further research needs.

Introduction

Important questions about water demand arise whenever decisions have to be made regarding water resources management. Typically, these questions are about how much water shall be used today and in the future, where it will be needed, and what purposes it will serve. The actual demands always depend on such time related variables as government policies, population levels and distribution, energy use and costs, per capita disposable income, technological development, consumer habits and lifestyles, and the prices of water withdrawals and wastewater disposal. Developing relations between those variables and using them to estimate water demands under different climatic, social, and economic conditions requires analytical approaches. This paper describes some of these approaches and shows how they can be used to analyze various demands for water within the framework of integrated water resources management (IWRM). To manage water demands more effectively, a balanced set of different demand measures should be sought that will both harness the efficiency of market forces and strengthen the capacity of governments to carry out their essential regulatory roles.

In many parts of the world water shortages and the degradation of water quality, both surface and groundwater, have reached alarming proportions. There are several obstacles to environmentally sound, economically efficient and socially responsible water management that cause such situations. Although various technical and management measures may be used to increase the availability of the resource, the most important thing is to manage existing supplies better. Emphasis should be placed on the efficient use of existing supplies, as well as their conservation, recycling, and reuse.

It has been already more than 30 years since Sewell and Roueche (1974) underlined that one of the most critical challenges is to shift from the more or less traditional supply-oriented extensive approach to water resources management to a demand-oriented intensive approach. The importance of the demand side of water resources management is perhaps more crucial and obvious today than in the past. As stressed by Gilbert White (2006): "The old paradigm of designing the cheapest reliable supply with little attention to demand determinants, pricing structures, and financing policies is no longer suitable." In the IWRM framework, a broad range of demand management measures must be considered.

The purpose of this paper is to synthesize and summarize the state of the art in the area of water demand management and to reflect on how this knowledge can be applied to water sector policies and projects. Because water demand management, by definition, is an interdisciplinary task, the readers of this paper may include persons with diverse professional backgrounds. For that reason, as well as because of the length of this paper, the treatment of the theoretical issues is kept on a fairly general level. However, references are made to basic textbooks and other publications where the interested reader may find more in-depth information. It is recognized throughout the paper that any attempt to influence and improve demand analysis methods in water resources management requires the reader to pay careful attention to the institutional, administrative, legal, and economic constraints under which water demand decisions are being made. The alternative approaches to water demand analysis described in this paper should always be interpreted in the context of these case-by-case varying constraints.

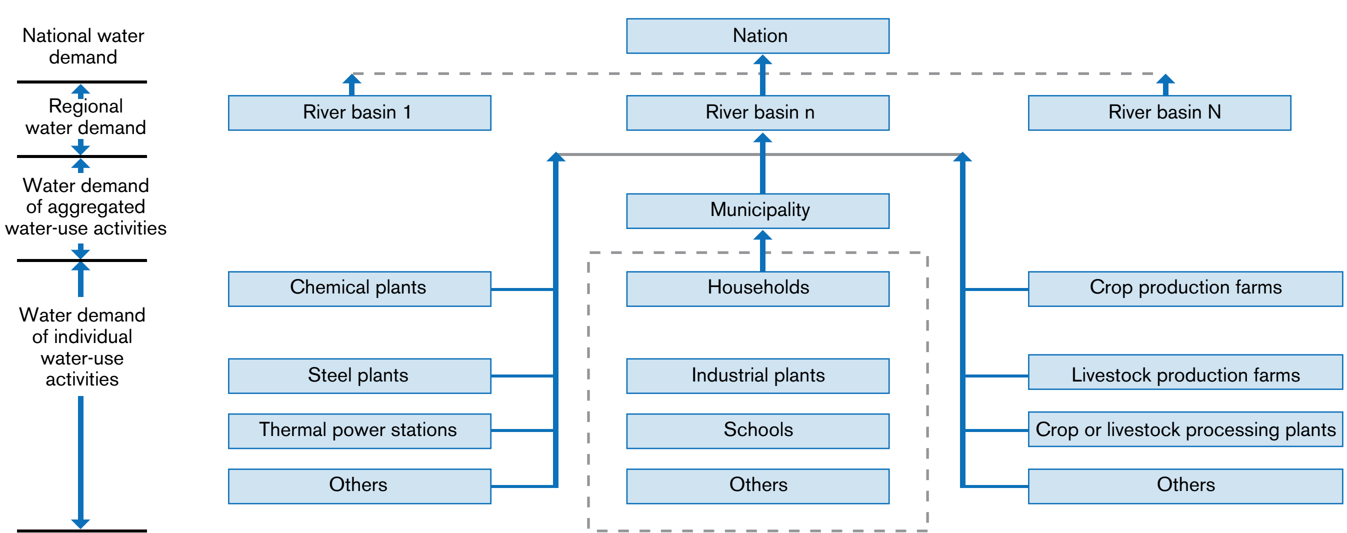
The paper begins with a discussion of some fundamentals concerning the analysis of water demands. Next, it provides a brief overview of the methodological framework of demand analysis and modeling approaches. The next four sections of the paper correspond to the different levels of water demand analysis shown in Figure 1: (1) the individual water-use activities, (2) the aggregated water-use activities, (3) the river basin planning level, and (4) the national level.

First, the demands of individual water-use activities are discussed (households, industrial plants, and agricultural farms). Next, the demands of individual water-use activities are combined into the demands of aggregated activities, illustrated by urban water demand management and forecasting. The discussion that then follows concerns the river basin and the national perspective in water demand analysis. The paper ends with few thoughts on the role of water demand analysis, its limitations, and further research needs.

Fundamentals of Water Demand Analysis

A useful way to begin the discussion of the fundamentals of water demand analysis is by examining the definitions of relevant terms, especially water use, demand and requirement, the dimensions of water demand, the demand

Figure 1. The Different Levels of Water Demand Analysis



Source: Kindler and Russell, 1984

elasticity dimensions of water demand, and demand management measures.

Water uses can be categorized as follows: (1) intake uses, (2) onsite uses, and (3) in stream uses. Intake uses include water for household, agricultural, and industrial purposes; that is, water uses that actually remove water from its source. Onsite uses consist mainly of water consumed by natural vegetation, rainfed agriculture, and evaporation from surface and groundwater bodies, swamps, and wildlife. In principle, the onsite uses deplete water supplies before they reach surface and groundwater resources. In stream uses include water for maintenance of aquatic ecosystems (especially wetlands), navigation, hydroelectric power generation, recreation, and some fish and wildlife uses.

Demand is a general concept used by economists to denote the willingness of consumers or users to purchase goods, services or inputs to production processes, since that willingness varies with the price of the thing being purchased. The demand function conforms to the negative relationship between price and quantity demanded, all other factors affecting demand being equal (*ceteris paribus* assumption). It is known that, in addition to price, water demand is affected by several other variables, including consumer income, the prices of substitute and complementary factors, and environmental parameters. Therefore, a general functional relationship between the quantity of water demanded q and k explanatory variables $x_1, x_2, ..., x_k$, one of them being water price, is $q = f(x_1, x_2, ..., x_k)$. When speaking of the demand for inputs to production processes (for example, industrial or agricultural water demand), it is called "derived" demand because the demand for water is derived from the demand for the final output of the production process.

Requirement refers to water use that does not obey the demand rule. In other words, the same quantity of water is purchased and/or used regardless of the price (if any). It is obvious that there do exist minimum requirements for many things in life that are unresponsive to price. But in agriculture and industry, the true "requirements" are usually only a small part of observed water use, and are almost never what large water projects are built to supply. Therefore, to treat all existing and future water uses as requirements is to ignore important possible ways of substitution and adjustment that can be seized upon as the cost of water to users goes up.

At this point it seems reasonable to look at the notion of "the price of water" and to ask where it comes from. In principle, there are two ways of establishing water prices. One is through the interaction of supply and demand in an open market. However, there are not that many examples of "water markets." The second option is setting water prices by means of administrative decisions. This underlies most of the water pricing schemes in existence. The questions of primary importance in the latter case are how the price is to be administered, how high it should be, and to what extent it should be varied in time and space. The ultimate purpose of managing the demand for water is to ensure that a given supply is allocated as close as possible to its "optimal" use pattern (Winpenny 1994). For the optimal allocation of resources, the price that water users pay for their marginal units of water withdrawal, consumptive use, and wastewater disposal services should reflect the marginal costs of supplying these units. Although this theoretical ideal is difficult to achieve, demand management measures can help to move the allocation of water closer to it. In addition, it should be remembered that the demand for water is not only a function of its price.

The elasticity of demand with respect to price P is the percentage by which the quantity demanded Q changes for a one percent change in price. For example, if the price elasticity of demand for water is −0.5, this means that a 1 percent increase in the price of water will result in a 0.5 percent decrease in water demand, with all other demand generating factors held constant. The demand for a commodity having no close substitutes is likely to be inelastic; that is, the absolute value of the PE (price elasticity) is < 1.0. If $PE = 0$ (perfect price inelasticity) a given commodity or service is a requirement. In other words, the more easily available substitutes are, the greater is the elasticity of demand.

The concept of elasticity can be used in relation to any one of the demand-determining variables (price and income are generally considered the most important). However, a distinction should be made between short- and long-term elasticities of water demand. As a rule, long-term demand is more elastic than short-term demand because longer time periods allow for more opportunities to adjust, and thus present more options for substitution.

Although this paper primarily concerns economic demand management measures, it is important to mention also that there are several other measures of importance. As shown in Table 1, they include educational, technical, regulatory, administrative/restrictive, and operational control measures.

All these measures have proved to be effective in reducing water demands and maximizing the benefits provided by the existing water infrastructure. They also free water for other uses and reduce environmental degradation. Efforts to reduce water demands can, therefore, contribute directly to the development goals of many countries, especially those that are chronically short of water or the capital to invest in water resources development.

The Modeling Approaches

There are two broad approaches to water demand modeling: econometric and programming. The theoretical framework of economic theories of demand for water as an input and consumer demand for water (Hanemann 1998) underlies most of the models built and applied.

In general, an econometric model specifies the statistical relationship that is believed to hold among the various economic quantities pertaining to a particular economic phenomenon under study. An econometric model can be derived from a deterministic economic model by allowing for uncertainty, or from an economic model that itself is stochastic. Some of the common econometric models are Box-Jenkins, ARIMA, and mulivariate regression models.

The modeling process usually proceeds by a series of iterations through the following steps:

(1) Choosing the model structure (specifying the model), that is, selecting variables and hypothesizing structural relationships, including whether or not simultaneous determination is involved for two (or more) variables; (2) Choosing functional forms; (3) Estimating model parameters; (4) Verifying and validating the model, and (5) Using the model.

In the case of programming models, analysis of demand for some inputs must be based on some knowledge of input-output relationships, although this is usually incomplete, especially for production involving several inputs. Consequently, the extent to which input-output relationships (production functions) can be estimated depends on the overall knowledge of the specific production processes and on data availability (for example see Kindler: 1988).

The programming approach requires knowledge of what is going on within and among many unit production processes. But for any given process one can be content with little observed data, because they can be calculated on the basis of the principles and rules of production practice. These calculations take into account how each unit process would operate under different assumptions about, for example, boiler efficiencies, pressures and temperatures of reaction, pump types, and so forth. Some of the necessary steps for developing a programming water demand model include the development of material and energy balances

Table 1. Categories of Demand Management Measures

No.	Category	Demand Management Measures
1	Economic (incentive-based)	Pricing structures and levels; subsidies, taxes and tax credits; rebates and buy-backs; low-interest loans; fines for regulatory non-compliance
2	Technical	Dual plumbing systems handling two qualities of water and toilets; water saving irrigation equipment
3	Educational	Education, information provision and conservation campaigns; water audits
4	Regulatory	Use and consumption regulations; building, plumbing and landscaping codes
5	Administrative/restrictive	Rationing, moral suasion, and voluntary use reduction
6	Operational control	Leakage detection and alleviation; pressure control and sewer infiltration control

Source: Herrington, 2006; World Bank, 1994.

for unit processes, the specification of factor inputs and their costs, and the calculation of wastewater residuals. The principal question is to determine whether the savings in costs of intake water and wastewater discharge justify the increased costs associated with making the change. Finding an answer to such questions is helped by the application of mathematical programming; it involves the use of optimization techniques such as linear, non-linear, or mixed-integer programming. The objective function is usually either to minimize the total cost of production or to maximize the net benefits of the system. The constraints take care of production requirements, availability of various input resources, and interrelations within and among the unit production processes.

Residential (Household) Water Demands

The issues concerning residential water demands in the high-income countries and in the developing countries must be discussed separately because of differing socioeconomic conditions among these groups of countries. It must be recognized right from the outset, that interrupted (intermittent) water supply is the norm in most developing countries and that this is one of the most common methods of controlling water use (Vairavamoorthy and Mansoor 2006). In fact, intermittent water supply is a control necessity and not a designed demand management measure. There are many serious shortcomings associated with intermittent water supply and, wherever possible, the goal should be full-day continuous supply.

High-Income Countries

The debates about residential water demand focus on both the efficiency of different demand management measures and their equity implications. There are several analysts who suggest that higher residential water prices are not necessarily the best measures for reducing demand, and that non-price measures (such as consumption regulations), which place direct controls on water use, are more viable means of reducing residential water demand. These opinions rely on the empirical research discussed below, which indicates that the elasticities of residential water demand are generally low. One of the reasons for this might be that in most high-income countries, residential water and sewerage bills are a small part of household budgets. The conclusion that the price of water is relatively ineffective in reducing water demand is sometimes strengthened by policy makers who argue that water pricing ignores the equity implications of water allocation decisions. Instead of pricing mechanisms they tend to favor targeted use restrictions to provide a basic level of water service at lower costs.

An excellent review of econometric residential water demand models developed by numerous authors in the last 30–40 years (mostly in the United States) is presented in the monograph by Renzetti (2002). He underlines that the primary purpose of these models is to "characterize the specific nature of the relationship between the observed quantity of residential water use and the explanatory variables suggested by economic theory." Among the principal issues analyzed is the determination of the price(s) of water. The difficulties in modeling include specification of the usually complex price-quantity function for residential water demand. A more fundamental problem is the lack of data on many potential demand explanatory variables and on certain characteristics of residential water, such as reliability and pressure. This confirms the problem raised by many water policy makers and water utility managers; namely, that information to determine the performance of price and non-price water demand management measures in their communities is generally insufficient. Some of the doubts mentioned above are confirmed by Renzetti (2002) who concludes that "residential water demands with the possible exception of outdoor water use in summer months are price and income inelastic."

The above conclusion is confirmed by most of the studies published after 2002. For example, Martinez Espineira (2005) used unit root tests to find that time-series of residential water use and other variables affecting that use are non-stationary. The application of the model developed in this study used monthly residential water use data from the city of Seville (Spain). The price elasticities of demand were estimated at about –0.1 in the short run and –0.5 in the long run. The author concludes: "…these estimates confirm that residential water is inelastic to price, but not perfectly." A similar conclusion was reached by Bithas and Chrysostomos (2006) in a study concerning residential water demand in the city of Athens (Greece).

Water prices and income were used as the main demand explaining variables in that study, which concluded that while increasing income would induce a drastic increase in water demand, economic instruments have little potential to influence water use.

It is worth quoting a comment made by Renzetti (2002) on the influence of climate change on residential water demands. He observes that, generally, "increases in temperature or evapotranspiration rates lead to higher residential water demands while increases in precipitation decrease demands."

Developing Countries

When looking at demand for residential water in developing countries it is important to distinguish among three principal categories of consumers: high-income, middle-income, and low-income (Vairavamoorthy and Mansoor 2006). In the high-income category, applicable demand management measures include in-house retrofitting and outdoor water saving options (garden, swimming pool). Water pricing measures must, however, be combined with extensive awareness-raising campaigns given that increased cost tends not to lead to water savings among the rich. The most effective demand management option when addressing consumption by middle-income households is water pricing. Increasing block tariff rates and undertaking an effective awareness-raising strategy seem to work for this group of consumers. Finally, low-income consumers, who rarely have individual connections to piped water, are simply the beneficiaries of demand management measures introduced for the first two categories of water consumers.

The most common water charging policy is the increased block tariff (IBT), where high volume residential consumers subsidize relatively poorer ones. The first block is charged at a low rate and it covers basic human needs only. The next block of so-called "normal" consumers is charged a price that fully recovers maintenance costs and the depreciation of capital assets. Finally, "luxury" consumers pay substantially more for water and thus subsidize the first block of users. Despite the subsidy, the IBT system has some disadvantages for the poor. The practice of several poor families sharing a single water connection implies that their total combined water usage exceeds the lowest IBT block. Other disadvantages of IBT as well as alternative tariff scheme proposals are discussed by Liu et al. (2003).

Water Demands of Industrial Plants

Almost all industrial plants use water as an input to their production activities, however, the purposes for which water is used vary. Water can be used as part of the product, it can be used to convey the product from one stage of production to another, it can used for washing and cleaning throughout the plant, and it can be used as the principal heat removal medium. Econometric and programming approaches are both used when modeling industrial water demand relationships.

In the 1960s, Bower, Lof, Kneese, and Russell at Resources for the Future in Washington, D.C., started developing programming models to analyze water use and wastewater disposal flows in the chemical, petroleum, pulp and paper, and metal processing industries. About 10 years later, these models were extended further by Calloway, Schwartz, and Thompson (1974). In the 1980s, they were once again put on the agenda of the International Institute for Applied Systems Analysis (Kindler and Russell 1984).

The basic concept in these models is that of a unit process characterized by fixed proportions between inputs and outputs, which are usually called "technical coefficients." In industrial production, one may identify such unit processes as, for example, water use, water treatment, coal supply and transportation, air pollution emissions, and so forth. In general, if one process differs from another in the type, proportions, or timing of inputs, they are treated as separate unit processes in the model. A unit process may be operated on a smaller or larger scale and various unit processes may be operated simultaneously, each one at the most appropriate level for its purpose. The choice of the best combination of unit processes (how to define "best" is another issue), replaces the traditional engineering choice of the best combination of inputs and outputs.

The advantages of programming models are significant. Above all, they are future-oriented and permit an analysis of water demands in hypothetical situations for which there are no statistical records. Most of the criticism of these models has been because of the purely economic character of the objective function (usually maximization of net benefits) when it is known that industrial enterprises have other motives in addition to profit maximization.

In his overview of industrial water demand studies, Renzetti (2002) indicated that econometric models are used less frequently than programming models. He quoted Stone and Whittington (1984), who point out that econometric (statistical) estimates of industrial water demand relationships are difficult mostly because of the small sample sizes. Some data are often missing even in the case of plants that are included in the sample. In addition, problems commonly arise with respect to the simultaneous determination of the price of water and the quantity used.

The current situation with regarding water use and demand studies is well characterized by Renzetti (2002) in his concluding remarks:

> ...The relationship between water intake, recirculation and discharge on the one hand and the prices of other inputs is a particularly understudied area. Second, internal water recirculation appears to be the primary means for firms to reduce water intake. Once again, however, it is not clear whether the primary motivation for adopting recirculation is to save on expenditures related to water intake, wastewater discharge, energy, raw materials or some combination of all of these. Third, both programming and econometric methods of modeling industrial water use ... are best seen as complementary rather than competing approaches. They have different data requirements and highlight different features of industrial water use.

Agricultural Water Demands

The amount of water involved in agriculture is significant. In several countries the agricultural sector uses more water than all other economic sectors combined. Worldwide, most of this water is provided by rainfall stored in the soil profile, and only 15 percent is provided through irrigation. The amount of irrigation varies from country to country and region to region, depending mostly on climate conditions and on the degree of development of the irrigation infrastructure.

The demand for crops is determined by crop prices and quantities. Several inputs are required to produce the desired amount of crops, water being one of them. Hence, the demands for these inputs are derived demands; that is, they stem from the specified levels of the primary set of outputs. This is, of course, an idealized picture of what actually happens even in predominantly market economies since it omits many adjustment mechanisms. For example, if water becomes scarce, agronomists can be expected to switch to crop varieties that are more resistant to droughts. Many other non-market forces also affect the determination of prices and quantities. These include price supports or restrictions in the size of the plot of land planted with a particular crop.

In the agricultural sector, the efficiency of water use is generally low. There are, however, several methods of increasing efficiency in irrigation. If incentives are in place, including pricing of irrigation water [see for example Tsur and Dinar (1997) and Tsur (2000)], farmers are motivated to adopt water-saving irrigation technologies. In principle, these technologies rely on the frequent application of small amounts of water as directly as possible to the roots of the plants. Reducing the pollution loads of water used by industries and in urban areas would also enable the reuse of some of that wastewater in irrigation. The practical implementation of these solutions is not easy because of human health issues, but there are large potential benefits from the use of wastewater for irrigation.

Agriculture will remain the dominant user of water at the global level. In many countries, in particular those situated in the arid and semi-arid regions of the world, this dependency can be expected to intensify. The contribution of irrigated agriculture to food production is substantial but, in the future, the rate of growth will be lower than in the past. Addressing the food and poverty crises in developing countries will require a new emphasis on small-scale water management in rainfed agriculture involving the redirection of water policy and new investments in that area. Possible water management improvements in rainfed agriculture are discussed in depth by Rosengrant et al. (2002) and IWMI (2007).

This paper concentrates on the water demands of irrigated agriculture only. The analysis of these demands can be facilitated by modeling, and both the econometric and programming models are applied. In the first of these two approaches, production functions are usually estimated to capture the relationships between crop yields and the land, rain, solar energy, irrigation water, and irrigation technology variables. However, the complexities of agricultural production often cannot be adequately captured in the form of a production function. Many factors other than the price of water can change the quantity of water demanded; their mutual relationships and possibilities for substitution cannot be explicitly expressed. Thus, it may often be more reasonable to model agricultural production and related processes (the programming approach), and derive approximate demand functions from them directly. In Figure 2, for example, a simple agricultural system of "one type crop—one type animal" is presented.

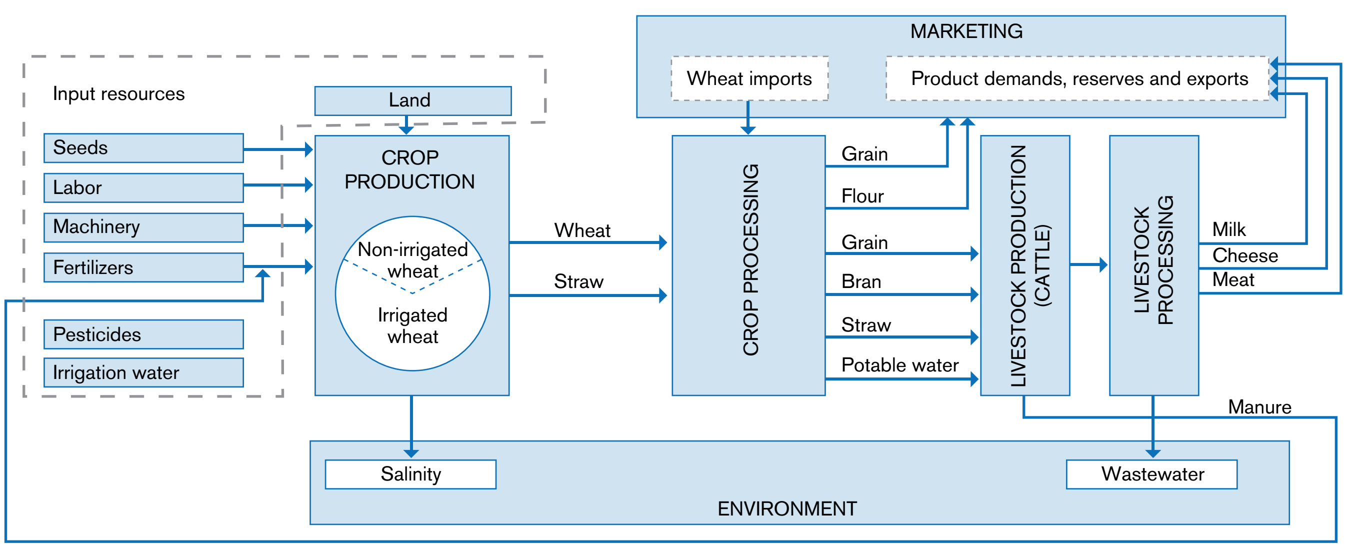
As illustrated in Figure 2, this system encompasses the process of producing wheat, its processing and product marketing, including alternative uses of some products for feeding livestock and livestock processing. The first and most important step in modeling is to define the objective function, which might be, for example, to maximize net benefits from agricultural production. The next step is to identify the decision variables. The cost associated with each variable can be subdivided into two categories: fixed costs, including capital investment depreciated over time; and variable costs that include resources (not concerned with capital investments) and the cost of various activities such as equipment maintenance, labor, and so forth. The problem is to find the set of decision variables that maximizes the objective function subject to constraints concerning available resources. By varying parametrically the cost of irrigation water, the model can be used to derive a demand function for that specific input to the production process.

Renzetti (2002) discusses several agricultural production programming as well as econometric models directly identifying agricultural water demand relationships. He makes the point that "programming and econometric approaches to modeling agricultural water use are best seen as complements rather than substitutes." Programming models describe better technological details under different behavioral assumptions and they more easily incorporate information regarding physical processes, among them climate change. Econometric models have the ability to directly estimate price elasticities, as well as establishing the statistical significance of different explanatory demand variables.

Renzetti (2002), quoting the influential work of Caswell and Zilberman, states that:

> ...adoption of new irrigation technologies is positively related to output and water prices while negatively related to soil quality. Subsequent work, however, appears to demonstrate that the

Figure 2. One Type Crop, One Type Animal Agricultural System



Source: Gouevsky and Maidment 1984.

strength of these relationships may not always be strong. In particular, for a given allocation of crops to available acreage, irrigation water demands are price inelastic. The demand for irrigation water becomes more responsive to price changes, however, once it is assumed that farmers are free to alter their output mix.

In Europe, the implementation of a cost recovery approach in water resources management and water pricing policies is promoted by the European Union (EU) Water Framework Directive, which is currently being implemented in all EU member countries. A recent publication by Iglesias and Blanco (2008) on the role of water pricing policies in irrigated agriculture is worth mentioning. The authors developed an innovative mathematical programming model to evaluate the impact of cost recovery in a large number of irrigation districts in Spain. The proposed model allows farmers' behavior to be simulated under different water pricing scenarios, taking into account the possibilities of adopting new production patterns and new irrigation technologies under changing environments, including climate change.

Urban Water Demands

A characteristic of the 21st century is that a growing majority of the world's population lives in urban centers. Urban water usage has increased steadily, reflecting more concentrated populations and intensified economic activities in urban areas. Although the volume of water dedicated to urban use is less than that used by agriculture and other sectors, its social and economic importance is enormous. In addition, urban water use has high embedded energy content.

During the coming decades, urban areas, especially those in developing countries, will experience the most rapid rates of population growth. As a result, urban residents must be provided with a variety of water services, including water supply, sewerage collection and treatment, and wastewater disposal. This is why the management of water demand in urban areas deserves particular attention.

Urban water usage is unique in its fragmentation, in terms of both physical use of the resource and the institutional structures that govern that use. Water use covers a wide range of activities that may be grouped into residential, industrial, commercial, and public uses, as well as system losses and unaccounted for water. Water use and demand analysis in the residential and industrial sectors have been discussed above. Commercial customers are very heterogeneous in their water use. They include food and beverage services, commerce conducted from offices, shops, hotels, and so forth. Water is used for cleaning, cooling, sanitation, and landscaping. Public water use includes a wide range of activities, such as street cleaning, watering municipal parks, use in hospitals, government services, public toilets, public swimming pools, and other similar public services. Lost and unaccounted for water includes, above all, leakages from mains and the distribution systems. These losses, expressed as a percentage of annual water production, vary substantially. For example, on average, 12.3 percent of annual production in the United States was reported as water losses in 2005 (Billings and Jones 2007). Water losses in the cities of developing countries are reaching extreme levels of up to 40 percent to 60 percent of the water supply (Vairavamoorthy and Mansoor 2006).

It should be recognized that each urban water sector has distinct quality requirements, usage processes, disposal methods, and jurisdictional oversight and responsibilities. As a result, there is no cohesive approach to planning and policy that can formulate consistent and effective responses to urban water issues, in particular protracted droughts. Programs are designed to modify the level and/or timing of demands for water by encouraging changes in consumer behavior through the appropriate water and sewerage disposal pricing systems, among other options.

The significant diversity of water uses in the urban commercial and public water use sectors means that there are not many studies available on the application of economic water demand measures (price incentives) in these sectors. Renzetti (2002) mentions only three studies on commercial water use: a mail survey of commercial establishments in Miami (USA); estimation of aggregate water demand equations for the publicly-supplied commercial sector in a US urban area (where price elasticities varied from −0.141 to −0.360); and a similar econometric study based on commercial water use data from 16 communities in Ohio (USA) showing short- and long-run elasticities of −0.234 and −0.918, respectively.

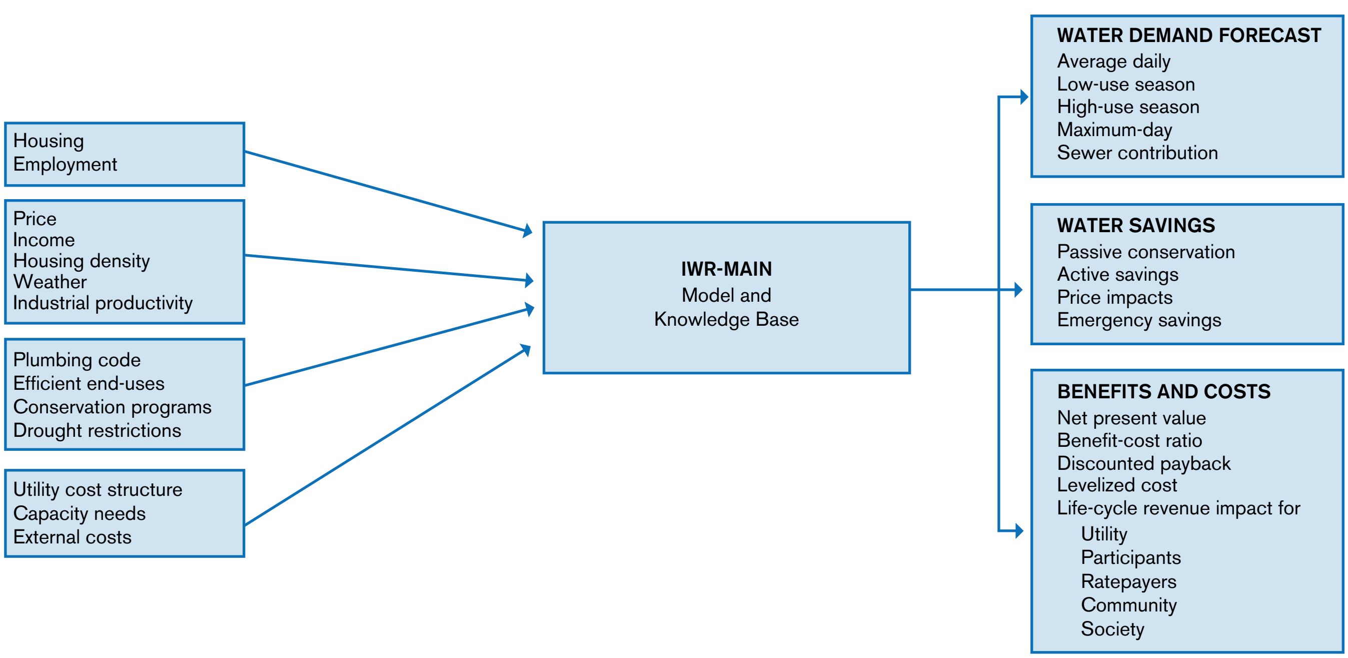
Boland (1998) analyses the state of the art in the application of different tools in urban water use analysis and forecasting. He comments on the simple bivariate models, per capita requirements method, unit use coefficient method, multivariate methods with and without economic explanatory variables, and econometric demand models. Concerning the econometric demand models he offers the following opinion:

> ...So far, econometric models are available mostly for residential water use and detached single-family dwellings. Such models have been highly successful, and are able to predict water use under a wide range of circumstances... Examples of econometric analysis of demand are ... the residential sector model(s) of IWR-MAIN. Unfortunately, few models of this kind have been developed for multi-family residential buildings, or for nonresidential uses. Further research is needed before this approach can be used to forecast urban water use in all sectors.

The IWR-MAIN Water Demand Analysis Software, Version 6, is presented by Opitz et al. (1998). The original version of that model was developed at the end of the 1960s and it was upgraded several times under the sponsorship of many institutions, mostly the Institute for Water Resources of the US Army Corps of Engineers. The currently available IWR-MAIN model, Version 6, includes a benefit-cost module for analyzing water demand management measures. It also includes an up-to-date database on residential water use, nonresidential water use, and end-use parameters. The model IWR-MAIN software package is designed for "(1) translating demographic, housing, and business statistics (for cities, counties or service areas) into estimates of existing water demands; and (2) using projections of populations, housing, and employment to derive baseline forecasts of water use. The forecast module disaggregates total urban water use into spatial, temporal, and sectoral components". Figure 3 summarizes the inputs and outputs of the IWR-MAIN Water Demand Analysis Software, whose complete description is presented in IWR-MAIN (1996).

Several water agencies across the United States have applied this model to forecast water demand. To what extent this model, especially its knowledge base, can be used outside of the United States is not entirely clear to the author of this paper. However, there are some examples similar to the IWR-MAIN application for analysis of demand-

Figure 3. IWR-MAIN Inputs and Outputs



Source: Opitz et al. 1998.

driven water policies in Volos, Greece (Kolokytha and Mylopoulos 2004).

To close this section, some comments should be made on forecasting urban water demands. Billings and Jones (2007) present four groups of forecasting methods: (1) judgment-based subjective methods, (2) extrapolation, (3) multivariate regression, and (4) nonparametric methods (e.g. neural networks and fuzzy logic). Their book is very much based on US practice, but the methodology is applicable worldwide. Together with the book by Baumann, Boland and Hanemann (1998), these two works provide a most complete discussion and evaluation of urban water demand management, planning, and forecasting methodologies.

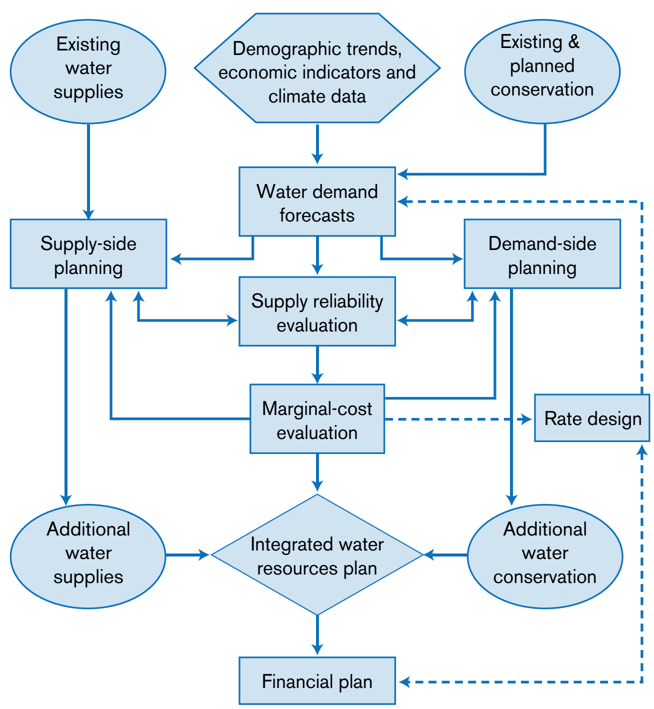
Water Demand Management at the River Basin and National Levels

So far, this paper has discussed water demand management issues with reference to individual (residential, industrial, and agricultural) and aggregated (urban) water use. The situation is different and more complex as we move up to the higher levels of aggregation. Many individuals and aggregated users interact at these levels to the extent that they share sources of water and sinks for wastewater disposal. In addition, the intake water users interact with instream (non-extractive) uses, including water required for the maintenance of aquatic ecosystems, navigation, hydroelectric power generation, recreation, and fish and wildlife uses. Those uses have not been discussed in this paper because none of them is priced directly, but it should be recognized that each of them has a specific value. Even in the absence of market-clearing prices, there are a number of ways to estimate the value of water in alternative uses. But this discussion, which is of fundamental importance for the efficient allocation of resources, is beyond the scope of this paper. For an in-depth treatment of this subject, the interested reader is referred to the book by Gibbons (1986). Here, it should only be stated that at the level of the river basin, water demand issues become part of the resource allocation problem, involving both the supply and demand sides of the water equation. Within the framework of integrated water resources management, a wide range of supply and demand management options must be considered in the scale of the entire basin.

When considering the river basin scale of water demand management, it is necessary to "shift the focus of analysis away from the estimation of water demands towards the use of that information" (Renzetti 2002). That information should be used within the framework of river basin models designed to incorporate interactions between water supply and the demands of different water users and uses, and assess the significance of these interactions from the perspective of water demand policy.

A number of schematics have been proposed to represent the river basin models. They have been available to assist water resources policy, planning, and management for decades. In principle, such models are built following a process that consists of several interrelated and highly iterative steps which, in principle, are similar from model to model. The modeling process is illustrated in Figure 4 by using the scheme proposed by Rodrigo et al. (1995) for integrated river basin planning.

Figure 4. The Integrated River Basin Modeling Process



Source: Rodrigo et al. 1995

The modeling steps are discussed by Beecher (1996). They begin with the identification of demographic trends, economic indicators, and climatic data for evaluating existing and future water supply and demand alternatives. This step includes an evaluation of water supply reliability, rate design, and analysis of marginal costs and benefits within the framework of demand-side planning. Building the integrated water resources plan involves determining its principal objectives, and developing specific criteria for evaluating feasible alternatives. Selection of the alternative that best satisfies the plan's objectives is enhanced by the development of a financial plan.

The river basin models in question are close to the regional models discussed by Renzetti (2002), employing econometrically estimated demand equations, and a computable general equilibrium approach or programming techniques. Examples of such models presented by this author include one of regional water use that combines linear programming models of irrigation water demand with an input-output model (I-O) of the economy of one of the US states in order to explore the relationship between water use and economic conditions. The linear programming model provides estimates of the marginal value of irrigation water in alternative applications. Taking into account future increases in water costs, the model allows the estimation of future changes in water use, crop patterns and farm income for the entire state. Another example, as an alternative to the I-O model, involves construction of an econometric model to consider the impact of a doubling of irrigation water prices in the region. Computable general equilibrium models are sometimes applied to assess water demand policies and gain a more complete representation of the regional economy.

In this context, a new generation of hydro-economic river basin models seems to be especially attractive. These models take account of the fact that economic issues and processes are becoming increasingly integrated with more traditional engineering and hydrologic models of water resources management (Heinz et al. 2007). Combining economic management concepts and performance indicators with an engineering, hydrologic, and nature conservation understanding of a water resources system can provide results and insights more directly relevant for demand management decisions and policies.

The hydro-economic models help water managers design, operate, and expand water resource systems efficiently and in accord with explicitly represented societal values and priorities. The cross-fertilization of engineering and economics allows more realistic representations in mathematical models of how water is managed in practice and how management could be improved. Hydro-economic models are distinguished by a solution-oriented and integrated approach. The central idea of these models is that water demands are not fixed requirements, but functions where different quantities of water at different times have varying total and marginal values. In this approach water management is driven by the economic value of water in addition to other requirements or priorities. Economic concepts used include: economic water demand, value of environmental services, consumer surplus, willingness-to-pay, and supply-side economics. Hydro-economic models are built with diverse aims, formulations, levels of integration, spatial and temporal scales, and solution techniques. Policy insights and management practices revealed by the application of these models promote integrated water resources management. Hydro-economic models go well beyond minimizing costs and maximizing profits; they provide a common framework through which the value of all water services can be considered and used to direct system planning and operation (Haron et al. 2008).

Several examples of the basin-wide applications of hydro-economic models are already available. For example, Guan and Hubacek (2008) present an integrated hydro-economic accounting and analytic framework developed for water resources management in North China, based on I-O modeling combined with a mass-balanced hydrological model. Another study (Gurluk and Ward 2008) reports development of a hydro-economic model in Turkey to study problems resulting from increasing demands for water in the Nilufer River basin, where important agricultural, tourist, and industrial activities are located. The model is solved using the GAMS system and, according to the authors, could be applied to other river basins worldwide. Hydro-economic models are also applied in Morocco (M'Barek et al. 2004). Changing climatic, economic, and social conditions have major impacts on the availability of water resources and rural poverty in developing countries like Morocco. The integrated model of the Draa valley is based on the hydro-economic river basin model developed at the International

Food Policy Research Institute (IFPRI). The paper by Maneta et al. (2007) reports on the preliminary results of research that aims to develop a detailed hydro-economic model for assessing the effects of alternative surface and groundwater policies in the Buriti Vermelho sub-catchment area of the São Francisco River basin in Brazil. A spatially explicit, farm-level, mathematical programming model has been developed. The model is capable of accommodating a broad array of farm sizes and characteristics to predict the effects of alternative water policies and neighbors' water use patterns on agricultural production.

The next level of demand aggregation is the nation as a whole. However, at this level, practically all available studies and statistics refer to national water use rather than water demand. It should be recognized that according to water availability and local conditions, water prices and wastewater disposal charges will vary substantially and, except for very small nations, there is no such thing as a uniform "nationwide" price of water. Most previous aggregated national water use forecasts significantly overstated actual water use.

Conclusions

When water is readily available, and thus relatively inexpensive, attempting to use it efficiently may not be a critical issue. However, it does becomes a critical issue as water demands from different economic sector increase, as the costs of supplying water increase, and as the availability of the resource decreases.

The purpose of this paper was to contribute to gain a better understanding of the current state of practice in the area of water demand management, including alternative methodologies, techniques, and applications. The paper explored various dimensions of water demand analysis, and showed that economic theories provide a good conceptual framework for modeling water demands and identifying variables that influence those demands, one of them being water price.

There are two broad approaches to water demand modeling: econometric and programming. The modeling task, however, is difficult. One of the key problems is the scarcity of adequate databases concerning water use under different physical, economic, and institutional conditions. This calls for the initiation of new data collection programs. In addition, one of the missing elements of great significance for water demand relationships is the quality of water withdrawn.

As pointed out in this paper, the demand side of water management deserves more attention than it has been given so far. To this end, models capable of producing demand functions for residential, industrial, agricultural, and urban water are useful additions to the tools of water management analysts. During the last few decades the methodologies used for estimating demand relationships have been improved significantly. It should be made clear, however, that these models still raise a good number of questions, many of which remain unresolved. The field is still open to a vast amount of research and investigation.

References

Baumann, Duane D., John J. Boland and W. Michael Hanemann. 1997. *Urban Water Demand Management and Planning*. New York: McGraw-Hill, Inc.

Beecher, J. A. 1996. Avoided Cost: an Essential Concept for Integrated Resources Planning. *Water Resources Update*, No. 104.

Billings, R. Bruce and Clive V. Jones. 2007. Forecasting Urban Water Demand, *American Water Works Association*, Second Edition.

Bithas, K. and S. Chrysostomos. 2006. Estimating Urban Residential Water Demand Determinants and Forecasting Water Demand for Athens Metropolitan Area, 2000–2010. *South-Eastern Europe Journal of Economics* 1, pp. 47–59.

Boland, J. 1998. Forecasting Urban Water Use: Theory and Principles. In Baumann, Boland and Hanemann, *Urban Water Demand Management and Planning.* New York: McGraw-Hill, Inc.

Calloway, J. A., A. K. Schwartz, and R. G. Thompson. 1974. Industrial Economic Model of Water. *Water Resources Research* 10:650–8.

Gibbons, D. C. 1986. The Economic Value of Water. Washington, D.C.: Resources for the Future.

Gouevsky, Ilia V. and David R. Maidment. 1984. Agricultural Water Demands. In J. Kindler and C. S. Russell (eds.), *Modeling Water Demands*. New York: Academic Press.

Guan, D. and K. Hubacek. 2007. Assessment of Regional Trade and Virtual Water Flows in China. *Ecological Economics*, 61, 159–170.

Gurluk, Serkan and Frank A. Ward. 2008. Hydro-economic Modeling for Water Resources Management: the Nilufer Basin, Turkey. Third International Conference on Water Observation and Information System for Decision Support, 27–31 May, 2008, Ohrid, Macedonia.

Hanemann, W. Michael. 1998. Determinants of Urban Water Use. In Baumann, Boland and Hanemann, *Urban Water Demand Management and Planning.* New York: McGraw-Hill, Inc.

Haron, J. J., M. Pulido-Velásquez, D. E. Rosenberg, J. J.Medellín-Azuara, J.R. Lund. 2008. Poster at the 13th IWRA World Congress, Montpellier, France, 1–4 September.

Heinz I., M. Pulido-Velázquez, J. R. Lund, and J. Andreu. 2007. Hydro-economic Modeling in River Basin Management: Implications and Applications for European Water Framework Directive. *Water Resources Management*, Vol. 21, No. 7, July.

Herrington, Paul R. 2006. The Economics of Water Demand Management. In David Butler and Fayyaz Ali Memon (eds.), *Water Demand Management*. London: IWA Publishing.

Iglesias, E. and M. Blanco. 2008. New Directions in Water Resources Management: The Role of Water Pricing Policies. *Water Resources Research*, Vol. 44, 1–11.

International Water Management Institute (IWMI). 2007., Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute.

IWR–MAIN. 1996. Version 6, Water Demand Analysis Software. *User's Manual and System Description*.

Kindler, J, C. S. Russell (eds.). 1984. *Modeling Water Demands*. New York: Academic Press.

Kindler, J. 1988. Modeling Derived Demand for Irrigation Water, *Agricultural Water Management*, 13, 403–410.

Kolokytha, E. G. and N. A. Mylopoulos. 2004. Evaluating Demand Management Aspects of Urban Water Policy. The City of Volos Case, Greece. *Water, Air & Soil Pollution*, Vol. 4, Nos. 4–5, October.

Liu, J., H. H. G.Sanije, and J. Xu. 2003. Water as an Economic Good and Water Tariff Design Comparison Between IBT-con and IRT-cap. *Physics and Chemistry of the Earth* 28, 209–217.

M'Barek, R., T. Schmidt and M. Koll. 2004. Hydro-economic Modeling in Southeast Morocco. *Rural Poverty Reduction through Research for Development. Deutscher Tropentag*, Berlin, October 2004.

Maneta, M., M. Torres, R. Howitt, S. A. Vosti, W. W. Wallender and L. Bassoi. 2007. A Detailed Hydro-economic Model for Assessing the Effects of Surface Water and Groundwater Policies: A Demonstration Model from Brazil. *Annual Meeting of the Agricultural and Applied Economics Association.* Portland, July.

Martinez-Espineira, R. 2005. An Estimation of Residential Water Demand Using Co-Integration and Error Correction Techniques. *MPRA Paper No. 615* and *Journal of Applied Economics v:10*.

Opitz, E. M., J. F. Langowski, B. Dziegielewski, N. A. Hanna-Somers, J. S. Willett, and R. J. Hauer. 1998. Forecasting Urban Water Use: Models an Application. In Bauman, Boland and Hanemann (eds). *Urban Water Demand Management and Planning.* New York: McGraw-Hill, Inc.

Renzetti, S. 2002. *The Economics of Water Demands*. INSERT City: Kluwer Academc Publishers.

Rodrigo, D., T. Blair, and B. Thomas. 1995. Integrated Resources Planning and Reliabilty Analysis: A Case Study of the Metropolitan Water District of Southern California (unpublished), mentioned in Baumann, Duane D., John J. Boland and W. Michael Hanemann (eds.). *Urban Water Demand Management and Planning.* New York: McGraw-Hill, Inc.

Rosegrant, Mark, Ximing Cai, Sarah Cline, and Naoko Nakagawa. 2002. The Role of Rainfed Agriculture in the Future of Global Food Production. *EPTD Discussion Paper No. 90, International Food Policy Research Institute*, Washington, D.C.

Sewell, W. R. D., and L. Roueche. 1974. The Potential Impact of Peak Load Pricing on Urban Water Demands, Victoria, B.C., A Case Study in *Priorities in Water Management*, University of Victoria, B.C. Canada.

Stone, J. C. and D. Whittington. 1984. Industrial Water Demands. In J. Kindler and C. S. Russell (eds.), *Modeling Water Demands*. New York: Academic Press.

Tsur, Y. 2000. Water Regulation Via Pricing: The Role of Implementation Costs and Asymmetric Information. In A. Dinar (ed.), *The Political Economy of Water Pricing Reforms*. New York: Oxford University Press. pp. 105–120.

Tsur, Y. and A. Dinar. 1997. On the Relative Efficiency of Alternative Methods for Pricing Irrigation Water and Their Implementation. *World Bank Econ. Rev.*, 11, 243–262.

Vairavamoorthy, K and M. A. Mohamed Mansoor. 2006. Demand Management in Developing Countries. In David Butler and Fayyaz Ali Memon (eds.), *Water Demand Management.* London: IWA Publishing.

White, Gilbert F. 2006. Foreword. In Duane D. Baumann, John J. Boland and W. Michael Hanemann, *Urban Water Demand Management and Planning*. New York: McGraw-Hill, Inc.

Winpenny, J. 1994. *Managing Water as an Economic Resource*. Development Policies Studies. London: Routledge and Overseas Development Institute.

World Bank. 1994, Water Resources Management, A World Bank Policy Paper, Washington, D.C.

World Bank Water Research Team. 1993. The Demand for Water in Rural Areas: Determinants and Policy Implications. *World Bank Research Observer* 8 (1).

3. Managing Droughts and Floods under Changing Environments

Juan B. Valdés[1]
SAHRA[2] and the University of Arizona

Abstract

According to reports from the Intergovernmental Panel on Climate Change (IPCC), climate change will intensify the hydrologic cycle, making extreme events like floods and droughts more frequent and intense. This paper discusses efforts to characterize floods and droughts, the use of paleoclimatic data to increase the instrumental record length, the use of climate projections from the most recent runs of the global circulation models (GCMs) for hydrologic applications, and the implication of climate variability and change in the management of water resources systems.

Introduction

The IPCC's 2007 assessment (IPCC-AR4 2007) indicates that anthropogenic climate change will result in significant challenges for water resources systems. On the one hand, higher mean temperatures, more frequent, longer-lasting heat waves, and increased summer dryness in most parts of the northern, middle, and high latitudes will raise the risk of droughts. On the other hand, there will also be an increased chance of intense precipitation and flooding caused by the greater water holding capacity of a warmer atmosphere (Frei et al. 1998). Consequently, precipitation events will tend to be more intense with longer drier periods in between.

The consequences of these dramatic changes are of great importance, affecting agriculture, energy, the water supply, wildlife, and nearly every aspect of human societies.

From a hydrology and water resources management perspective, changes in the variability of hydroclimatic factors are even more important than changes in their mean values. The IPCC reports indicate that climate change will result in an intensification of variation in the hydrologic cycle (see Figure 1).

Climate projections, for instance, show that droughts will be more frequent and more intense in southern Europe, particularly in the Iberian Peninsula, a region of high economic activity (Figure 2).

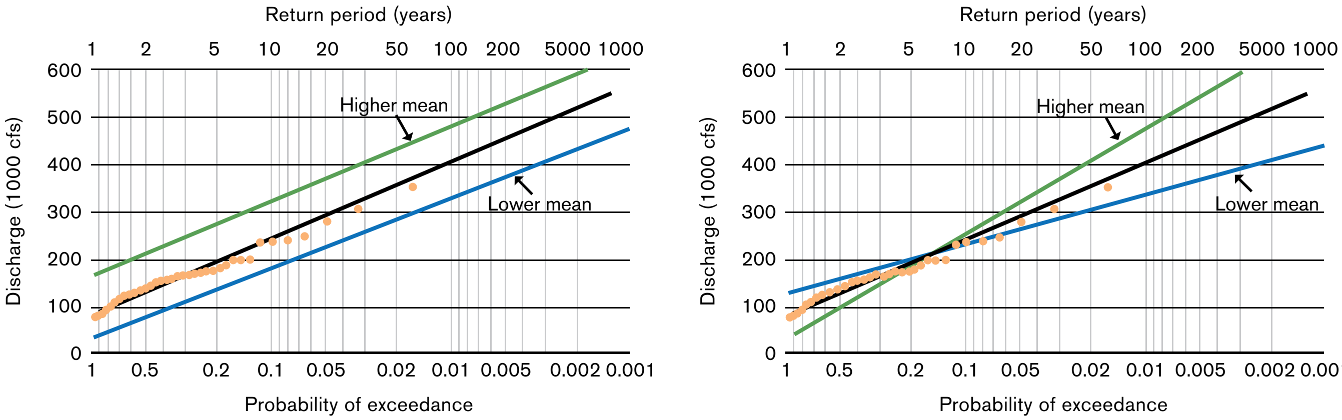
This paper reviews some critical aspects for the discussion of how to approach the management of water resources under extreme hydrologic events in a changing climate.

Characterization and Forecasting

In order to devise appropriate water resources management plans, hydrologic extremes—floods and droughts—need to be first characterized in their magnitude and recurrence. Floods tend to be easier to characterize and there is ample scientific literature on determining their magnitude

1. Julio Cañón, Francina Domínguez and Aleix Serrat-Capdevila of SAHRA and Javier González from the University of Castilla La Mancha (Spain) provided significant input to the writing of this article. Mary Black of SAHRA provided significant editing that greatly improved this manuscript. All contributions are greatly acknowledged by the author.
2. National Science Foundation Science and Technology Center for Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA).

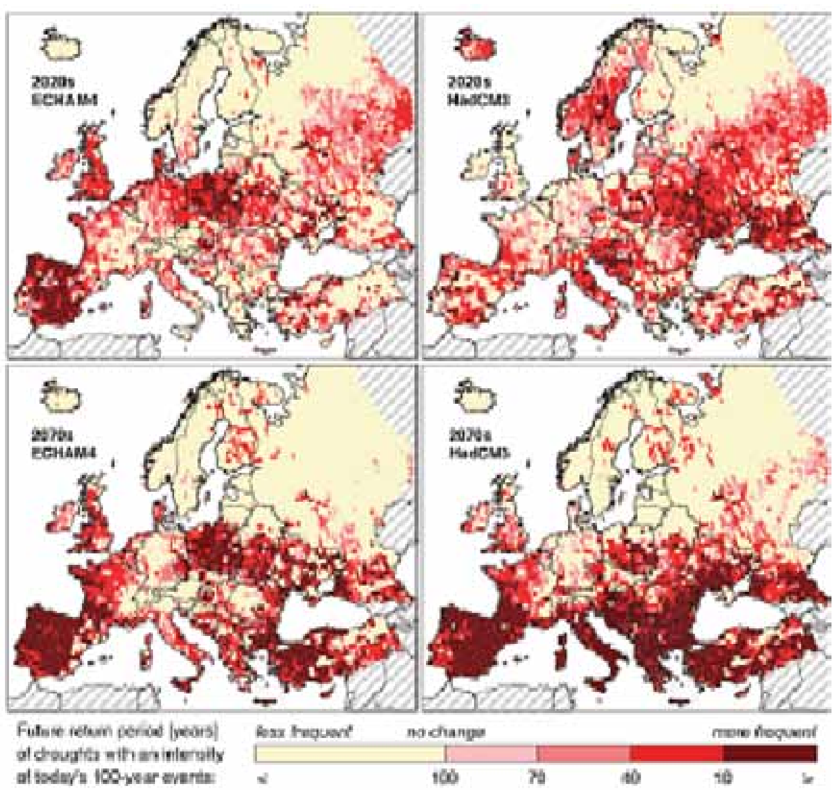
Figure 1. Variations in the Hydrologic Cycle



Source: SAHRA

Note: The scenario at left shows a shift in the mean above or below current values. The scenario at right shows minimums decreasing and maximums increasing, in accordance with IPCC projections.

Figure 2. Change in the Recurrence of 100-year Droughts



Source: IPCC 2007.

Note: Based on comparisons between climate and water use in 1961 to 1990 and simulations for the 2020s and 2070s (based on the ECHAM4 and HadCM3 GCMs, the IS92a emissions scenario and a business-as-usual water-use scenario). Values calculated with the model WaterGAP 2.1 (Lehner et al. 2005b).

and frequency. This is not the case for droughts, whose characterization will be emphasized here.

Characterization of Droughts

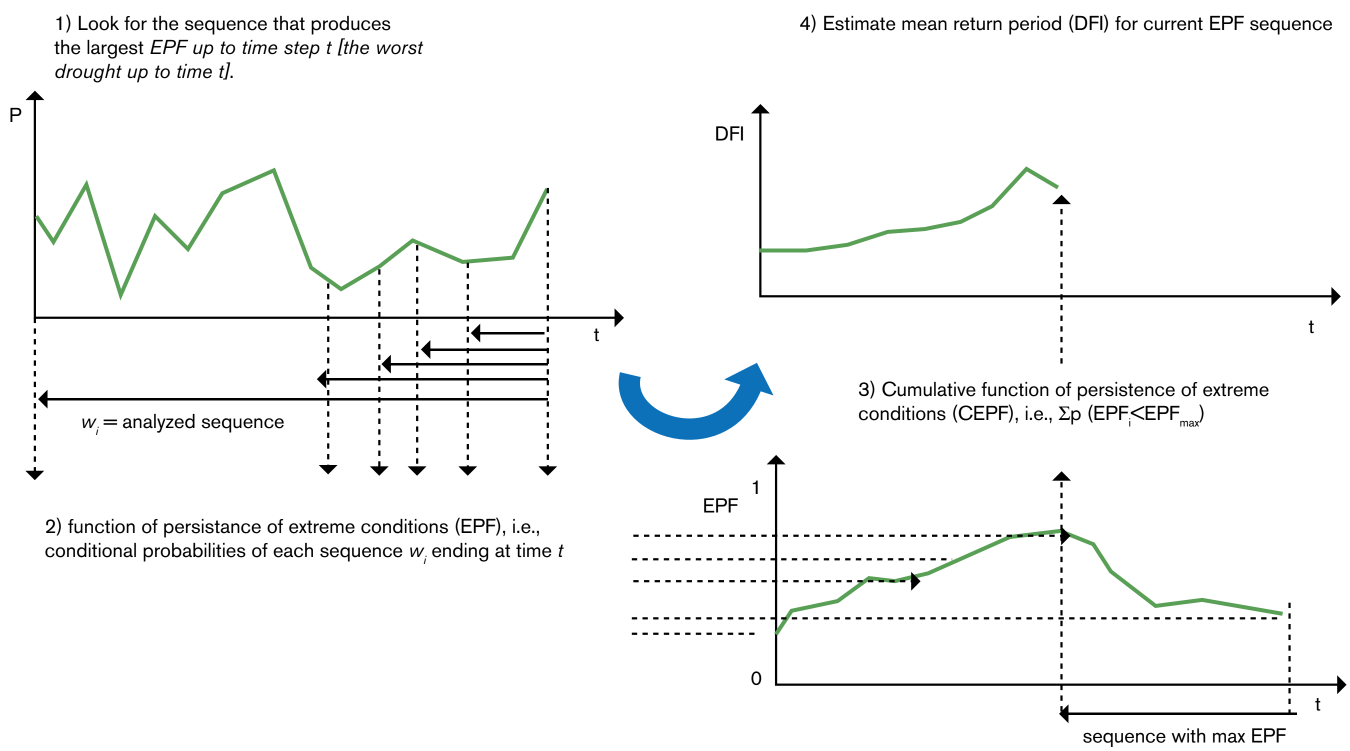
Droughts are difficult to typify because they have multiple statistical signatures (that is, magnitude, duration, frequency, intensity/peak). In addition, they tend to extend over large areas, and long records are needed to appropriately characterize them. According to the context, droughts may be considered meteorological, hydrological, or agricultural hazards. Huschke (1959) provides a definition of drought that captures most of the aspects of these extreme events. He states that draughts are "A period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area."

Several indices are used to describe droughts. The most widely used are the Palmer Drought Severity Index (PDSI) (Palmer 1965) and the Standardized Precipitation Index (SPI) (McKee et al. 1993). The strengths and limitations of these indices have been reported in the literature (for example Alley 1984). To address the multiple characteristics of a drought in a single index, González and Valdés (2006) proposed an alternative measure, the Drought Frequency Index (DFI). The DFI is a stochastic index that characterizes a persistent deviation of a variable (that is, precipitation) toward the lower tail of its probability density function. The result is a retrospective, sequential measure of the persistence of low values evaluated by their mean frequency of occurrence. Therefore, the index offers an integrated measure of the severity and duration of a drought in each time step relative to its probability of occurrence, expressed as a mean return period.

Figure 3 summarizes the procedure to calculate the DFI for a particular hydroclimatic signal X (for example, precipitation, streamflow, or soil moisture), which realization produces a time series $X_0, X_1, \ldots, X_i$. Since droughts are often described not as isolated realizations but as sequences of persistent low values, the algorithm looks for the sequence of length W, that ends at the evaluated time step and produces the largest extreme persistent function (EPF). This sequence represents the worst drought situation that has taken place up to that moment, based on the chosen criteria.

The EPF is solved through numerical integration procedures. After locating the sequence that produces the

Figure 3. Schematic Representation of DFI Calculation Procedure



maximum EPF when evaluated up to the current time step t, a drought is characterized by the estimated mean return period of sequences with EPF values that are at least as large as the current maximum and have equal or shorter duration. The estimated mean return period is the DFI (Gonzalez and Valdés 2006),

$$DFI \approx \frac{\tau(W-1)^k}{1-F_w(F_c,W)} \quad (1)$$

where DFI = return period of the extreme sequence W that exhibits the largest EPF up to the evaluated time step t; (τ, k) = parameters whose maximum likelihood estimates for any random, independent processes are 1.13 and 0.20, respectively; F_w = cumulative extreme persistent probability function varying between 0 (brief) and 1 (highly persistent) as a function of W and F_c; F_c = upper EPF threshold that defines the occurrence of a drought.

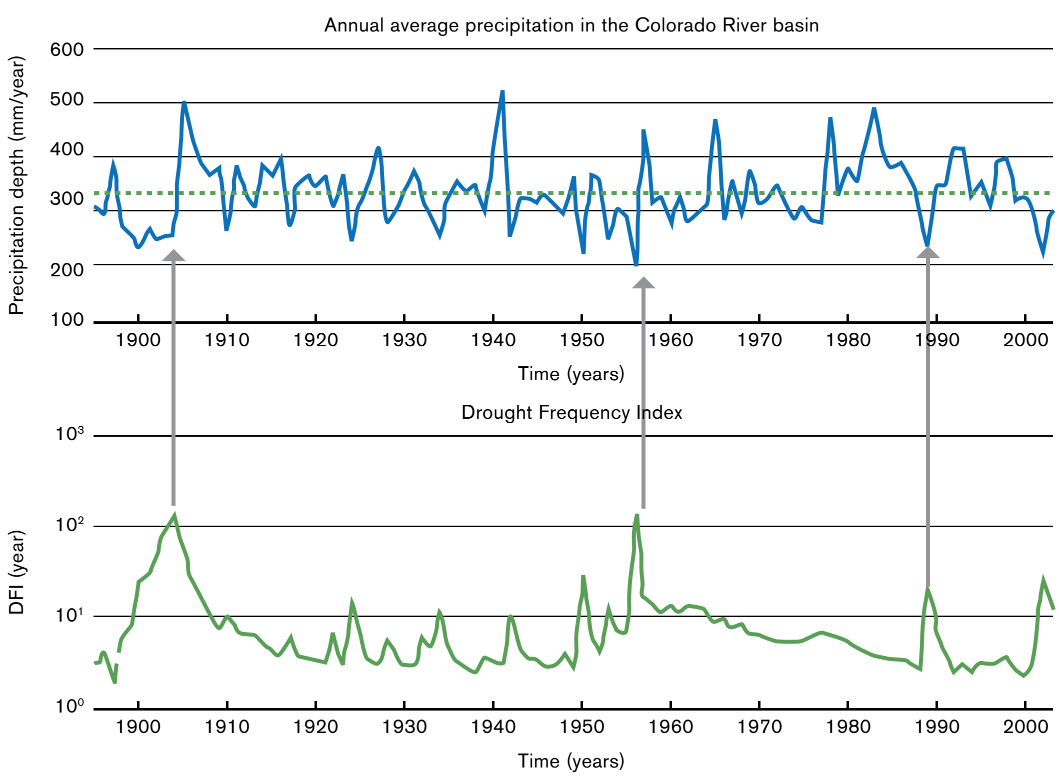
An example of the application of the DFI to the annual precipitation series in the Colorado River basin in the southwestern United States is shown in Figure 4, where the highest value corresponds to a period of low precipitation and long duration. A second highest DFI value corresponds to a period of shorter duration but lower precipitation. This shows the ability of the DFI to represent multiple characteristics of a drought episode.

Compared with indices like the SPI and PDSI, the DFI is advantageous because it encompasses duration and intensity of persistent extremely low events in terms of its return period. In addition, the DFI can incorporate different variables in its calculation and allows for the analysis of droughts from several perspectives. For example, the DFI may be based on annual precipitation values or the net balance between water inflows and outflows, among others.

Characterization of Floods

The characterization of floods requires the following steps, depending on whether the need is for planning and design of hydraulic structures or for real-time operations.

Figure 4. DFI Applied to Annual Precipitation in the Colorado River Basin (US)



Planning and design

- Selection of return period, occurrence probability
- Selection of design storm, spatial and temporal variability of precipitation
- Antecedent conditions
- Rainfall-runoff modeling
- Hydraulic routing

Real-time

- Characterization of spatial variability of rainfall: radar, satellite, telemetric gages
- Rainfall-runoff transformation
- Precipitation forecast: meso scale and regional models

Regarding the selection of the return period, it is now standard practice to use a criterion like the 100-year flood value (the "1 percent standard") to regulate the floodplain. There is increasing pressure in regulation to also provide risk estimates for people living outside this area, since many floods affect regions above this level. Thus the 500-year floodplain is also being mentioned as a criterion for flood insurance. The relatively short length of the records makes the sampling error of the estimates beyond the 100-year to have significant variability. An example of this is shown in Figure 5, where the estimated value of floods and their confidence intervals (defined as return periods) is shown.

The 500-year flood estimate may also be the 200-year or the 1,000-year estimate based on the 5 percent and 95 percent confidence intervals of the log-Pearson III distribution.

In addition to this sampling variability, it is worth noting that the instrumental record already indicates an intensification of the maximum for floods in several parts of the world, particularly since the early 1970s. An example of this situation is shown in Figure 6, where the annual maximum daily flows in the Caroni River in Venezuela show a definite and statistically significant increase.

Lins and Wolock (2008) conducted a study of more than 200 gages in the United States. Preliminary results indicate that there is no significant increase in the percent of gages that achieve flood alert status in the sample.

The state of the practice in dealing with extremes has been to use the instrumental record and a hypothesis of stationarity (that is, the future will have the same statistical

Figure 5. Estimated and Bound of Return Periods for the French Broad River (North Carolina, US)

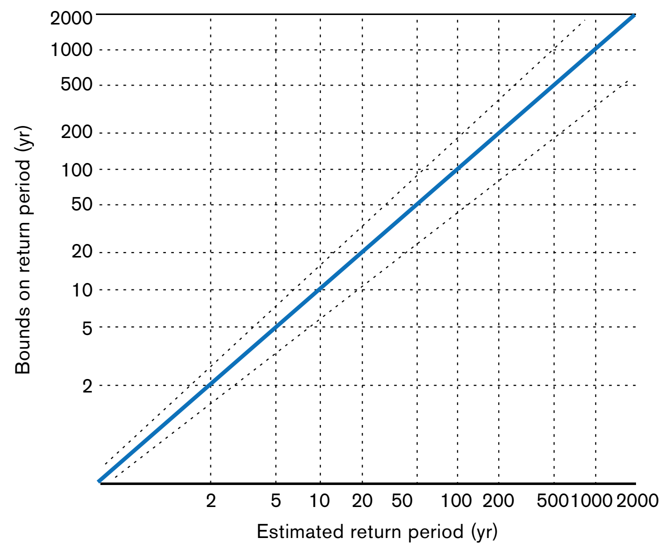
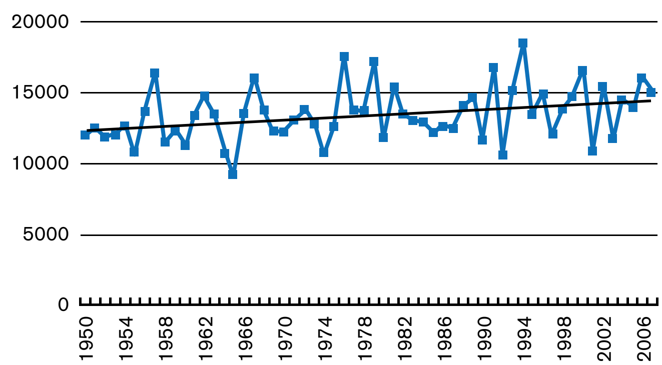


Figure 6. Maximum Daily Flows of the Caroni River at San Pedro de las Bocas (Venezuela)



characteristics of the past and all extreme values came from the same distribution). In the last decades, the influence of climatic precursors like El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) changed that perspective, and the forecasts and predictions are made conditional on these precursors. Still the assumption of stationarity remained. The evidence of anthropogenic climate change observed in the instrumental record makes this assumption less strong and alternative ways to analyze extremes need to be used. These changes in annual maxima, observed already in the instrumental record, will intensify according to the predictions of the GCMs. This has led several researchers to postulate the "end of stationarity" (Milly et al. 2008), under which the standard practice of using observed annual maxima to derive an extreme value distribution like log-Pearson III or Gumbel would no longer be valid.

Thus, the operational and scientific question is "How do we proceed from here?" The obvious answer is to increase the operationality of physically-based rainfall runoff models, which will still require extreme values of precipitation usually obtained from historic records and incorporated as IDF (intensity-duration-frequency) curves.

Forecasting and Teleconnections

Short-term Forecasting

The last decades have seen significant advances in measuring precipitation both from ground sensors as well as air- and space-borne sensors. In the United States there have been significant improvements in the collection and analysis of radar information. There has not been, however, a significant improvement in the lead time for flash-flood forecasting, probably because of limitations of radar coverage in areas of steep orographic changes.

Figure 7 shows the average lead time for flash flood forecasting in the last 20 years (until 2003). Significant increases in lead time in the 1980s and early 1990s were not followed by similar improvements in the late 1990s and early 2000s (Seo 2006).

This is also the case for other types of floods as indicated by studies carried out by NOAA NWS.

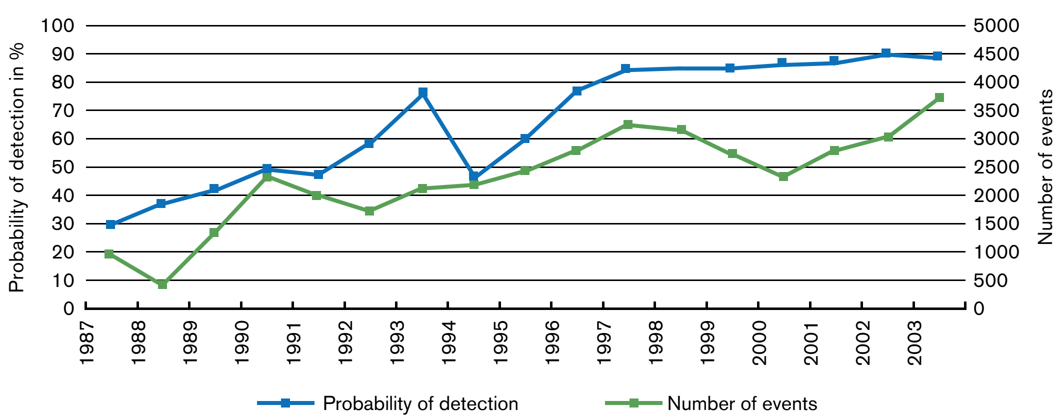
Major Climatic Precursors

The hydroclimatology of many regions in the world is affected by events in other places, particularly the oceans, in what are called climatic precursors. For example, sea surface temperatures (SSTs) in the tropical and northern Pacific Ocean are one of the most important sources of interannual climate variability in many regions of the world.

The global patterns of hydroclimatological responses to El Niño Southern Oscillation (ENSO) are a direct result of the physical alternations in the ocean/atmosphere system. As with the physical variation in said system during ENSO phases, hydroclimatological consequences display contrasting patterns in ENSO events. Many of the rainfall and river discharge anomaly patterns, for instance, are almost mirror images of one another.

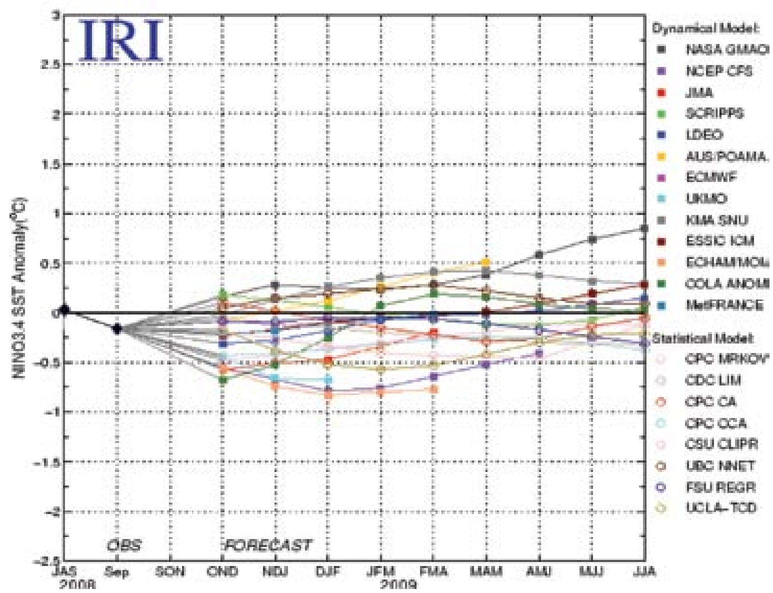
This is the case in the southwestern United States, where ENSO plays a major role during the winter season (Sheppard et al. 2002). Days with higher precipitation and streamflow are more frequent than average during El Niño winters, while La Niña periods are drier than average (Cayan et al. 1999). Although ENSO events also affect climate during the summer season (Castro et al. 2006a 2006b) it is during the winter season that the stronger climate anomalies in the region are associated with ENSO events. Many currently available models produce experimental and operational forecasts of ENSO, allowing their use in long-term forecasting of hydroclimatic variables. Figure 8 shows

Figure 7. Flash-Flood Probability of Detection



Source: Seo 2006.

Figure 8. ENSO Forecasts for October 2008 to August 2009



Source: IRI 2010

an 18-month forecast of ENSO. As can be seen, most of the models indicated warming or neutral conditions for 2009 (June-August).

The simulations of past and future climates made by GCMs permit an understanding of the ability of these models to represent major climatic precursors like ENSO. Dominguez et al. (2008) analyzed the ability of the coupled global models to accurately represent the interannual variability of SSTs, both in the historical simulations (20c3m) and future climate projections for three different emission scenarios (sres B2, A1B and A2). Using the historical simulations (20c3m), they performed rotated principal component analysis (R-PCA) on the winter sea surface temperature (SST) anomalies for the two models that presented the best precipitation, temperature, and climatological geopotential height patterns (mpi ECHAM5 and ukmo HADCM3). Joseph and Nigam (2006) also found that the spatiotemporal structure of ENSO is well modeled by the ukmo-HADCM 3 model (the mpi-ECHAM5 model was not analyzed in their study). Based on the spatial signature of the dominant winter mode, and its corresponding principal component time series, it may be seen that the dominant mode of SST anomalies for both models is an ENSO-related SST pattern. In fact, the detrended principal component time series and detrended SST anomalies averaged over the ENSO 3.4 region are almost identical.

Other well-known patterns, such as the Pacific Decadal Oscillation, did not emerge as dominant models of the R-PCA analysis.

Following the historical analysis, Domínguez et al. (2008) focused on future ENSO projections for the two models. Using the methodology developed by Trenberth (1997), the ENSO 3.4 index is calculated for each of the emission scenarios (B1, A1B and A2), for the two models, and compared to historical observations based on the Climate Prediction Center's ENSO 3.4 index (Figure 5 and Table 2). The SST anomalies are calculated based on detrended SSTs, in order to account for the warming of the ocean. Dominguez et al. (2008) found that the ukmo hadcm3 model had a smaller intensity of SST anomalies than the mpi echam5 model. When compared to the historical observations, the ukmo-hadcm3 model is more realistic in frequency, intensity, and duration. Alternative emission scenarios have no clear influence on the frequency of ENSO events (approximately 3.4 events per decade), on their intensity or duration. This is consistent with previous work that has found no statistically significant changes in amplitude of ENSO variability, indicating that the coupled climate models project little influence of global warming on ENSO conditions (van Oldenborgh et al. 2005; Philip and van Oldenborgh 2006). While these studies have shown that the mean state of the Pacific Ocean changes considerably in a warmer climate, changes in ENSO properties are small because the effects of higher temperatures on SST, thermocline depth, and wind stress cancel overall (Philip and van Oldenborgh 2006).

Long-term Forecasting

Examples of the application of statistical techniques that use projections of ENSO to extend the lead time for seasonal forecasts of precipitation and streamflow are given by Liu et al. (1998). The Kalman filter was used to combine persistence modeling with several ENSO projections (see Figure 9). This approach found significant predictive power to merge multiple ENSO forecasts (weighted by their skills) and persistence values for seasonal prediction of precipitation and streamflows. Figures 10 and 11 show examples of the performance for the prediction of seasonal streamflows in the Nare and Grande rivers in Colombia. As seen in Figure 10, La Niña episodes have a more significant impact on the streamflows in both basins.

The performance of the forecasting model as measured by its root mean square error (RMSE) of prediction and normalized by climatology shows that significant forecasting skill exists up to 18 months ahead for seasonal forecasts**.**

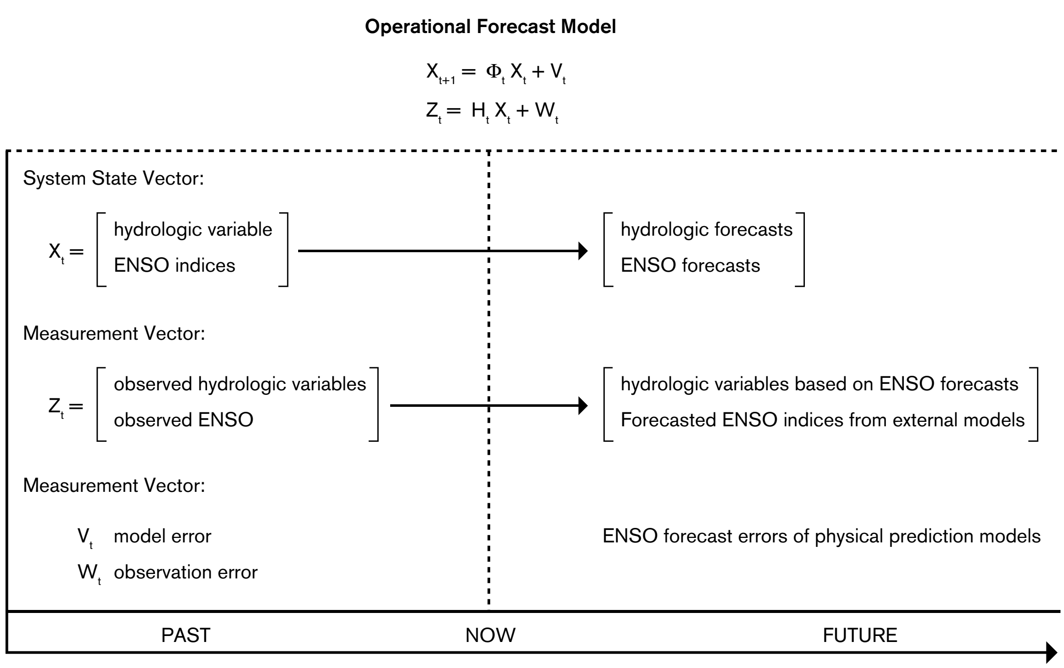
Extending the Instrumental Record: Paleoclimate Reconstructions

Short historical records usually do not allow the reliable description of drought episodes, particularly when dealing with their multivariate characteristics. However, proxy data of climate-like tree ring reconstructions of droughts provide useful information about past events, allowing the analysis of current conditions (Cook et al. 1999).

Gonzalez and Valdés (2004) suggest a bivariate (duration and magnitude of a drought) approach to adapt and include dendrochronology reconstructions with historical records to characterize droughts. The proposed approach uses the stochastic structure of the residuals of paleo reconstructions to generate equally likely representations of past drought events. The bivariate analysis was applied to paleo and historical records in Texas and proved to be advantageous to characterize droughts compared to univariate analyses, such as utilizing the duration or the magnitude of a drought alone.

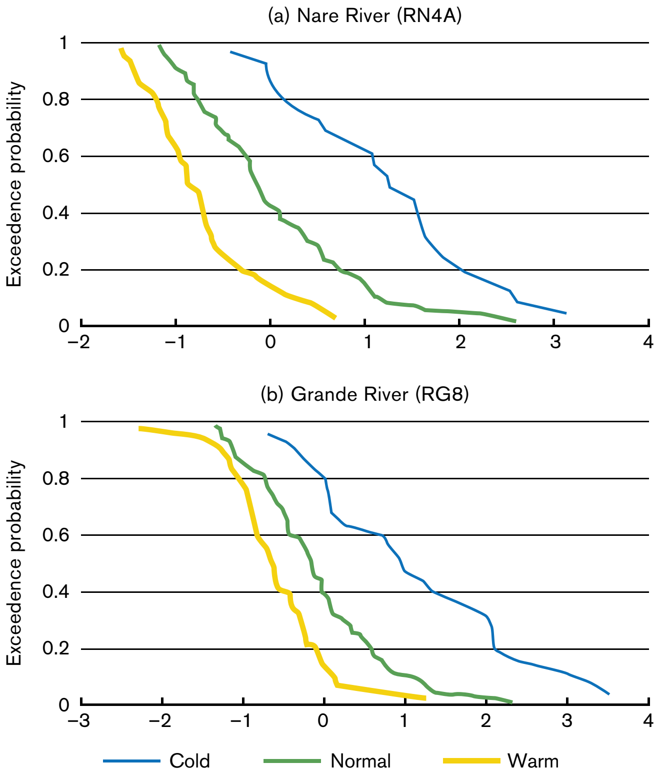
Drought reconstructions from tree rings explain a fraction of the variance of the index applied to study droughts (PDSI,

Figure 9. Schematic Representation of Kalman-based Forecast Model



Source: Liu et al. 1998.

Figure 10. Cumulative Frequency Distribution of Standardized Streamflow in Two Colombian Rivers Conditioned on ENSO

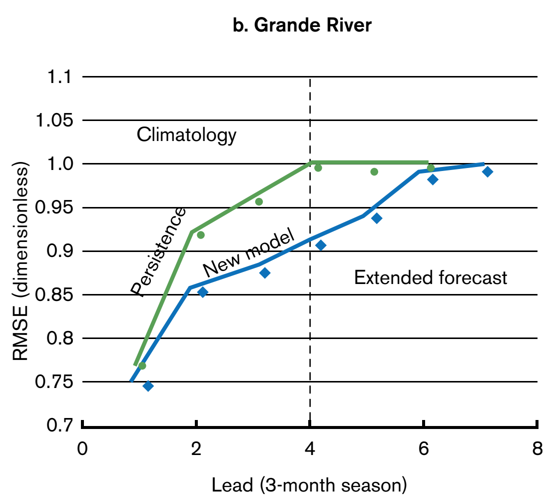


Source: Liu et al. 1998.

streamflow, rainfall). Thus, the reconstructed indices exhibit less variability than the historical ones. This has influence in drought analyses because deviations from normality are generally lower (for example, the mean of the reconstructed drought deficits is underestimated). A way to use those reconstructions is analyzing their tendencies (for example, the bidecadal drought rhythm analyzed in Cook et al. 1997). But combining them in a statistical analysis of droughts with instrumental data is not a simple task. As an example, in the drought reconstruction for the continental United States (Cook et al. 1999; *http://www.ncdc.noaa.gov*), the PDSI grid reconstruction No 63, in Texas, has a correlation coefficient of 0.67. However, only in 47 percent of the dry years (PDSI-1) the original PDSI and the reconstruction simultaneously indicate a dry year. A methodology to convert such valuable information in a form that can be compared with instrumental data was developed by Gonzalez and Valdés (2003) and applied to Texas PDSI series. Seven chronologies of different length were found (International Tree-Ring Data Bank – National Geophysical Data Center, *http://www.ngdc.noaa.gov*).

Correlation analysis of the chronologies with the monthly PDSI series showed the higher correlation of tree rings with the PDSI of summer months (June, July and August), already known (Cook et al. 1996). Consequently, the reconstruction is only of the average PDSI during the summer months in accordance with previous findings (as in Cook et al. 1999).

Figure 11. Normalized RMSE of Standardized Streamflow Forecasts for the Nare and Grande Rivers in Colombia



Source: Liu et al. 1998.

Since the summer season is the rainiest season in this region, the summer PDSI is a good estimator of the annual PDSI (Summer-Annual=0.94). Given the differences in lengths of chronologies, the final reconstruction is composed of five different sub-reconstructions, coming from five different regression models. Those models are mathematically identical but each one uses a different number of predictors (similar to Meko et al. 2001). Figure 12 shows the reconstructed series including their confidence intervals.

Climate Variability and Change

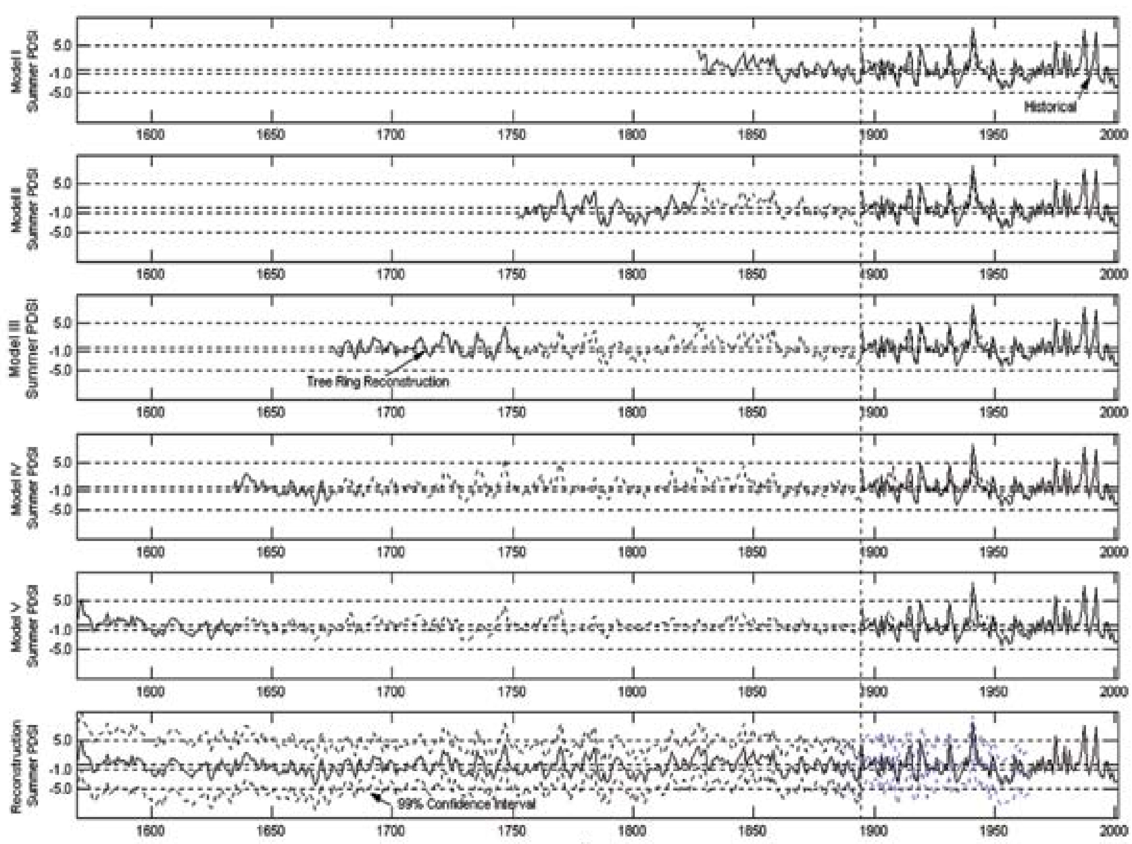
Observed Changes in the Instrumental Record

Important evidence of changes in the hydroclimatic signals in the instrumental record indicates that the climate is already changing in many parts of the world. One example already shown (Figure 6) is the increase in the magnitude of maximum daily flows in the Caroni River in Venezuela. Other changes include the shift from snowfall to rainfall, a trend that has major implications in the management of water resources in places like the western part of the United States. Figure 13 shows the shifts noted in the instrumental record in which the statistically significant shifts in snow water equivalents for the southwestern United States are shown.

Climate Changes According With the IPCC-AR4 Results

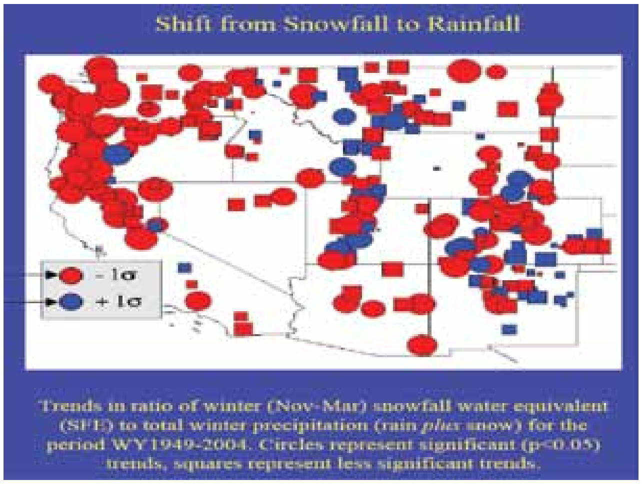
There has been significant progress in the spatial resolution of the GCMs and their ability to represent land features more accurately. An increase in spatial resolution expected in future GCM models that will require concomitant increases in computer power.

Figure 12. Tree Ring Reconstruction of Droughts and 99 Percent Confidence Interval



Source: Gonzalez and Valdés 2003.

Figure 13. Changes in Precipitation Type in the US Southwest



Trends in ratio of winter (Nov-Mar) snowfall water equivalent (SFE) to total winter precipitation (rain *plus* snow) for the period WY1949-2004. Circles represent significant ($p<0.05$) trends, squares represent less significant trends.

Source: Knowles, et al. 2006.

Thus, several steps are required for the hydrologic application of these models in specific regions. The first step is to select a model or a subset of the models that perform the best for the region under analysis (as in Giorgi and Mearns 2002; Dominguez et al. 2008). The second step is to do a bias correction of the time series (as in Wood et al. 2002). The final step is to downscale the series to an appropriate resolution level for water resources management (Cañon et al. 2008). Cañon et al. (2009) developed a user-friendly software that streamlines the first three tasks (data extraction, bias correction, and model evaluation).

Climate Downscaling

As mentioned earlier, climate change projections reported in the IPCC-AR4 are primarily based on global coupled climate models. These models represent the land-ocean-atmosphere system by solving the equations of fluid motion at the global scale, with resolutions ranging from about 5° (GISS EH, GISS ER, and INM CM3.0) to 1.1° (MIROC3.2 hires). Hydrologic studies using raw coupled climate output yield poor results because of their coarse resolution and unrealistic land surface hydrologic representation, particularly in their treatment of lateral flow (Xu 1999). The spatial resolution of these models is still coarser than that required for regional impacts assessment. As a result, downscaling is required before any impact study can be undertaken at the local scale. There are basically two methods to downscale climate models: statistical and dynamic downscaling. Wilby and Wigley (1997) presented an early review of both downscaling methodologies, while Xu (1999) later focused on downscaling techniques for hydrologic applications. More recently, Fowler et al. (2007) presented a very thorough review of both statistical and dynamical downscaling techniques updating and extending the work of Xu (1999).

Statistical downscaling methods are based on the premise that a stochastic or deterministic relationship exists between a predictor (geopotential height, moisture fluxes, humidity, and so on) and a local or regional predictand (usually precipitation and/or temperature) (Fowler et al. 2007). Their computational efficiency has made these methods very popular and, in some cases, they have been shown to provide equal or superior projections to the more computationally demanding dynamical downscaling techniques (Kidson and Thompson 1998; Wilby et al. 2000). A summary of the advantages and limitations of statistical downscaling is presented in Table 1.

An alternative approach to statistical downscaling uses regional climate models (RCMs), which are also referred to as limited area models (LAMs). The lateral boundary conditions are derived from GCMs. Table 2 summarizes the main advantages and limitations of this approach.

Cañon et al. (2008) proposed a methodology for statistical downscaling in which a statistical method is used to

Table 1. Advantages and Limitations of Statistical Downscaling

Advantages	Limitations
Computationally inexpensive compared to dynamic downscaling	Requires long and reliable observational record
Easily transferable to other regions	Depends on choice of predictors
Based on accepted statistical procedures	Assumes stationarity in predictor-predictand relationship
Can generate variables not available through GCMS	Climate feedbacks are not included

Source: Adapted from Fowler 2007.

Table 2. Advantages and Limitations of Dynamical Downscaling

Advantages	Limitations
Based on physically consistent processes	Computationally intensive
Able to better capture orographic and rain-shadow effects	Dependent on driving GCM boundary conditions
Can capture non-linear effects such as ENSO	Depends on RCM physical parameterizations
Projections can be significantly different from GCMs, providing "added value"	RCMs bring additional uncertainty
Could account for changes not observed in historical record	Usually available for "time-slices," because of computational expenses

Source: Adapted from Fowler 2007.

downscale hydroclimatic variables while incorporating the variability associated with quasi-periodic global climate signals such as ENSO. The method extracts statistical information of distributed variables from historic time series available at high resolution (that is, the PRISM database from Daly et al. 1994). The historical information is divided into two sets for the reconstruction and validation of dominant oscillation modes. Then, the method uses an iterative gap-filling approach based on Multichannel Singular Spectrum Analysis (MSSA) to reconstruct, on a cell-by-cell basis, the specific frequency signatures associated with the GCM's future projections of temperature, precipitation, and ENSO signal. Application of the methodology is shown below for the southwestern United States.

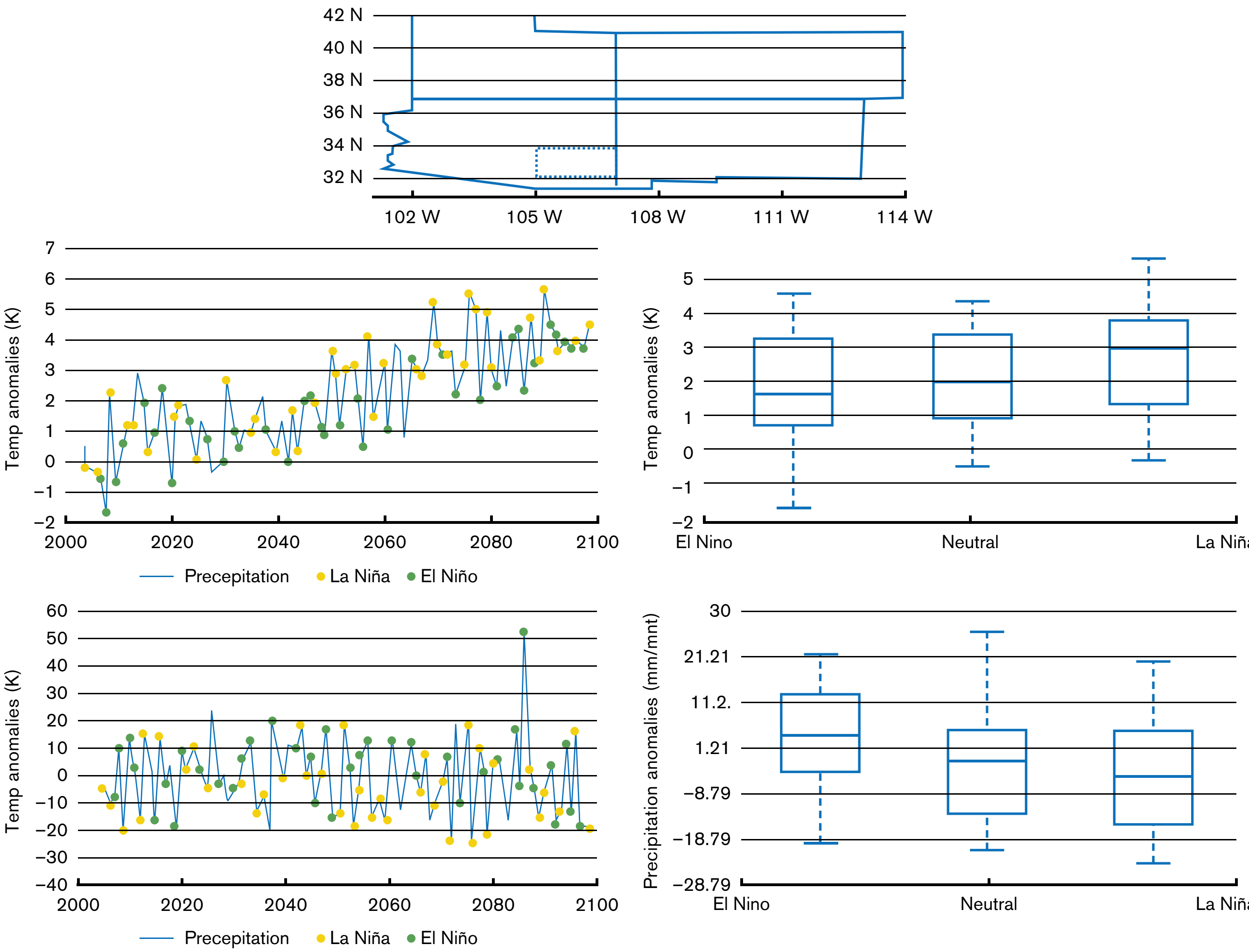
Climate Change Case Studies

Expected Climate Changes in the Southwestern United States

According to the climate models included in the IPCC's fourth assessment report (AR4), projections for the southwestern United States indicate that the region faces generalized temperature increases with largest warming in the summer months, and a likely decrease in precipitation (IPCC 2007). In the Colorado river basin, the largest in the region, increasing evaporation losses because of higher temperatures will generate decreased river flows and increased drought conditions (Christensen and Lettenmaier 2006; Hoerling and Eischeid 2007). In fact, the Southwest is one of the few regions in the world where there is consistent agreement among projections from 21 different coupled climate models that point to a decrease in streamflow (Milly et al. 2005). As a result, Barnett and Pierce (2008) estimate a 50 percent chance that live storage in lakes Mead and Powell, the two largest reservoirs in the Colorado system, will be depleted by 2021.

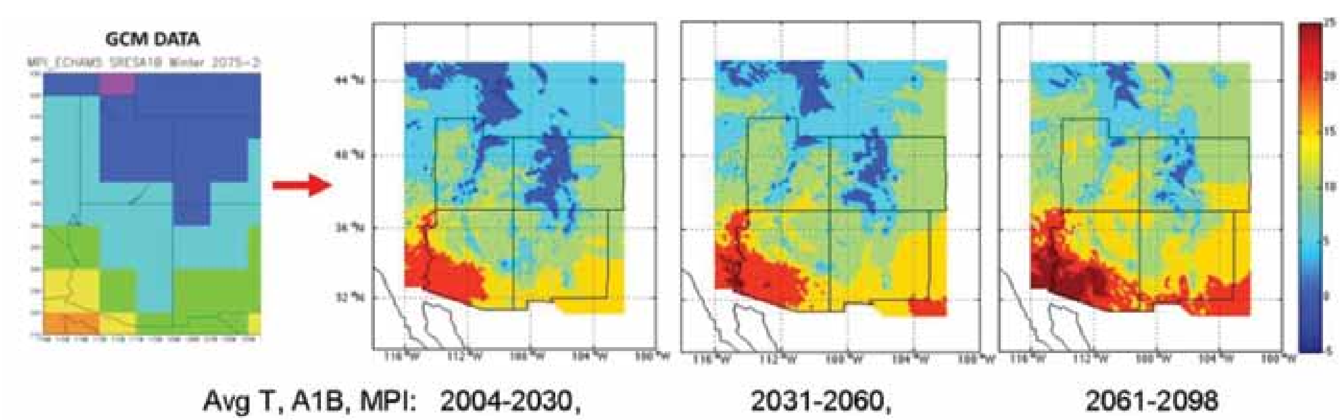
In addition to future climate trends, the variability associated with projected ENSO conditions—an important driver for winter climate variability in the region—will contribute to the occurrence of extreme responses in the system. Dominguez et al. (2008) evaluated the ability of the IPCC coupled models to represent the climate of the Southwest and the future winter ENSO projections, particularly the seasonal precipitation variability. The two models that more accurately represent the seasonal precipitation over the region and, in addition, realistically represent ENSO variability—the Max Planck Institute's ECHAM5 and the UK Met Office HadCM3—were selected using two different criteria. The first criteria is similarity in precipitation and temperature estimates in historical and future data using a modification of the Reliability Ensemble Analysis (REA) estimate (Giorgi and Mearns 2002). The second criteria is similarities in 500mb geopotential height patterns to determine the model's capability to capture monsoonal precipitation. While Dominguez et al. (2008) did not find statistically significant changes in ENSO future variability or in future winter teleconnections in the Southwest, they showed that the projected future aridity of the region will be dramatically amplified during La Niña years, which will be characterized by higher temperatures and lower precipitation than the projected trends (see Figure 14). These results have important implications for water managers in the Southwest who must prepare for more intense winter aridity associated with future ENSO conditions. Cañon et al. (2008) downscaled the GCM projections from a resolution of 192-km to a spatial resolution of 4-km, a scale that is meaningful for hydrologic modeling and decision-making purposes. Figure 15 presents an example of the spatial downscaling for the southwestern United States, which shows the regional variability of temperature and precipitation.

Figure 14. Projected Future Aridity Will Be Amplified During La Niña Years



Source: Cañon et al. 2008.
Note: Winter temperature (left) and precipitation (right) time series SRES A2 projections for the cell delineated in the top panel (−111 W – 109 W, 32 N – 34 N) using the mpi-echam5 model. Red dots correspond to La Niña years while green squares correspond to El Niño.

Figure 15. Example of Downscaled GCM Projections for the Southwestern United States



Source: Cañon et al. 2008.
Note: The map to the left represents data at the GCM resolution.

Climate Change in the Senegal River Basin

The Senegal River basin is shared by four countries: Mauritania, Senegal, Mali, and Guinea, and is the second largest perennial water course in the Sahel and in West Africa. Flows are characterized by a very high seasonal and interannual variability. Virtually all the water flow is because of a 4-month rainy season that occurs in the green upper basin some 1,500 km away from the mouth of the river, when the Intertropical Convergence Zone (ITCZ) travels north of the Equator. This can be seen in the precipitation climatology of the basin (Figure 16a), as replicated by the ensemble of CMIP3 model runs off the IPCC's 4th assessment report. Although all the models capture quite well the seasonality of precipitation, high disparities are observed between its modeled magnitudes.

The high interannual and seasonal variability of precipitation in the Senegal basin can be observed in Figure 16(b), which shows precipitation projections for the center cell of Figure 17.

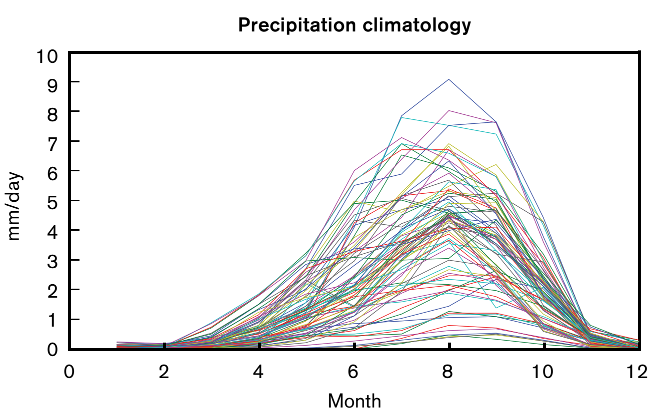
The traditional agricultural system in the basin is flood-recession agriculture, and its organization is based on risk management strategies. Since before the West African Empires of Ghana and Mali, a mutual relationship exists among farming, pastoral, and other activities. In the Senegal Valley, this institutionalized relation spans the farming, fishing and pastoral sectors. These sectors also have adaptive strategies for risk management (such as crop, land, and livestock diversification) to minimize losses in case of eventualities. Currently, the problems in the basin stem from both the changes in the socioeconomic structures that the region is undergoing, and the competing demands of irrigated agriculture (made possible by dams), flood recession agriculture, and other demands. The management of the Manantali (which regulates 40 percent to 60 percent of the annual flow) and Diama reservoir system is further challenged by drying trends in the sub-Saharan region over the last 50 years, which are mostly attributed to the effects of global climate change (Magistro 2001). These effects may be the result of a combination of both human and climatologic factors as well as their feedbacks.

The same analysis carried out for the study of the southwestern United States was used in the Senegal basin. As in the case of the United States, the spatial resolution of the GCM results is too coarse for hydrologic applications. An example of the resolution of the UK model as applied to the basin is shown in Figure 17.

The selection procedure proposed by Dominguez et al. (2008) was applied to the Senegal River basin and the results are shown in Figure 18.

As seen in the figure, the models best suited to the basin are the CSIRO and the MRI models. The downscaling procedure proposed by Cañon et al. (2008) will also be applied to this basin. The ongoing work in the setting of a collaborative partnership with the Senegal International River Valley Authority is to develop a decision support system (DSS) for the management of the water resources

Figure 16. Precipitation Climatology as Modeled by the IPCC's CMIP3 Models (Figure to the left is (a) and that to the right is (b)



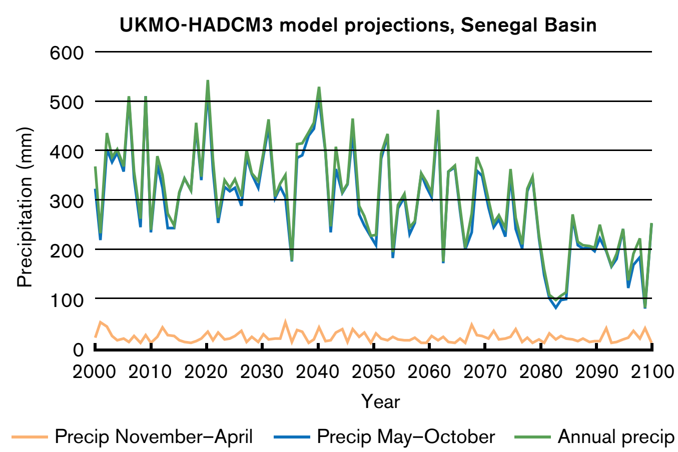


Figure 17. UK Model GCM Applied to the Senegal River Basin

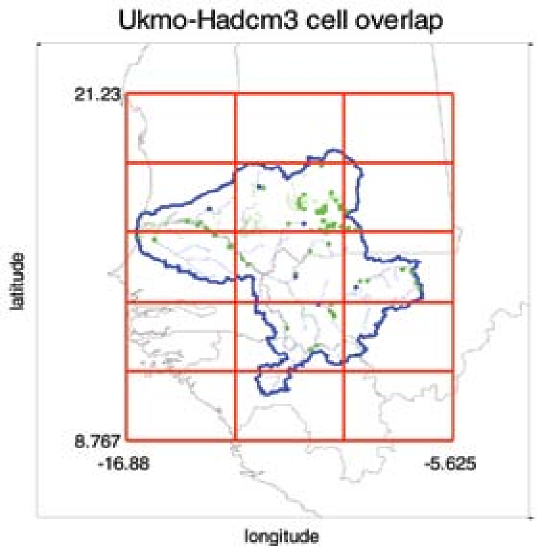
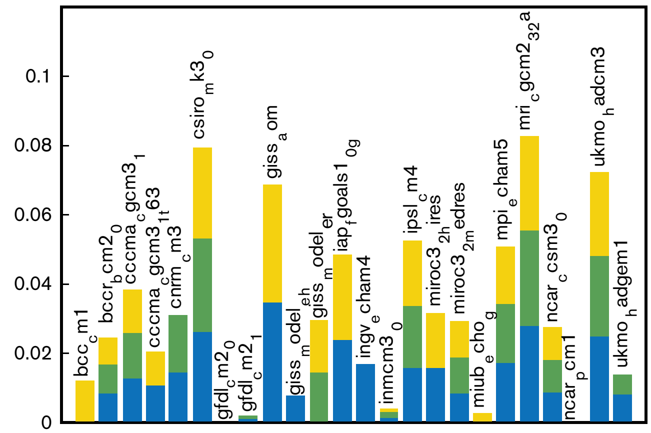


Figure 18. Reliable Ensemble Analysis (REA) Results for the Senegal River Basin



The colors represent the different emission scenarios

of the basin to better cover both traditional and modern demands.

Water Resources Management under Changing Conditions

Multiple Reservoir Operation in the Conchos River Basin (Mexico)

Multiple reservoir systems often cannot fully satisfy demands from different users of the system (that is, irrigation districts, urban centers, and streamflows in riparian areas) during droughts. The issue is even more critical when international agreements and local policies require operators to fulfill specific requirements when using and distributing water that is available at any time or that is expected to be delivered in the future. Using the Drought Frequency Index (DFI) developed by Gonzalez and Valdés (2003) as a drought indicator, Cañon et al. (2008c) developed a hierarchical nonlinear optimal operation model of a system of five reservoirs and three irrigation districts in the Conchos River basin of Mexico that minimizes water deficits and maximizes net benefits to users, including the expected deliveries to the United States.

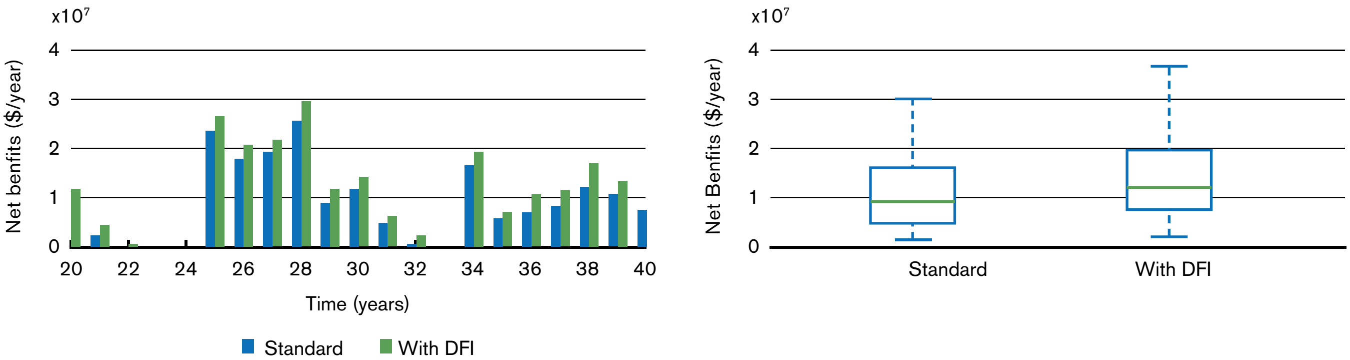
As previously discussed, the DFI characterizes droughts according to their duration and intensity, using a probabilistic criterion that takes into account the persistence of extremely low precipitation values. Performances with and without the DFI show that including the DFI improves the reliability of the reservoirs to deliver water to users during periods of drought, especially at the first stages of prolonged dry conditions. This is reflected in an overall improvement of net benefits associated with crop production in the Mexican irrigation districts and in better deliveries downstream to the Rio Grande into the United States (in compliance with the international treaty of 1944). Figure 19 shows the results of the operation of the Conchos system utilizing an optimization model directly, and results obtained with the same optimization model but using the DFI as a trigger for rationing during severe droughts.

Decision Support Systems in the San Pedro River Basin (Mexico-US)

Lansey et al. (2008) developed a DSS for the Upper San Pedro basin to evaluate development scenarios for the region. The development of the DSS greatly benefited from contact with and involvement of the region's main stakeholders, particularly the Upper San Pedro Partnership (USPP), a group composed of public and private organizations including the cities of Sierra Vista and Fort Huachuca. Several development scenarios were evaluated and their results are presented for different reaches of the river as shown in Figure 20.

To account for climate change, Serrat-Capdevila et al. (2008) coupled climate model projections with the

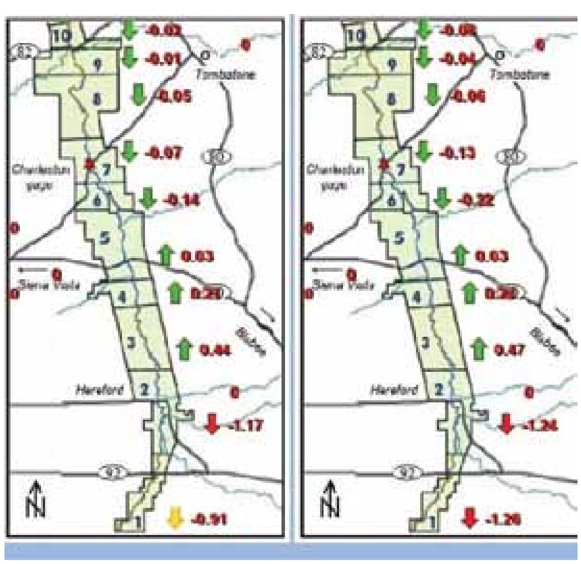
Figure 19. Optimization Results, Conchos River Basin (Mexico)



Source: Cañon et al. 2009.

groundwater budget of the San Pedro basin for the USP DSS, building on the contributions of Serrat-Capdevila et al. (2007) and addressing some of its limitations. After carrying out a reliability ensemble analysis and a bias correction to select the best climate models for the region, precipitation estimates at the basin scale were used to calculate recharge using a basin-wide lumped equation. An approach to infer changes in recharge because of evaporative losses and increases in the riparian corridor's evapotranspiration (ET) was developed. The findings of a detailed analysis of existing evapotranspiration measurements allowed the calculation of riparian ET rates for the current century. Using the Penman-Monteith equation and GCM meteorological projections, it was possible to issue future projections of ET in warmer scenarios. At present, the previous changes in recharge, temperature, and riparian ET are being linked to the San Pedro DSS. The ultimate goal of the current work is to help set a new sustainable yield accounting for climate change impacts that go beyond the Congressionally-mandated attainment of associated goals by 2011.

Figure 20. DSS Results for 2010 and 2020 Development Scenarios



Source: Lansey et al. 2008.
Note: The arrows indicate an increase or decrease in the aquifer level for the years 2010 and 2020.

References

Alley, W. M. 1984. The Palmer Drought Severity Index: Limitations and Assumptions. *J. Climate Appl. Meteorol.*, 23: 1100–1109.

Barnett, T. P., and D. W. Pierce. 2008. When Will Lake Mead Go Dry? *Water Resour. Res.*, 44, W03201, doi:10.1029/2007WR006704.

Cañon, J., F. Dominguez, and J. Valdés. 2008. Statistical Downscaling Incorporating Future ENSO Projections, submitted to *Climatic Change*.

Cañon, J., J. Gonzalez and J. Valdés, 2009: Reservoir operation and water allocation to mitigate drought effects in crops: a multilevel optimization using the Drought Frequency Index, *J. Water Res.* Pl.-ASCE., 135, 6, 458–465.

Castro, C., R. A. Pielke Sr., and J. Adegoke. 2006a. Investigation of the Summer Climate of the Contiguous U.S. and Mexico Using the Regional Atmospheric Modeling System (RAMS). Part A: Model Climatology. *J. Climate*, in press.

Castro, C., R. A. Pielke Sr., J. Adegoke, S. D. Schubert, and P. J. Pegion. 2006b: Investigation of the Summer Climate of the Contiguous U.S. and Mexico Using the Regional Atmospheric Modeling System (RAMS). Part B: Model Climate Variability. *J. Climate*, in press.

Cayan, D. R., K. T. Redmond, and L. G. Riddle. 1999. ENSO and Hydrologic Extremes in the Western United States. *J. Climate*, 12, 2881, 2893.

Christensen, N., and D. Lettenmaier. 2006. A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin, *Hydrol. Earth Syst. Sci*., 3: 1–44.

Cook, E. R., D. M. Meko, D. W. Stahle and M. K. Cleaveland. 1996. Tree-rings Reconstruction of Past Drought Across the Coterminous United States: Tests of Regression Method and Calibration/Verification Results. In J. S. Dean, D. M. Meko, and T. W. Swetnam (eds.), *Tree Rings, Environments, and Humanity.* Radiocarbon, 155–169.

Cook, E. R., D. M. Meko, and C. W. Stockton. 1997. A New Assessment of Possible Solar and Lunar Forcing of the Bidecadal Drought Rhythm in the Western United States. *J. Climate*, 10, 1343–1356.

Cook, E. R., D. M. Meko, D. W. Stahle, and M. K. Cleaveland. 1999. Drought Reconstructions for the Continental United States. *J. Climate*, Vol. 12, no. 7, 1145–1162.

Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A Statistical-topographic Model for Mapping Climatological Precipitation Over Mountainous Terrain, *J. Appl. Meteor*., 33: 140–158.

Dominguez, F., J. Cañon, and J. Valdés. 2008. IPCC-AR4 Climate Simulations for the Southwestern US: The Importance of Future ENSO Projections, submitted to *Climatic Chang*.

Fowler, H., S. Blenkinsop, and S. Tebaldi. 2007. Linking Climate Change Modeling to Impacts Studies: Recent Advances in Downscaling Techniques for Hydrological Modeling, *Int. J. Climatol*, 27: 1547–1578.

Frei, C., C. Schär, D. Lüthi, and H.C. Davies. 1998. Heavy Precipitation Processes in a Warmer Climate, *Geophys. Res. Lett*., 25(9): 1431–1434.

Giorgi, F., and L. Mearns, 2002: Calculation of Average, Uncertainty Range, and Reliability of Regional Climate from AOGCM Simulations Via the "Reliability Ensemble Averaging" (REA) Method, *J. Climate,* 15: 1141–1158.

González, J. and J. B. Valdés. 2003. Bivariate Drought Recurrence Analysis Using Tree Ring Reconstructions, *ASCE J. Hydrol. Eng*., 8(5): 246–258.

——. 2004. "The Mean Frequency of Recurrence of In-Time-Multidimensional Events for Drought Analyses," *Natural Hazards and Earth Environmental Science*, (4), 17–28.

——. 2006. The new Drought Frequency Index: Definition and Comparative Performance Analysis, *Water Resour. Res*., 42(11), doi10.1029/2005WR004308, W11421.

Hoerling, M., and J. Eischeid. 2007. Past Peak Water in the Southwest. *Southwest Hydrology*, 6(1): 18–19, 35.

Huschke, R. E. 1959. *Glossary of Meteorology*. Boston: American Meteorological Society.

Intergovernmental Panel on Climate Change (IPCC AR4). 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*, ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. Miller. Cambridge and New York: Cambridge University Press.

International Research Institute for Climate and Society (IRI), Columbia University, New York, USA. *ENSO Prediction Plume.* 2 July 2010. <http://iri.columbia.edu/climate/ENSO/currentinfo/SST_table.html#figure>

Joseph, R., and S. Nigam. 2006. ENSO Evolution and Teleconnections in IPCCs Twentieth-century Climate Simulations: Realistic Representation? *J. Climate*, 19: 4360–4377.

Kidson, J. W., and C. S. Thompson. 1998. A Comparison of Statistical and Model-based Downscaling Techniques for Estimating Local Climate Variations, *J. Climate*, 11(4): 735–753.

Kim, T., J. B. Valdés, B. Nijssen, and D. Roncayolo. 2006. Quantification of Linkages Between Large-Scale Climatic Patterns and Precipitation in the Colorado River Basin. *Journal of Hydrology*, 321, 137–186.

Knowles, N., M.D. Dettinger, D. R. Cayan, 2006: Trends in Snowfall versus Rainfall in the Western United States, *J. Climate*, 19 (18): 4545–4559.

Lansey, Kevin J., 2008. Personal communication. Dept. of Civil Engineering, University of Arizona. Tucson, AZ.

Lehner, B., P. Doll, J. Alcamo, T. Henrichs and F. Kaspar, 2006: Estimating the Impact of Global Change on Flood and Drought Risks in Europe, *Climatic Change*, 75(3):273–299.

Lins, H.F. and D. Wolock, 2008. Personal communication. U.S. Dept. of the Interior, U.S. Geological Survey. Reston, VA.

Liu, Z., J. B. Valdés, and D. Entekhabi. 1998. Merging and Error Analysis of Regional Hydrometeorologic Anomaly Forecasts Conditioned on Climate Precursors, *Water Resour. Res.*, 34(8): 1959–1969.

Magistro J., and M. Lo. 2001. Historical and Human Dimensions of Climate Variability and Water Resource Constraint in the Senegal River Valley. *Clim Res.*, 19: 133–147.

McKee, T. B., N. J. Doesken, and J. Kleist. 1993. The Relationship of Drought Frequency and Duration to Time Scales, Preprints, 8th Conference on Applied Climatology, Jan. 17–22, Anaheim, California, pp. 179–184.

Meko, D. M., M. D. Therrell, C. H. Baisan, and M. K. Hughes. 2001. Sacramento River Flow Reconstructed to A.D. 869 from Tree Rings. *J. Amer. Water Resour. Assoc.*, 37(4): 1029–1039.

Milly, P., K. Dunne, and A. Vecchia. 2005. Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate. *Nature,* 438, 347–350.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z.W. Kundzewicz, D. P. Lettenmaier, R. J. Stouffer. 2008. Stationarity Is Dead: Whither Water Management? *Science* Vol. 319 1, February.

Palmer, W. C. 1965. *Meteorological Drought*. Research Paper No. 45, U. S. Department of Commerce, Weather Bureau, Washington, D. C.

Philip, S. Y. and G. J. van Oldenborgh. 2006. Shifts in ENSO Coupling Processes Under Global Warming. *Geophys. Res. Lett.*, 33, doi: 10.1029/2006GL026196.

Seo, Dong-Jun, 2006. Personal communication. Hydrologic Research Laboratory, National Weather Service/NOAA. Silver Spring, MD.

Serrat-Capdevila, A and J. B. Valdés. 2006. An Alternative Approach to the Operation of Multinational Reservoir Systems: Application to the Amistad and Falcon System (Lower Rio Grande/RioBravo). *Water Resources Management*, August 20.

Serrat-Capdevila, A., J. B. Valdés, J. Gonzalez, K. Baird, L. J. Mata, and T. Maddock. 2007. Modeling Climate Change Impacts—and Uncertainty—on the Hydrology of a Riparian System: The San Pedro Basin (Arizona/ Sonora). *J. Hydrol.*, 347: 48–66, 2007.

Serrat-Capdevila, A., J. B. Valdés. 2008. From GCM Projections to DSS Models: A Holistic Assessment of Climate Change Impacts in the San Pedro Basin (Arizona/Sonora). (To be submitted to the *Journal of Hydrology*).

Sheppard, C. R. C., M. Spalding, C. Bradshaw, and S. Wilson. 2002. Erosion vs. Recovery of Coral Reefs After 1998 El Niño: Chagos Reefs, Indian Ocean. *Ambio* 31, 40–48.

Trenberth, K. E. 1997. The Definition of El Niño. *Bull. Amer. Met. Soc.*, 78: 2771–2777.

VanOldenborgh, G. J., S. Y. Philips, and M. Collins. 2005. El Niño in a Changing Climate: A Multi Model Study. *Ocean Science*, 1, 81–95.

Wilby, R. L., L. E. Hay, W. J. Gutowski (Jr.), R. W. Arritt, E. S. Takle, Z. Pan, G. H. Leavesley, and M. P. Clark. 2000. Hydrologic Responses to Dynamically and Statistically Downscaled General Circulation Model Output. *Geophys. Res. Lett.*, 27: 1199–1202.

Wilby, R. L., and T. M. L. Wigley. 1997. Downscaling General Circulation Model Output: A Review of Methods and Limitations. *Progress Phys. Geog.*, 21: 530–548.

Wood, A. W., E. Maurer, A. Kumar, and D. Lettenmaier. 2002. Long Range Experimental Hydrologic Forecasting for the Eastern U.S. *J. Geophys. Res.*, 107(D20):4429.

Xu, C. Y. 1999. From GCMs to River Flow: A Review of Downscaling Methods and Hydrologic Modeling Approaches. *Progress in Physical Geography*, 23(2), 229–249.

4. Sediment Transport and Deposition in Rivers: The Case for Non-Stationarity

Robert H. Meade[1]

Abstract

This paper focuses on the significance of stationarity for sediment studies in rivers and how this concept has worked against monitoring programs by implying that predictive models could substitute for measurements. A differentiation between intrinsic non-stationarity and non-stationarity of measurement and purpose is discussed, based on examples from the Colorado, the Amazon and other rivers.

As a conclusion it welcomes non-stationarity and calls for more continuity in the methods, not only with the hope that the lessons learned from one project might be applied with more quantitative assurance to the next, but that the collection of reliable data continues after the design and construction of projects, in order to better evaluate their impacts and consequences fifty years from now.

Introduction

The “news” that stationarity is dead (Milly et al. 2008) may come as a relief to many fluvial sedimentologists. Stationarity, as a concept and as an underlying assumption of predictive hydrologic assessment, has been of only limited use in studies and assessments of riverine sediment. And the presumption, by managers and supervisors, that a workable model of riverine sedimentation, stochastic or otherwise, was only waiting to be discovered has led to frustration on the part of working scientists and, perhaps more tragic, to the neglect and decay of comprehensive monitoring programs.

The late Carl Nordin, who mentored several members of the HEF Expert Panel, used to emphasize that hydrology is a historical science. That is, that the foundations of our science are the historical data that have been collected routinely and carefully over long time periods at selected observation points around the world, and that the quality of our science is grounded in the quality of our historical data. During the last several decades, however, the presumption of stationarity has been part of the thinking that has led water managers and research administrators to neglect the traditional routine collection of data. It has also led them to urge working scientists to concentrate their efforts on (1) finding faster and cheaper ways of getting the minimal amount of data needed to fulfill a perceived specific need, and (2) devising a workable model that can be expanded and improved until the day when we no longer will have to spend so much time and money on monitoring.

This discussion will follow the concept of non-stationarity of fluvial sedimentation in three directions: (1) the intrinsic non-stationarity of river sediment, (2) non-stationarity of measurement, and (3) non-stationarity of investigative purpose.

1. Opinions expressed are those of the author, and do not necessarily reflect official policies and attitudes of the U.S. Geological Survey, with which the author (now Emeritus) has enjoyed a long (53-year) and productive association.

Stationarity in Riverine Sedimentation

Before plunging into the discussions of non-stationarity, let us begin with instances and examples where the assumption of stationarity has been useful in sediment studies. It has been useful in two places: (1) long-term records in un-engineered rivers that flow through stable (or at least, stabilized) landscapes, and (2) sand transport, for which the movement of particles can be predicted from the physics of fluid flow.

Long-term records of sediment transport are not commonly available in un-engineered rivers that drain stabilized landscapes because the expense of data collection is difficult to support in streams that are not seen as problematical. The few examples we do have of such data—based on sufficiently intensive samplings (daily) during a sufficiently long period of record (decades)—demonstrate (in temperate humid areas, at least) such stationarity generalities as (1) 90 percent of an average annual sediment load is transported in only 10 percent of the time, and (2) during the infrequent high-intensity event (such as a hurricane-induced flood), the river can be expected to transport more sediment in a few days than it had transported during the previous several years (Meade et al. 1990, Table 1 and Figure 3). More widely used (mainly because their construction requires fewer years of representative sediment data) are sediment-rating curves, in which suspended sediment (either as concentration, in milligrams per liter, or as sediment discharge, in tons per day) is plotted against water discharge (in cubic meters per second) (Meade 1982, Figure 2; Meade et al. 1990, Figs. 2 and 4; Nordin et al. 1994, p. 252). This conventional procedure allows an investigator to synthesize a long-term record of sediment discharge by combining a short record of sediment observations with a much longer record of water-discharge measurements. So long as the sediment regimes retain some reasonable semblance of stationarity, sediment-rating curves can be useful and practical predictors of sediment loads in rivers.

Lured by the certainties of Newtonian physics and the predictability of the effects of fluid forces on non-cohesive sediment particles, many fluvial sedimentologists have restricted their efforts to the study of the transport and deposition of sands and gravels. Many experimental studies have been made (usually in laboratory flumes), many transport models have been devised, and an enormous scientific literature has accumulated. These studies have been of practical value in understanding the morphology and stability of river channels (most of which are floored by sand or gravel), and in dealing with associated practical problems such as scouring around bridge piers. But because most of the load of sediment carried by rivers consists of finer and more cohesive materials (silt, clay, organic particles, and organic aggregates) these studies have been of limited use to engineers and managers who need reliable predictions of total sediment fluxes.

Intrinsic Non-stationarity of Riverine Sedimentation

Most of the short-term non-stationarity that is visible in river sediment records has been caused by humans (Meade 1969 and 1996; Syvitski et al. 2005). In the first place, sediment records tend to be concentrated in river basins where sediment is viewed as an actual or potential problem. So it is almost inevitable that the records we do have will be strongly biased toward non-stationarity. The underlying dilemma of such records is this: If the record is of long-enough duration to provide clear insights into the scope of short-term (seasonal, year-to-year) variations in sediment transport, then its integrity is likely to have been compromised by long-term influences on sedimentation such as changes in land use in the drainage basin, or the construction of dams and other engineering works in the river channel.

The effects of changing land uses (deforestation, agriculture, mining, urbanization) usually begin as years-to-decades increases in riverine sedimentation that eventually taper off more gradually at longer time scales of decades to centuries. A specific example from the Piedmont of Maryland (USA) is the diagram first published by Wolman (1967, p. 368), which shows how, between the years 1800 and 2000, sediment yields increased as the original forests were converted to croplands, decreased again as farms were abandoned and the lands reverted to woodlands and pasture, then spiked abruptly as the lands were disrupted by the intensive construction of suburban housing, and decreased again as roads were paved and lawns were planted.

More immediate changes usually result from the construction of engineering works. Because most river engineering works are placed in channels or on adjacent riparian lands, and because they are specifically designed to alter the existing hydraulics of flow, then one should expect them to produce the most pronounced effects on river sediment transport and deposition. Dams, large and small, produce the most abrupt effects; and dams are ubiquitous on six of the seven continents (that is, excluding only Antarctica). Vörösmarty et al. (2003) estimate (1) that more than 40 percent of global riverine water discharge is interrupted locally by large reservoirs, (2) that approximately 45,000 dam-impounded reservoirs trap 25–30 percent of the total sediment being carried seaward by the world's rivers and streams, and (3) that some 800,000 smaller impoundments worldwide have an "additional but unknown impact." Since these impacts (of dams as well as those of other engineering activities in rivers) have been incurred over many decades, we can find only a very few instances in which the data have been sufficient to document the long-term effects on sediment loads.

The data that show these impacts usually are presented in three ways: (1) as paired maps that compare river sediment loads before and after engineering works were installed, (2) as sediment-rating curves (before-and-after graphs of river sediment concentrations or tonnages versus water discharge at fixed stations downriver of dams and other engineering works, or constructed from measurements made upstream and downstream of major impoundments), and (3) as historical time series, taken from records of sediment monitoring stations that have been operated consistently for periods measurable in decades. Examples of the paired-map form portrayals of sediment discharges are those showing the impacts of dams on rivers of the southeastern United States (Meade and Parker 1985, Figure 30; Meade et al. 1990, Figure 14) and those showing pre-engineering and post-engineering sediment discharges in the Mississippi River system (Meade 1995, Figure 6A). Examples of before-and-after sediment-rating curves are those for the Roanoke River of North Carolina (Meade 1982, Figure 10) and the lower Mississippi River (Meade and Moody 2008 Figure 6, 2009 Figure 6).

Examples of historical time series are fairly rare, and most of the long-term (multi-decadal) sets of continuous historical data on riverine sediment loads have been collected in either China or the United States. Multi-decadal records of data from China's Yellow River portray different longitudinal patterns of scour and deposition in the lower 700 kilometers of main channel and proximal floodplain that can be related to different operation routines at Sanmenxia Dam and Reservoir (Zhao et al. 1987). Fifty-year-long records of declining sediment discharges in the lower Yangtze River have been analyzed to discriminate the effects of dam construction and reforestation in the Yangtze basin from the effects of progressive climate change (Xu et al. 2007). In the United States, the U.S. Bureau of Reclamation record of sediment discharge in the Colorado River near the border with Mexico (Yuma, Arizona 1911–1979) shows a large variation in annual fluxes (between 100 and 300 million tons per year) before 1930, and the abrupt decrease that followed the closure in 1933 of the Hoover Dam, 500 kilometers upriver (Meade and Parker 1985, Figure 29; Meade et al. 1990, Figure 12). Concerning the Rio Grande of the southwestern United States and northeastern Mexico, records collected at six stations over several decades by the U.S. Geological Survey and the International Boundary and Water Commission show the downriver changes that followed the closures of four dams: Elephant Butte in 1915, Falcon in 1953, Amistad in 1969, and Cochiti in 1974 (Meade and Parker 1985, Figure 28). And a half century of consistent historical record at stations along the Mississippi River has provided insights into the impacts of extensive river engineering, beginning with the closure of major dams during the 1950s on the Missouri River (the principal source of sediment to the Mississippi) and continuing through the completion of other works such as river-training structures and bank revetments (Meade and Moody 2008, 2009).

Non-stationarity of Measurement

The same dilemma mentioned above—that any sediment record long enough to provide insights into the ranges of short-term variations is likely to be long enough to include the effects of long-term changes that reflect non-stationarity—is also applicable to the techniques and strategies of the measurement of riverine sediment. Sampling equipment and techniques for the collection of sediment data have evolved over decades, and sometimes the changes have been applied with revolutionary suddenness. Likewise, the strategies for computing such things as total annual sediment loads from the collected and analyzed data have changed over the years. Non-stationarity is introduced when such changes are enacted without proper calibrations between the old and the new.

A Case in Point: The Colorado River at the Grand Canyon

During the mid-1940s, following nearly 20 years of regular sediment sampling using the Colorado River Sampler (a vertical bottle that was opened on the river bottom and quickly drawn up to the river surface), the equipment was changed to a depth-integrating sampler with a horizontally-aligned isokinetic nozzle that admitted water and suspended sediment at ambient velocities. Subsequent perusals of the ensuing sediment records led to the observation that the mid-1940s were the beginning years of a drastic reduction (by half) of sediment discharges in the Colorado River, which investigators attributed to improvements in rangeland grazing practices (Hadley 1974) and to regional climate change (Graf et al. 1991). These interpretations went largely unchallenged because (1) a perfunctory calibration study had been made at the time the samplers were changed and (2) the mid-1940s were the beginning years of a prolonged drought in the southwestern United States. However, a more thorough calibration study in the Colorado River (using the old Colorado River Sampler and a more recent isokinetic sampler) has confirmed that most of the mid-1940s "reduction" in the suspended-sediment discharge of the Colorado River was merely an artifact of the change in sediment samplers (Topping et al. 1996).

After the general adoption in the United States of isokinetic samplers in the late 1940s and early 1950s, sediment sampling techniques settled into routines that allowed for the collection, over periods of several decades, of procedurally-consistent data sets. Manuals were produced not only for field methods, but also for laboratory procedures and for computational methods (Guy 1969; Porterfield 1972; Guy and Norman 1982; Edwards and Glysson 1999; see also Carvalho 2008).

Sampler technology continued to improve to meet newly perceived needs. For collecting suspended sediment in large rivers, collapsible-bag samplers were developed to avoid the air-pressure-compensation difficulties in using standard samplers at great river depths. An experimental model that was used successfully in comprehensive studies of the Orinoco and Amazon rivers (Meade 1985; Richey et al. 1986) was later used, with equal success, in a 5-year study of sediment-borne contaminants in the Mississippi River (Meade and Stevens 1990; Meade et al. 1995). More recently, the Federal Interagency Sedimentation Project has developed collapsible-bag samplers of more streamlined design that have been tested in a laboratory flume for their sampling characteristics (Davis 2001 and 2006; McGregor 2006). These samplers probably represent the optimal choices for present and future studies of suspended sediment in large rivers.

These are perilous times in the history of sediment sampling in rivers. The time-tested methods of sampling (isokinetic depth-integrating and point-integrating sampling, and the related field processing and laboratory analysis of sampled materials) have become prohibitively (in the eyes of water managers) expensive and time consuming, and the search is on for cheaper surrogate methods. Surrogate methods include devices that operate on such principles as those of bulk optics (turbidity), laser optics, pressure difference, and acoustic backscatter (Gray et al. 2002; Gray and Gartner 2009). The Acoustic Doppler Current Profiler (ADCP) has also been applied to the estimation of suspended sediment (Filizola and Guyot 2004), but this application cannot yet be considered quantitative because the necessary calibrations between acoustic backscatter and suspended sediment concentration have not been made (Dinehart and Burau 2005; Gamaro 2008).

Any project that adopts any of these surrogate methods should realize that the adoption process entails a responsibility for a thorough calibration with the older and more established methods. Moreover, these calibrations need to be continued over the years. All rivers are different (Schumm 2005); therefore, even if the first investigator to apply a new surrogate method has done a calibration, we cannot assume that all subsequent investigators do not also have to undertake one. Suspended sediment particles can be expected to differ in their properties (such as grain size, surface area, optical reflectance, acoustical reflectance, aggregation state) from one river to the next (or from one season to the next in the same river). These are the very properties that the surrogate methods use as measures of sediment concentration. Furthermore, the presence or absence of organic aggregates and organic detritus (such as twigs and leaves) can complicate the calibration process to a significant degree. One should anticipate that every river will have to be calibrated anew, and that separate calibrations may well be needed at different sampling sites and at different seasons on the same river.

In the long term, it may make more economic sense to continue to collect samples and make direct measurements of suspended sediment, rather than to avidly pursue each newly introduced "magic bullet." The known uncertainties of reliable direct measurements are preferable to the much greater uncertainties that surrogate methods cannot avoid.

Non-stationarity of Purpose

There is no firm consensus regarding whether sediment is a liability or an asset in river systems. Depending on one's outlook and purpose, sediment may be viewed as a potential liability in the design of reservoirs, in the maintenance of channels for navigation, as an unfortunate result of poor soil conservation, as a conveyor of adsorbed pollutants, and as a threat to the habitats of aquatic species. Likewise, one may consider sediment to be an asset because it is the foundation material of which rivers construct their channels and floodplains. Sediment also transfers useful nutrients and soil onto riparian agricultural lands, sequesters adsorbed contaminants, and restores riparian and coastal wetlands. Consequently, as the times change, so do the lenses through which riparian societies view riverine sediment.

Major programs in the monitoring of riverine sediment began in the United States in conjunction with the design of major dams. Elephant Butte Dam on the Rio Grande and Hoover Dam on the Colorado River were among the first. After the Second World War, massive data collection programs were undertaken on the Rio Grande and the Missouri River. The emphasis was on data for reservoir design, and the basic question was: How many years will we be able to operate this reservoir before the river is able to fill it with sediment? Data required for making this assessment were the measured tonnages of transported sediment and the calculated volumes that they would occupy once they were deposited.

In more recent decades, emphasis has shifted to the role of suspended sediment in water quality, and the relevant parameter has been shifted from mass per unit time (sediment discharge) to mass per unit volume (sediment concentration). The advantage of concentration over discharge is that it is more readily measured and more easily enforced, and therefore of more immediate interest to the Environmental Protection Agency, which considers suspended sediment to be a major pollutant on par with nutrients such as nitrate. Many of the recent assessments view suspended sediment through this lens (Gray et al. 2000; Langland et al. 2001; Blevins 2006; Sprague et al. 2007).

Diametrically at odds with those who consider sediment as a pollutant are those who see sediment as a necessary resource in the maintenance and restoration of riparian and coastal floodplains and wetlands. Exchanges of sediment between river channels and their floodplains can be highly significant in un-engineered rivers. In a 1,500 kilometer reach of the Brazilian Amazon, for example, the quantity of sediment transferred between the channel and the floodplain exceeds the quantity of sediment transported out of the reach by the channel itself (Dunne et al. 1998; Meade 2007). Much of the decline in the area of the coastal wetlands of the Mississippi River delta in Louisiana has been attributed to the decline in the delivery of sediment by the river (Blum and Roberts 2009). The data needed for assessments such as these range from traditional measurements of sediment tonnages to remote sensing analyses of the aerial extents of the wetlands involved.

Conclusions

Milly et al. (2008) noted that "In a non-stationary world, continuity of observations is critical." As investigators in fluvial sedimentology, we have little influence on continuity of societal purpose or even on the course of major events in the control, maintenance, and restoration of rivers. But we can strive for more continuity in our methods, not only with the hope that the lessons we learn from one project might be applied with more quantitative assurance to the next, but that we might continue to collect reliable data after the design and construction of projects so as to better evaluate their consequences. The rivers that the World Bank builds dams across this year may be the same rivers it is asked to help restore fifty years from now.

References

Blevins, D.W. 2006. The Response of Suspended Sediment, Turbidity, and Velocity to Historical Alterations of the Missouri River. *U.S. Geological Survey Circular* 1301. *http://pubs.usgs.gov/circ/2006/1301*

Blum, M.D., and Roberts, H.H., 2009, Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise: *Nature GeoScience*, v. 2, p. 488–491.

Carvalho, N. O. 2008. *Hidrosedimentologia Prática* (2d edition). Rio de Janeiro: Editora Interciência.

Davis, B.E. 2001. The US D-96: An Isokinetic Suspended-sediment/Water-quality Collapsible-bag Sampler. [U.S.] *Federal Interagency Sedimentation Project Report* PP. *http://fisp.wes.army.mil/Report%20PP,%20US%20D-96%20011114%20.pdf*

Davis, B. 2006. FISP's Suite of Federally Approved Suspended-Sediment/Water-Quality Collapsible-Bag Samplers. [U.S.] *Federal Interagency Sedimentation Conference, 8th, Reno, Nevada, April 2–6, 2006, Proceedings http://pubs.usgs.gov/misc_reports/FISC_1947–2006/pdf/1st-7thFISCs-CD/8thFISC/8thFISC.pdf*

Dinehart, R. L., and J. R. Burau. 2005. Repeated surveys by acoustic Doppler current profiler for flow and sediment dynamics in a tidal river. *Journal of Hydrology*, v. 314, p. 1–21.

Dunne, T., Mertes, L.A.K., Meade, R.H., Richey, J.E., and Forsberg, B.R., 1998, Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil: *Geological Society of America Bulletin*, p. 110, p. 450–467.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment (2nd edition): *U.S. Geological Survey Techniques of Water-Resources Investigations*, book 3, chapter C2, 89 p. *http://pubs.usgs.gov/twri/twri3-c2/*

Filizola, N., and Guyot, J.L., 2004, The use of Doppler technology for suspended sediment discharge determination in the River Amazon: *Hydrological Sciences Journa*l, v. 49, p. 143–153.

Gamaro, P.E.M., 2008, Verdades e mitos sobre medição de sedimento em suspensão com medidores acústicos Doppler: *Proceedings of VIII Encontro Nacional de Engenharia de Sedimentos*, Campo Grande, Brazil, 2–8 November 2008.

Graf, J.B., Webb, R.H., and Hereford, R., 1991, Relation of sediment load and flood-plain formation to climatic variability, Paria River drainage basin, Utah and Arizona: *Geological Society of America Bulletin*, v. 103, p. 1405–1415.

Gray, J.R., and Gartner, J.W., 2009, Technological advances in suspended-sediment surrogate monitoring. *Water Resources Research*, Vol. 45, W00D29, Special issue on Advances in Monitoring in Hydrology.

Gray, J.R., Glysson, G.D., and Mueller, D.S., 2002, Comparability and accuracy of fluvial-sediment data—a view from the U.S. Geological Survey*: American Society of Civil Engineers Specialty Conference, Hydraulic Measurements & Experimental Methods, Estes Park, Colorado, July 28-August 1, 2002, Proceedings*. *http://water.usgs.gov/osw/techniques/asce.pdf*

Gray, J.R., Glysson, G.D., Turcios, L.M., and Schwarz, G.E., 2000, Comparability of suspended-sediment concentration and total suspended solids data: *U.S. Geological Survey Water-Resources Investigations Report* 00–4191, 14 p. *http://pubs.usgs.gov/wri/wri004191/*

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: *U.S. Geological Survey Techniques of Water-Resources Investigations*, book 5, chapter C1, 58 p.

Guy, H.P., and Norman, V.W., 1982, Field methods for measurement of fluvial sediment: *U.S. Geological Survey Techniques of Water-Resources Investigations*, book 3, chapter C2, 59 p.

Hadley, R.F., 1974, Sediment yield and land use in southwest United States, in *Effects of Man on the Interface of the Hydrological Cycle with the Physical Environment*: International Association of Hydrological Sciences Publication 113, p. 96–98.

Langland, M.J., Edwards, R.E., Sprague, L.A., and Yochum, S., 2001, Summary of trends and status analysis for flow, nutrients, and sediments at selected nontidal sites, Chesapeake Bay basin, 1985–1999*: U.S. Geological Survey Open-File Report* 01–73, 49 p. *http://pa.water.usgs.gov/reports/ofr01–73.pdf*

McGregor, J., 2006, The US D-99: An isokinetic depth-integrating collapsible-bag suspended-sediment sampler: *[U.S.] Federal Interagency Sedimentation*

Project Report RR, 19 p. *http://fisp.wes.army.mil/Report%20RR.pdf*

Meade, R.H., 1969, Errors in using modern stream-load data to estimate natural rates of denudation: *Geological Society of America Bulletin*, v. 80, p. 1265–1274.

Meade, R.H., 1982, Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States: *Journal of Geology*, v. 90, p. 235–252.

Meade, R.H., 1985, Suspended sediment in the Amazon River and its tributaries in Brazil during 1982–1984: *U.S. Geological Survey Open-File Report* 85–492. *http://pubs.er.usgs.gov/djvu/OFR/1985/ofr_85_492.djvu*

Meade, R.H., 1995, Setting: Geology, hydrology, sediments, and engineering of the Mississippi River, in Meade, R.H., editor, Contaminants in the Mississippi River, 1987–92: *U.S. Geological Survey Circular* 1133, p. 12–28. *http://water.usgs.gov/pubs/circ/circ1133*

Meade, R.H., 1996, River-sediment inputs to major deltas, in Milliman, J.D., and Haq, B.U., editors, Sea-Level Rise and Coastal Subsidence: *Causes, Consequences, and Strategies*: Dordrecht, Kluwer Academic Publishers, p. 63–85.

Meade, R.H., 2007, Transcontinental moving and storage: the Orinoco and Amazon Rivers transfer the Andes to the Atlantic, in Gupta, A., editor, Large Rivers: *Geomorphology and Management*: Chichester, John Wiley & Sons, p. 45–63.

Meade, R.H., and Moody, J.A., 2008, Changes in the discharge of sediment through the Missouri-Mississippi River system, 1940–2007: *Proceedings of VIII Encontro Nacional de Engenharia de Sedimentos*, Campo Grande, Brazil, 2–8 November 2008.

____. 2009, Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007: *Hydrological Processes*, v. 24, p. 35–49. *http://water.usgs.gov/nrp/proj.bib/Publications/2010/meade_moody_2010.pdf*

Meade, R.H., Moody, J.A., and Stevens, H.H., Jr., 1995, Sampling the big rivers, in Meade, R.H., editor, Contaminants in the Mississippi River, 1987–1992: *U.S. Geological Survey Circular* 1133, p. 41–51

Meade, R.H., and Parker, R.S., 1985, Sediment in rivers of the United States, in National Water Summary 1984: *U.S. Geological Survey Water-Supply Pap*er 2275, p. 49–60. *http://pubs.er.usgs.gov/usgspubs/wsp/wsp2275*

Meade, R.H., and Stevens, H.H., Jr., 1990, Strategies and equipment for sampling suspended sediment and associated toxic chemicals in large rivers—with emphasis on the Mississippi River: *The Science of the Total Environment*, v. 97/98, p. 125–135.

Meade, R.H., Yuzyk, T.R., and Day, T.J., 1990, Movement and storage of sediment in rivers of the United States and Canada, in Wolman, M.G., and Riggs, H.C., editors, *Surface Water Hydrology*: Boulder, Colorado, Geological Society of America, *The Geology of North America*, v. O-1, p. 255–280.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., and Stouffer, R.J., 2008, Stationarity is dead: Whither water management?: *Science*, v. 319, p. 573–574.

Nordin, C.F., Mejía, A., and Delgado, C., 1994, Sediment studies of the Orinoco River, Venezuela, in Schumm, S.A., and Winkley, B.R., editors, *The Variability of Large Rivers*: New York, American Society of Civil Engineers, p. 243–265.

Porterfield, G., 1972, Computation of fluvial-sediment discharge: *U.S. Geological Survey Techniques of Water-Resources Investigations*, book 3, chapter C3. *http://pubs.usgs.gov/twri/twri3-c3/*

Richey, J.E., Meade, R.H., Salati, E., Devol, A.H., Nordin, C.F., Jr., and dos Santos, U., 1986, Water discharge and suspended sediment concentrations in the Amazon River: 1982–1984: *Water Resources Research*, v. 22, p. 756–764.

Schumm, S.A., 2005, *River Variability and Complexity*: Cambridge University Press.

Sprague, L.A., Clark, M.L., Rus, D.L., Zelt, R.B., Flynn, J.L., and Davis, J.V., 2007, Nutrient and suspended-sediment trends in the Missouri River basin, 1993–2003: *U.S. Geological Survey Scientific Investigations Report* 2006–5231. *http://pubs.usgs.gov/sir/2006/5231/*

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., and Green, P., 2005, Impact of humans on the flux of terrestrial sediment to the global coastal ocean: *Science*, v.308, p. 376–380. *http://instaar.colorado.edu/~kettner/publication_folder/Science2005.pdf*

Topping, D.J., Parker, R.S., Nelson, J.M., and Bennett, J.P., 1996, The apparent mid-20th century load decreases in the Colorado River basin: An investigation of the Colorado River Sampler: *Geological Society of America Abstracts with Programs*, v. 29, no. 7, p. 261.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, J.P.M., 2003, Anthropogenic sediment retention: major global impact from registered river impoundments: *Global and Planetary Change*, v. 39, p. 169–190.

Wolman, M.G., 1967, A cycle of sedimentation and erosion in urban river channels: *Geografiska Annaler*, v. 49A, p. 385–395.

Xu, K-h., Milliman, J.D., Yang, Z-s., and Xu, H., 2007, Climatic and anthropogenic impacts on water and sediment discharges from the Yangtze River (Changjiang), 1950–2005, in Gupta, A., editor, *Large Rivers: Geomorphology and Management*: Chichester, John Wiley & Sons, p. 609–626.

Zhao, Y-a., Pan, X-d., Fan, Z-y., and Han, S-f., 1987, Sedimentation in the lower reaches of the Yellow River and its basic laws, in Brush, L.M., Wolman, M.G., and Huang, B.W., editors, *Taming the Yellow River: Silt and Floods*: Dordrecht, Kluwer Academic Publishers, p. 477–516.

5. Land-Ocean Interactions: Human, Freshwater, Coastal, and Ocean Interactions under Changing Environments

Jeffrey E. Richey
School of Oceanography, University of Washington

Abstract

Particularly complex and pressing challenges exist at the interface between the upland terrestrial and freshwater realm, and the evolving ocean. Deciphering how signals propagate downstream to interact with changing coastal dynamics is a multifaceted task. This paper presents a "systems-level" overview of the key processes and transitions, from land to rivers to oceans and their marine fate. It also summarizes the types of issues confronted in coastal-focused topic areas.

The paper comments on a portfolio of World Bank projects in the environment and water arena, as a means of identifying what existing projects are, and what their requirements might be. In addition, it presents a case study of the Mekong River basin, as an example of a full suite of land-to-ocean issues that must be addressed.

Finally, it advances the concept of a virtual river/coastal basin, driven by a dynamic information framework, as a means to provide a convergence of cross-sector information. The paper ends with a summary of lessons learned.

From Land to Ocean

River basins and their downstream coastal zones are facing a series of challenges critical to their future. These challenges are centered on the availability and distribution of water. Floods and droughts, the development of hydropower, climate change, and global economic development, all play a role. Floods and droughts have an impact on biodiversity, freshwater resources, agriculture, and livelihoods. While the development of hydropower provides much-needed energy, it also alters the flow regime and sediment transport of rivers. Climate change affects all aspects of the system, bringing changes in temperature and rainfall regimes, and reducing snow cover. Global economic development and food shortages also have an impact on river basins and coastal zones and are a growing concern. International efforts must be made to predict and mitigate potential changes in climate. As climate evolves, management options cover a range of issues, from bringing safe water to local villages for the rural poor, to adaptation strategies for large infrastructure.

Particularly complex and pressing challenges exist at the interface between the upland terrestrial and freshwater areas, and the evolving ocean. Deciphering how signals propagate downstream to interact with changing coastal dynamics is a multifaceted task. The mission is further complicated by man's pervasive alteration to the natural system. Rising energy demands are met with ambitious hydraulic projects that change the timing and volume of sediment and water discharged to the sea. Reductions in the supply of sediment to the coastal zone and concurrent changes in ocean conditions create synergies that have negative impacts on coastlines. Coastal erosion and flooding are projected to accompany rises in sea levels and increased storm frequency and intensity. Coastal interactions (disasters associated with sea level rise, increased frequency and intensity of storms, saltwater intrusion and salinization of aquifers) are getting more attention. Nutrients and contaminants from upriver deposited in coastal areas as well as salt water intrusion (exacerbated by the depletion of near shore aquifers) can change the chemical environment along the coasts. The scale of management issues facing countries in the coastal zone are multinational in nature, and will have to be looked at in a new way.

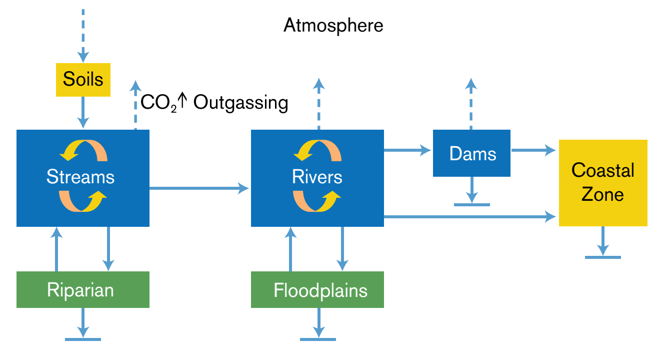
Further exacerbating the situation is the surprisingly sparse understanding of what is involved because it lies at the boundaries between more traditional disciplines and more traditional geographies. For example, it is rare for oceanography programs to fund near-shore research since most of them take place in the open ocean on board large ships. Similarly, terrestrial/freshwater ecology programs rarely approach issues relating to salty water. Overall, this intersection is poorly understood and the paucity of data and complexity in processes creates significant challenges. An immediate challenge is to incorporate the best understanding of the dynamics involved in changing environmental conditions in these sectors into World Bank policies and projects. This needs to be done in a cross-sector manner and in a way that optimizes a multi-stakeholder return.

A Template for Land to Ocean Fluxes

This section provides a summary of land to ocean fluxes and processes as a way to establish a template to evaluate specific regions (which, in turn, depend on their connections to other parts of the system). The analysis is expressed using carbon as the currency, reflective of both the fundamental role carbon plays in establishing ecosystem dynamics, and as the (eventual) basis for carbon trading options. The analysis that follows draws substantially on Richey (2004, 2005).

Fluvial systems integrate hydrological and biogeochemical cycles, over scales from small streams to regional and, ultimately, to continental basins (Figure 1). The transfer of organic matter from the land to the oceans via fluvial systems is a key link in the global carbon cycle because it represents the main pathway for the preservation of terrigenous production in modern environments (Ittekot and Hawke 1990; Degens et al. 1991; Hedges et al. 1992). Hence, the role of rivers in the global carbon cycle is most typically expressed as the fluvial export of total organic and dissolved inorganic carbon from land to the ocean (for example, Likens et al. 1981).

Figure 1. Schematic of the Major Reservoirs and Pathways in Fluvial Systems



Source: Adapted from Richey (2004).
Note: Inputs from land occur directly or pass through the riparian zone. Streams coalesce to form larger rivers that exchange with their floodplain. Rivers can pass directly to the coastal zone, or be retained behind dams. Dotted lines indicate exchange with the atmosphere, grounded arrows indicate sinks, arrows within the boxes indicate internal transformations.

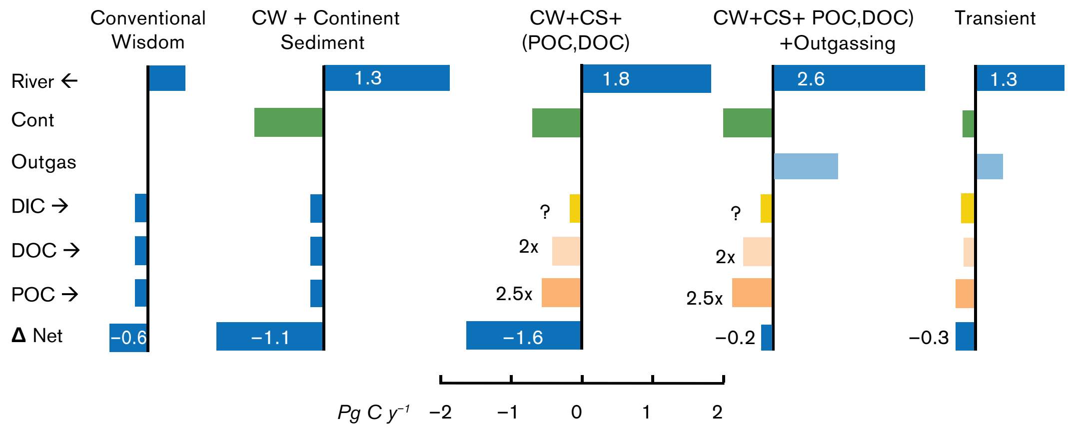
As will be discussed in more detail later, the most common estimations of the magnitude of these fluxes found in the literature are 0.4 petagrams (a petagram is 1,015 g) of carbon per year (PgC y-1) for total organic carbon (evenly divided between particulate and dissolved organic phases), and 0.4 PgC y-1 for dissolved inorganic carbon. While these bulk fluxes are small components of the global carbon cycle, they are significant compared to the net oceanic uptake of anthropogenic carbon dioxide (Sarmiento and Sundquist 1992) and to the interhemispheric transport of carbon in the oceans (Aumont et al. 2001). But these estimates contain very considerable uncertainty. Each term is briefly evaluated below (see Figure 2).

Mobilization from Land to Water and Riparian Zones

The fluxes from land to rivers are generally inferred directly from the fluxes out of a basin, especially at a global scale. Although there is considerable truth to this for dissolved species (especially conservative ones), it is less true for particulate species, especially with human intervention.

The modern terrestrial sediment cycle is not in equilibrium (Stallard 1998). Meade et al. (1990) estimated that agricultural land use typically accelerates erosion ten- to one-hundred-fold, via both fluvial and Aeolian processes. Multiple reports in the literature support this conclusion.

Figure 2. Uncertainty Scenarios in the Fluxes of Carbon through Fluvial Systems Relative to Atmospheric CO_2



Source: Adapted from Richey (2004).

Note: Including atmosphere to rivers (River ← Atm, as sum of other fluxes), continental sedimentation (Cont Sed, alluvial, reservoirs), outgassing from rivers to atmosphere (Outgas → Atm), export of DIC to the sea (DIC → sea, as 50% of total DIC, to represent just atmospheric weathering component), DOC export to the sea (DOC → sea), export of POC to the sea (POC → sea), and by difference the net exchange with the atmosphere (Δ Net Atm). For the purposes here, it is assumed that the export fluxes to the sea constitute a sink, with no return to the atmosphere, on an immediate decadal time scale. Particulate inorganic C is not included (as it is abiotic and does not interact with the other pools). Units are Pg C y-1 (scale at bottom lines up with the axis of each graph at 0). Scenarios include: CW (conventional wisdom on DOC and POC export, no continental sedimentation or outgassing), + Cont Sed (adding continental sedimentation to CW), +POC,DOC (adding the higher values for POC and DOC fluxes discussed in the text to +Cont Sed), +Outgassing (adding outgassing to the +POC,DOC), and Transient (inferring anthropogenic transients, based on the +Outgassing scenario).

With the maturation of farmlands worldwide, and with the development of better soil conservation practices, it is probable that human-induced erosion is less than it was several decades ago. Overall, however, there has been a significant anthropogenic increase in the mobilization of sediments (and associated particulate organic carbon or POC) through fluvial processes. The global estimates of the quantities, however, vary dramatically. Stallard (1998) poses a range of scenarios, from 24 to 64 Pg y-1 of bulk sediments (from 0.4 to 1.2 Pg y-l of POC). Smith et al. (2001) estimate that as much as 200 Pg y-1 of sediment is moving, resulting in about 1.4 PgC y-1.

Where does this material go? Does it all go downstream via big rivers, ultimately to the ocean, or is it stored inland? Stallard (1998) argues that between 0 and 40 Pg y-1 of sediments are stored as colluvium and alluvium and never make it downstream. Using a different approach, Smith et al. (2001) estimate that about 1 PgC y-l of POC is stored this way.

Within-River Transport and Reaction Processes

Within-river transport processes carry these eroded materials downstream through the river network. Transport is not passive; significant transformations occur along the way. Rivers exchange with their floodplains (depending on how canalized and diked a river is). The movement of POC is, of course, directly linked to the movement of suspended sediments. Sediments are deposited and remobilized multiple times and over long timescales. In the Amazon, for example, Dunne et al. (1998) computed that as much sediment was being recycled within a reach as was leaving it. Presumably, a significant amount of the erosion-excess sediment discussed in the previous section makes it some distance downstream but is then slowed and retained within the alluvial floodplains.

An additional process—the mineralization to pCO_2—within flowing water significantly affects organic matter (OM). Most river and floodplain environments maintain pCO_2 levels that are supersaturated with respect to the atmosphere. High partial pressures of CO_2 translate to large gas evasion fluxes from water to atmosphere. Early measurements in the Amazon suggested that global CO_2 efflux (fluvial export plus respiration) from the world's rivers could be on the order of 1.0 PgC y-1. Recent measurements of temperate rivers lead to estimates of global river-to-atmosphere (outgassing) fluxes of −0.3 PgC y-1, which is nearly equivalent to riverine total organic carbon (TOC) or dissolved inorganic carbon

(DIC) export (Cole and Caraco 2001). Richey et al. (2002) computed that outgassing from the Amazon alone was about 0.5 PgC y-1. Assuming that the fluxes computed for the Amazon are representative of the fluvial environments of lowland humid tropical forests in general, surface water CO_2 evasion in the tropics would be on the order of roughly 0.9 PgC y-1 (three times larger than previous estimates of global evasion). Factoring in recent Amazon results, a global flux of at least 1 PgC y-1 directly from river systems to the atmosphere is likely.

Pre-aging and degradation may alter significantly the structure, distribution, and quantity of terrestrial organic matter before its delivery to the oceans. As noted by Ludwig (2001), the organic matter that runs from rivers into the sea is not necessarily identical to the OM upstream in river catchments. Cole and Caraco (2001) observe that the apparent high rate of decomposition of terrestrial organic matter in rivers may resolve the enigma of why organic matter that leaves the land does not accumulate in the ocean (Hedges et al. 1997). Overall, this sequence of processes suggests that the OM that is being respired is translocated in space and time from its points of origin, such that, over long times and large spatial scales, the modern aquatic environment may be connected with terrestrial conditions of another time.

Input to Reservoirs

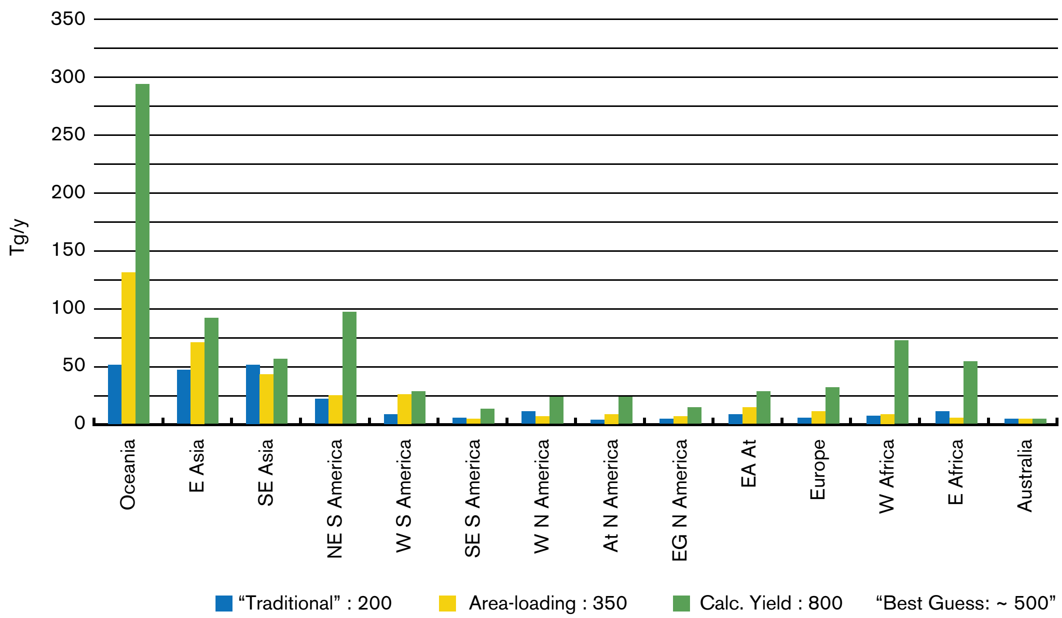
Reservoir construction and the accompanying fragmentation in the flow of the world's large rivers have had a tremendous impact on the hydrologic cycle and the fate of dissolved and particulate material. Starting about 50 years ago, large dams were seen as a solution to water resource issues, including flood control, hydroelectric power generation, and irrigation. Now, there are more than 40,000 large dams worldwide (World Commission on Dams 2000). This has resulted in a substantial distortion of freshwater runoff from the continents, raising the "age" of discharge through channels from a mean of between 16 and 26 days to nearly 60 days (Vorosmarty et al. 1997). Whereas erosion has clearly increased the mobilization of sediment off the land, the proliferation of dams has acted to retain those sediments. Vorosmarty et al. (2003) estimate that the aggregate impact of all registered impoundments is on the order of 4 to 5 PgC y-1 of suspended sediments (of the 15 to 20 PgC y-1 total that he references). Stallard (1998) extrapolates from a more detailed analysis of the coterminous United States to an estimate of about 10 PgC y-1 worldwide (versus 13 PgC y-1 efflux to the oceans), for a storage of about 0.2 PgC y-1 (which he includes as part of his overall calculation of continental sedimentation).

Export to the Coastal Zone

The conventional wisdom is that the flux of particulate and dissolved organic matter are each about 0.2 PgC y-1 and dissolved inorganic carbon (DIC) is 0.4 PgC y-1 (for example, Schlesinger and Melack 1981; Degens 1982; Meybeck 1982, 1991; Ittekot 1988; Ittekkot and Laane 1991; Ludwig et al. 1996; Ver at al. 1999). That these analyses converge is not terribly surprising. They are all based on much of the same (very sparse) field data and use variations of the same statistically based interpolation schemes. Let us evaluate these numbers. Because direct measurements are few, POC flux estimations are typically a product of the flux of total suspended sediments (TSS) and the estimated weight-percent organic carbon (w%C) associated with the sediment (because the bulk of POC is organic carbon sorbed to mineral grains). The first problem is an adequate resolution of the TSS flux. Data on TSS are frequently poor and of unknown quality. Many reported data are surface samples, and the depth integrations necessary to accurately characterize sediment flux are on the order of two to three times higher. Additionally, much sediment moves during episodic storm events, when measurements are almost never made. Finally, most measurements of both water flow and chemistry are made some distance from the actual mouth (in the Amazon for example, the last regular sampling station, Óbidos, is over 700 km from the sea, with an island the size of Connecticut). Overall, estimates of sediment/POC inputs to the ocean should be considered to vary by a factor of at least 2.5, particularly in Oceania, Southeast Asia, and South Asia (Figure 3).

As summarized by Vorosmarty et al. (2003), estimates of total suspended sediment transport to the oceans have ranged from 9 PgC y-1 to more than 58 PgC y-1, with more recent studies converging around 15 to 20 PgC y-1. These estimates are generally based on extrapolations of existing data, which are weighted to the large rivers of passive margins and temperate regions. Milliman and Syvitski (1992) called attention to the much higher yield

Figure 3. Uncertainties in Sediment/POC Loading



Note: By geographic region, with emphasis on Oceania and SE Asia, as calculated by 3 different methods.

rates from steep mountainous environments (without directly computing a global total). More recently, Milliman et al. (1999) estimated that the total sediment flux from the East Indies alone (the islands of Borneo, Java, New Guinea, Sulawesi, Sumatra, and Timor, which represent about 2 percent of the global land mass) is about 4 PgC y-1, or 20 to 25 percent of the current global values. This type of environment (steep relief, draining directly to the oceans) is found elsewhere in the world, so the results are not likely to be unique. Data from Taiwan support these high levels, with isotopic analyses of the carbon showing that a significant part of the flux is human-driven (Kao and Liu 2002).

To obtain particular organic matter flux estimates, these values (and their uncertainties) must be multiplied by region-specific carbon values. The total uncertainties in both sediment and carbon must then be propagated. To account for this range, POC flux can be computed as an ensemble based on different combinations of weight-percent organic carbon and total suspended sediment fluxes, resulting in a range of 0.3 PgC y-1 to 0.8 PgC y-1, with a "more likely" level of about 0.5 PgC y-1 (depending on the assumptions used). Therefore, it is possible that the common estimate of 0.2 PgC y-1 is low and that the overall value lies in the range of 0.2 to 0.5 PgC y-1.

Marine Fate

Long-term preservation of terrestrially derived organic matter in the oceans occurs largely within sediments that accumulate along continental margins. Organic carbon within these sediments is thought to be preserved largely because it is adsorbed to mineral grains (Keil et al. 1994; Mayer 1994; Bishop et al. 1992). Hedges and Keil (1997) estimated that carbon preservation along continental margins over the Holocene was split roughly evenly between sediments accumulating within the delta or sedimentary plume of rivers and non-deltaic sediments accumulating outside the direct influence of major rivers (but within range of multiple smaller systems).

The storage efficiency of deltaic and non-deltaic systems is different. The amount of organic carbon in non-deltaic continental shelf sediments falls in a narrow range (0.5–1.1 milligrams of carbon per square meter [mg C m^2] of mineral surface), and typically more than 90 percent of the preserved organic matter is adsorbed to mineral surfaces. Deltaic sediments are distinctly different, containing only a fraction of the organic carbon (by weight) found in other margin sediments. Suspended sediments from the Amazon River, for example, have loadings (-0.67 mg C m^2) that are three times higher than the corresponding deltaic sediments (Keil et al. 1997), so more than two-thirds of the terrestrial particulate organic load delivered to the Amazon delta is lost from the mineral matrix and is not preserved. The Mississippi, Yellow, and other river/delta systems also show extensive loss of terrestrial organic matter. Thus, many deltaic systems bury only a small fraction of the potential organic load normally sorbed to mineral particles, with the balance presumably desorbed or mineralized (and entering the dissolved inorganic matter pool).

The organic matter lost by mineralization and not buried is one of the factors in maintaining the historical perspective that marginal seas are net heterotrophic (Chen 2004). But Chen (2004) reviews more recent evidence, based on direct measurements of pCO_2 (again, showing the critical importance of actual field measurements of key parameters!) and comes to the conclusion that these seas are net autotrophic, driven primarily by nutrients delivered via upwelling (with enhanced nutrients delivered by rivers leading to eutrophication constituting only a minor source), and net consumers of atmospheric CO_2. The overall implication of this sequence of processes is that much of the anthropogenically mobilized riverborne organic matter (and perhaps the naturally mobilized OM) is liable to remain in the marine environment over timescales longer than the current increase of atmospheric carbon dioxide.

The World Bank Environmental/Water Resources Project Portfolio

The avowed purpose of the Bank's Hydrology Expert Facility (HEF) is to bring (new) expertise to bear on World Bank projects in the overall water-related portfolio. To help focus this effort, it is useful to briefly examine the World Bank portfolio of projects (Figure 4).

The projects that can be considered water and water resources (W&WR) are shown in graph (a) of Figure 4 and represent the majority category, with 22 percent of the total projects. The same graph shows that the ecosystems and biodiversity category accounts for 18 percent of all projects. This category establishes the conditions for inputs to the water systems. Graphs (b) and (c) break down the water and water resources category into its constituent projects by World Bank sector for inland waters (Graph b) and coastal and marine waters (Graph c). The main components of inland water projects are water supply (32 percent of all projects in this category), and irrigation and drainage (24 percent). The number of coastal and marine projects is small and is dominated by the "miscellaneous" category, which includes a broad array of projects. Marine projects are relatively evenly split into projects dealing with fisheries, marine, and coral reefs. Further insight into the 41 coastal projects can be obtained by re-filtering the sector analysis. Graph (d) shows that 34 percent of projects focus on biodiversity, 32 percent focus on pollution, 29 percent on integrated coastal management (ICM), and 5 percent on reconstruction.

Region-Specific Evaluations

How does this portfolio relate to how land-ocean connections function, as both natural and managed systems?

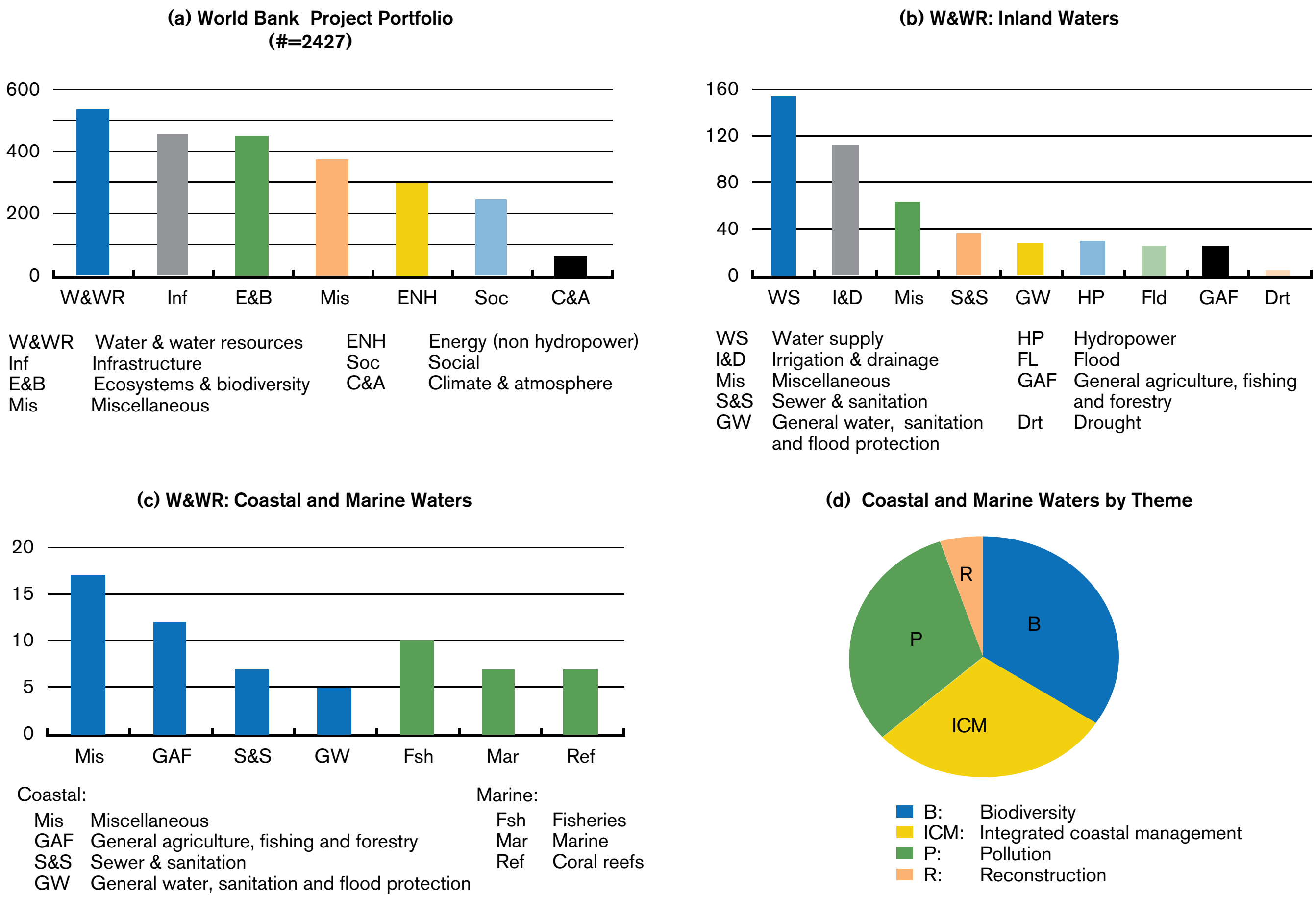
As shown earlier in Figure 4, World Bank projects and interests cover a wide range of sectors. They include projects in coastal subsidence and sea level rise, coastal estuaries and wetlands, carbon in coastal wetlands, coral reefs, and hydropower.

Coastal Subsidence and Sea Level Rise

This section discusses impacts to deltas related to human activities. Deltas respond to both landward and seaward pressures (Figure 5). Construction of levees and the alteration of natural dispersal processes decrease sediment input to the delta plain, while eustatic sea level and erosive storm activity continues to rise with warming ocean temperatures. The result is that the world's deltaic coastlines are extremely vulnerable to anthropogenic change. While there are many examples, the following illustrate the nature of the problem.

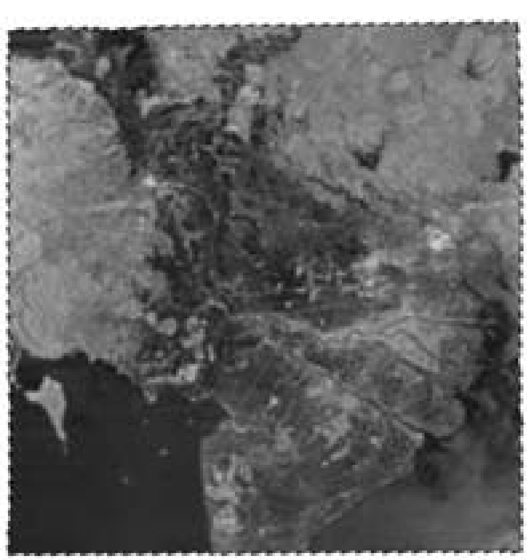
The Mississippi River delta is a prime example of a heavily impacted dispersal system. Alteration of source and dispersal processes is exacerbated by oil and gas extraction, and groundwater off-take. The upriver-supplied nutrient load promotes the formation of a "dead zone." In addition, the fate of river-borne organic carbon is being altered where the Mississippi delta has grown to the shelf break, allowing direct deposition to deeper water and

Figure 4. World Bank Project Portfolio: Environment and Water Resources



Source: http://www.worldbank.org/projects
Note: (a) The number of active, proposed, and pipelined projects to do with environment and natural resource management since about 1984 are broken down by primary categories. The water and water resources category is broken down into (b) Inland Waters sectors (sector as defined by the data source) and (c) Coastal and marine waters. The coastal and marine category can be recombined (d) into theme areas.

Figure 5. The Mekong Delta



promoting submarine landslides. A significant issue is the increased vulnerability of coastal communities to storms (lessons from Katrina and Rita) (Day et al. 2007).

Hydrologic/sediment changes on the Nile River have driven the Nile Delta into a destruction phase over the last 150 years (Stanley and Warne 1998). The High Aswan Dam and Reservoir have trapped almost one hundred percent of sediment delivery to the estuary, and drastically altered the hydrography. Effects include accelerated coastal erosion and straightening of the shoreline, reduction in wetland size, increased landward incursion of saline groundwater, and buildup of salt and pollutants to toxic levels in the wetlands and delta plain. Moreover, seasonal floods capable of flushing agricultural products/pollutants created by Egypt's expanding population are being reduced or eliminated.

The demands of expanding populations present multiple challenges in balancing a return to any semblance of natural conditions and the advantages inherent in them. Restoration efforts aim to re-establish dynamic interactions, with emphasis on reconnecting the river to the deltaic plain. Science must guide restoration, which will provide insights into coasts facing climate change in times of resource scarcity. Integrating the delivery of sediment and discharge of freshwater to the delta with large-scale hydrology models to make better predictions about coastal erosion, subsidence, groundwater salinity intrusion, and other forces at play would help set a rigorous template for decision making.

Coastal Estuaries and Wetlands

Estuaries are depositional environments that are often dominated by fine-grained sediments. Sedimentation is promoted by the existence of estuarine turbidity maximum (ETM), a zone of convergence at the mouth of a river. Salinity effects enhance flocculation and the increase settling rate. Contaminants such as trace metals, polychlorinated biphenyls (PCBs), pesticides, and polyclyclic aromatic hydrocarbons (PAHs) are adsorbed to the surface of particles and settle out of the water column in the estuary. Benthic communities are adversely affected by the toxic sediments. Sediment quality guidelines (SQGs) have been established through experiments in US estuaries (lead by Edward Long), and have been validated abroad (McCready et al. 2006).

There are many examples throughout the world of specific coastal estuaries and wetlands where changes in both upstream hydrology and marine-side forces have had an impact on the region, and become subject to remedial actions. For example, the iSimagaliso Wetland Park, on the east coast of South Africa, is suffering under the impact of a series of factors. Immediate threats include:

- Degradation of the iSimagaliso Wetland ecosystem because of closure of the mouth of the St. Lucia estuary;
- The presence of commercially viable mineral deposits in the coastal dune cordon;
- Large-scale commercial afforestation in endemic grasslands and water catchments on the park's fringes; and
- Spread of invasive alien plants that are threatening the highly productive communities growing in moist environments, particularly on the alluvial floodplains along the coast line and in the valleys of the Lubombo Mountains.

The root causes of these threats include:

- Land uses and land tenure, such as the transformation of the Umfolozi swamps for improved agricultural production, which disrupt terrestrial and wetland processes;
- Poverty; and
- Weak institutional environment.

The issue is well-phrased, in this excerpt from a GEF project, on the iSimangaliso Wetland Park, in South Africa.

> "The challenge faced by the Wetlands Authority is therefore to respond to the twin imperatives of conservation and development in a manner that aligns with the shift in national (and global) priorities from a strong focus on conservation-in-isolation to a new approach that integrates biodiversity conservation with regional development."

Carbon in Coastal Wetlands

Beyond the role of coastal wetlands in fisheries, agriculture, and coastal protection, there is the substantial, but tricky, role of wetlands in carbon storage (mitigation of CO_2 emissions), as well as in adaptation (M. Hatziolos, pers. comm.). Mangrove forests appear to provide a double dividend with respect to mitigation and adaptation in addressing climate change at the local level. But a potential glitch with respect to natural carbon capture and storage is working out the carbon cycle under different conditions of mangrove and wetland (including mudflats) disturbance. The net carbon storage appears to be very closely related to hydrology and exposure of soils, as well as methane release. If progress is to be made on possible carbon credits and offsets through mangrove reforestation or protection, then good measures of net carbon storage or emissions under these different conditions are needed.

This stresses the importance of maintaining the hydrology intact (or at least ensuring environmental flows) to support healthy mangroves so that the increasingly important carbon storage service is maintained. Similar concerns with mudflats (which are apparently even greater natural stores of carbon than peatlands) revolve around dredging, filling, and building over these carbon reservoirs. These key ecosystem services, which are not adequately valued or acknowledged by decision makers, are being lost.

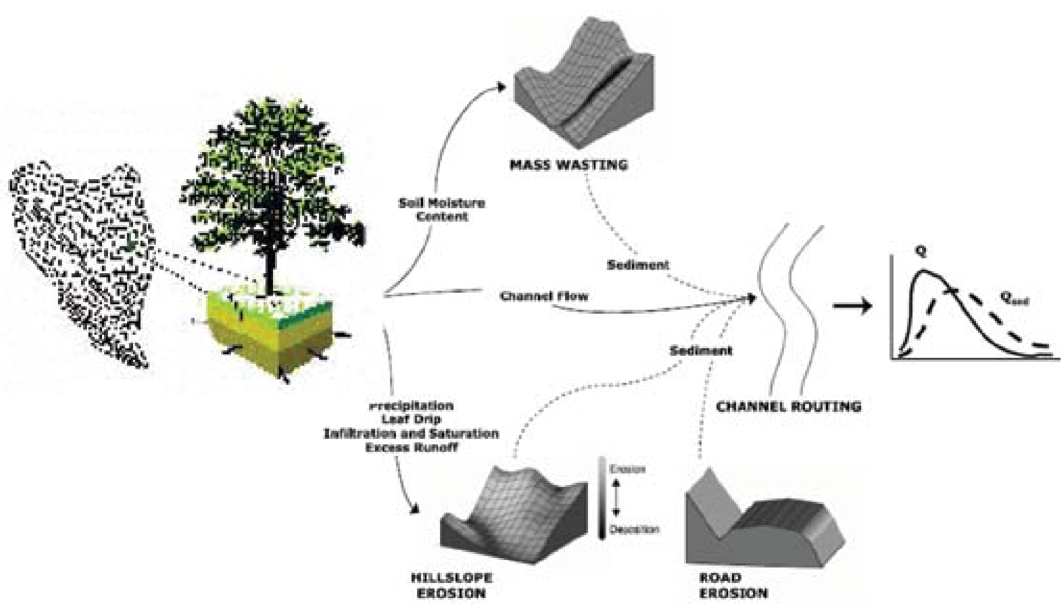
Coral Reefs

Coral reefs represent an intersection between changing ocean conditions, immediate population pressures (overfishing, destructive fishing), and impacts from land. For example, the Coral Triangle covers all or parts of Indonesia (Central and Eastern), East Timor, The Philippines, Malaysia (part of Borneo), Papua New Guinea, and the Solomon Islands. Sometimes referred to as the “Amazon of the Seas,” it is the epicenter of marine life abundance and diversity on the planet. While the area covers only 2 percent of the world’s oceans, it contains more than 75 percent of all known coral species, more than 30 percent of the world’s coral reefs, nearly 40 percent of coral reef fish species, and the greatest extent of mangrove forests anywhere in the world. Regional-scale gradients exist in reef biodiversity, with decreasing diversity with distance from the Indo-Australian archipelago. Bellwood and Hughes (2001) best explain this variation with large-scale patterns in the availability of shallow-water habitat. The challenge now is to identify the relation between taxonomic composition, species richness, and ecosystem function in reef systems. Low-diversity regions are particularly sensitive to anthropogenic impacts, and underscore the need for “integrated management at multinational scales.”

The boundary of the Coral Triangle region coincides with the most productive region in the world in terms of sediment discharge (Figure 3). According to Milliman and Syvitsky (1992), this part of the world accounts for 50 percent of the global sediment flux to the ocean, but only about 3 percent of the land area. This is because of the role of small, mountainous rivers with highly erodible rock, combined with high population pressures. The ability to attribute changes in the landscape production of sediments to loadings on reefs would help develop suitable management practices. An emerging class of coupled hydrology/sediment models is a step in that direction (Figure 6).

For example, Kimbe Bay (Papua New Guinea) is home to at least 860 species of reef fish and 350 species of hard coral, making it one of the world’s richest marine environments. This unique area is under threat from logging and development, destructive fishing, and rapid population growth. The Derawan Islands (Indonesia) feature some of the most significant green turtle nesting beaches in Southeast Asia and a unique saltwater lake with four endemic, stingless jellyfish species. The area’s reefs are extremely diverse because of the influence of the Berau River on the coastal waters, illustrating the sensitive link between land and sea in some places.

Figure 6. A Coupled Hydrology-Sediment Model, DHSVM 3.0



Source: Doten et al. (2006).
Note: Based on computing the probability of mass wasting and surface erosion.

This region is the focus of the emerging Coral Triangle Initiative (CTI) on Coral Reefs, Fisheries, and Food Security that aims to bring together six governments in a multilateral partnership to conserve the extraordinary marine life in the region. In December 2007, government representatives from environment and fisheries ministries in Indonesia, Malaysia, Papua New Guinea, The Philippines, Solomon Islands, and Timor-Leste met to agree upon a way forward for the CTI. After the meeting, President Yudhoyono of Indonesia launched the CTI. The GEF saw the CTI as one of the most important initiatives in its history expecting to see at least $25 million focused on the program.

The guiding principles agreed to by the Coral Triangle governments illustrate the complexity of objectives that require cross-sector approaches. These principles are also relevant to other such projects. The principles are:

- Support people-centered biodiversity conservation, sustainable development, poverty reduction, and equitable benefit sharing.
- Be based on solid science.
- Be centered on quantitative goals and timetables adopted by governments at the highest political levels.
- Recognize the transboundary nature of some important marine natural resources and communities.
- Be inclusive and engage multiple stakeholders.

Hydropower

Pressed by growing demands for clean(er) energy throughout the world, the hiatus in dam building is ending with a gathering "hydropower renaissance." While not yet quantified, the consequences will be considerable. A more detailed discussion is provided below in the discussion of the Mekong River case study.

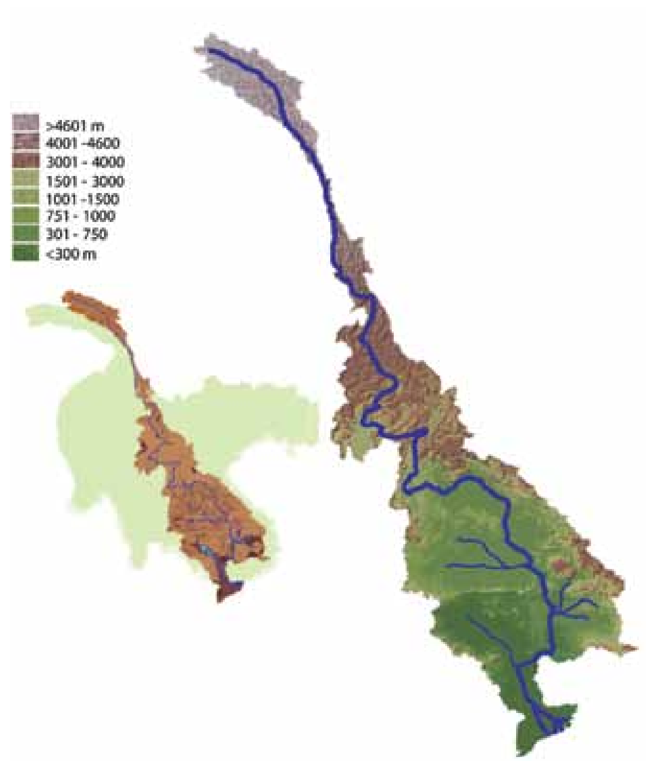
The Mekong River Basin: A Case Study

Transboundary river basins, where a river passes through several countries, pose particularly vexing problems in water resource allocation. These problems encompass not only water, but also fisheries production, sediment transport, and navigation. The 6-country Mekong River basin is a very important example of this class of issues. Emerging conditions in the Mekong River basin represent a confluence of issues. Transnational agencies play important roles in mediating among competing interests. A key player in the Mekong basin is the Mekong River Commission (MRC), which is based in Vientiane, Laos. The mandate of the MRC includes current and future water resource management of the riparian countries (Laos, Thailand, Cambodia, and Vietnam) of the lower Mekong, according to the terms of the Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin (April 5, 1995). Institutions such as the MRC need to be able to work with regional political realities, and also harness the most "complete" science in order to inform decision makers.

The Region

The Mekong is a large, diverse transboundary river basin. It has the world's 8th largest discharge (ca. 0.47 km^3/yr), 12th largest length (ca. 4,800 km), and 21st largest drainage area (ca. 795,000 km^2) (Figure 7). The Upper Mekong basin covers an area of 189,000 km^2 in China, Burma, and the northern part of Laos. This area has a mountainous terrain with elevations ranging between 400

Figure 7. The Mekong River Basin



and 5,000 m, and provides about 16 percent of the annual flow to the Lower Mekong basin (which encompasses 606,000 km^2). The Northern and Eastern Highlands, with elevations of up to about 2,800 m, are the wettest regions in the basin. In contrast, the Khorat Plateau (in northeastern Thailand), is a dry region with intense evapotranspiration. The main feature of the lower Mekong is Cambodia's Tonle Sap (or "Great Lake") a complex and important ecosystem driven by an annual flood pulse. The lake's fisheries, which are critically dependent on the subtleties of the flow regime, are important for their biodiversity as well as a critical food source, providing 60 to 80 percent of the fish protein to the region. Finally, the river passes through the delta in Vietnam, and discharges to the South China Sea.

Population growth and socioeconomic development in the Mekong River basin in the second half of the 20th century and into the 21st century has been accompanied by unprecedented changes in land cover and land use. All Mekong regions were affected, although to a different extent, depending on environment, population growth, socioeconomic development, and each country's style of transition to a market economy. The irrigated area has expanded greatly with the construction of large reservoirs for irrigation and power production. During this same period, the Mekong experienced floods (that caused great loss of life and material damage), as well as crop-damaging droughts. These hydrologic disasters have been attributed to man-made changes, primarily deforestation (forests are perceived as streamflow moderators and precipitation attractors). Rising crop damage from droughts has also been blamed on deforestation by some, while other analysts contend that croplands lower evapotranspiration relatively more than forests, and that this should lead to increased, not reduced, streamflows. Alternatively, low dry-seasons have been attributed to the Chinese dams.

Conflicting opinions and lack of scientific evidence on streamflow trends hinder policy making and international agreements, and exacerbate conflicting interests between countries and stakeholders, as well as between the goals of conservation and development.

Initial Applications of System Models

A significant problem is lack of regional data, particularly discharge and rainfall. Decades of strife have led to pronounced gaps in data records. Trends that have been "perceived" could also be because of channel scouring or silting at gauge locations, defective gauge operation, poorly developed rating curves, and/or undetected trends in precipitation.

The recent application of basin-wide models is providing key insights into the functioning of the Mekong basin. As will be discussed below, an important aspect of model application is not only the computed (relative to observed) flows, but that model development itself "forces" data integration. Takeuchi et al. (2008) report on a series of model applications. Costa-Cabral et al. (2007) used the VIC model to provide a detailed analysis of the interactions of landscape structure and use, climate, and water movement. Costa-Cabral et al. (in prep.) analyze the potential consequences of land use change, dams, and climates. A provocative result of this work is that the lack of increase in streamflow in northeastern Thailand, which would have been expected but is not being observed, could be the result of the use of bunded paddies in which collected rainwater, added irrigation water, or both, is prevented from running off the paddy and eventually infiltrates or evaporates, returns an amount of water to the atmosphere that surpasses the large evapotranspiration losses from the original forest. Hence, a decline in the region's runoff ratio has accompanied the expansion of agriculture.

The MRC is developing its own model environment, following the Decision Support Framework (DSF; not published) based on the SWAT, ISIS, and IQQM models, and is looking at including the VIC model in this portfolio. The experiences in the development and application of these models call attention to the importance of matching models, applications, and capabilities.

Upcoming Issues for the Mekong

Political stabilization and increased global energy and market demands have intensified pressures on the Mekong.

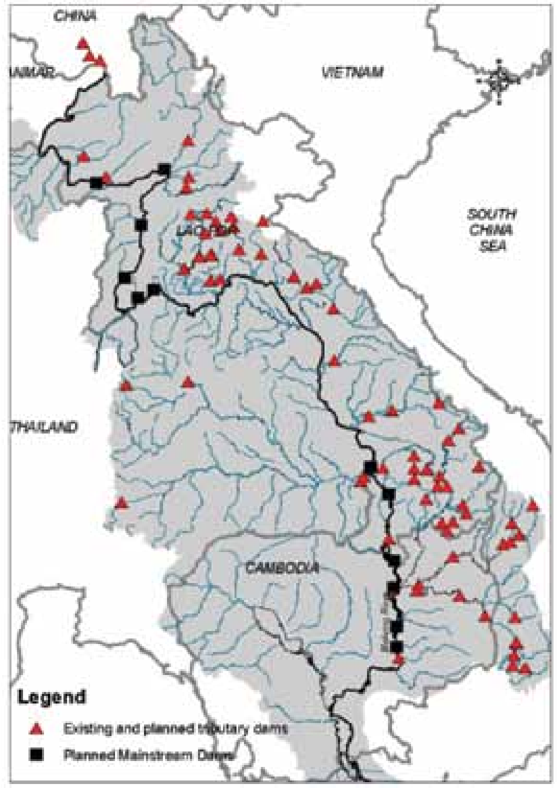
Agricultural expansion and dramatic deforestation in northeast Thailand have resulted in a decreased recurrence of low streamflows. However, in an apparent paradox, crop yields are increasingly vulnerable to precipitation shortages, and drought has become a major issue in this region. The Thai government has funded the construction of thousands of small reservoirs on individual farms to help mitigate the problem. The expansion of agriculture in northeast Thailand towards less favorable lands has increased crop vulnerability to climate change. It may be possible to counteract this with a technological response, such as rice varieties that are more resistant to drought. Irrigation may continue to expand and intensify in all countries, even though it faces institutional as well as natural resources constraints (MRC 2003). The future of the low-yield, labor intensive rainfed rice cultivation may be in decline.

The cumulative impacts of all upstream events converge with changes along the coast itself as well as with changing marine conditions. Vietnam is particularly at risk of sea level rise (for example, Dasgupta et al. 2007). Direct impacts along the coast include conversion of mangrove forests to aquaculture, particularly shrimp farming (Tong et al. 2004), which has become susceptible to viral infections and salinity intrusion.

Reservoir impacts on the flow of the Mekong are currently relatively limited. The two existing reservoirs in the Chinese Mekong (Manwan and Dachaoshan) have limited regulation potential. The Pak Mun dam is a run-of-the-river dam, fed by the Mun-Chi river system in Thailand. The Ubol Ratana (also called Nam Pong) dam, located in the Pong tributary of the Chi River in Thailand has been in operation since 1966 and is used for power generation, irrigation, water supply (including for industry), and flood control. The Nam Theun II dams in Laos are under construction.

A series of dams, currently in the planning stages will further impact the Mekong River basin. The Chinese government is planning the construction of a cascade of hydropower reservoirs along the upper Mekong, with a reported (massive) 23 km^3 of active storage beyond 2020. The so-called "Hydropower Renaissance" (*sensu* World Bank SDN Weeks, February 2008) includes the Mekong. On the order of 100 dams are under discussion in the tributaries of Laos, and on the mainstream as far down as Cambodia. The potential impact of even a subset of these dams would be very high. The "far-field" cumulative flow impacts, even if all were run-of-rivers dams, would be substantial by the Tonle Sap and the Mekong Delta, and on into the South China Sea. Sediment trapping would significantly reduce the flux of sediments and associated nutrients downstream. Of

Figure 8. Map of Projected Mainstem and Tributary Dams

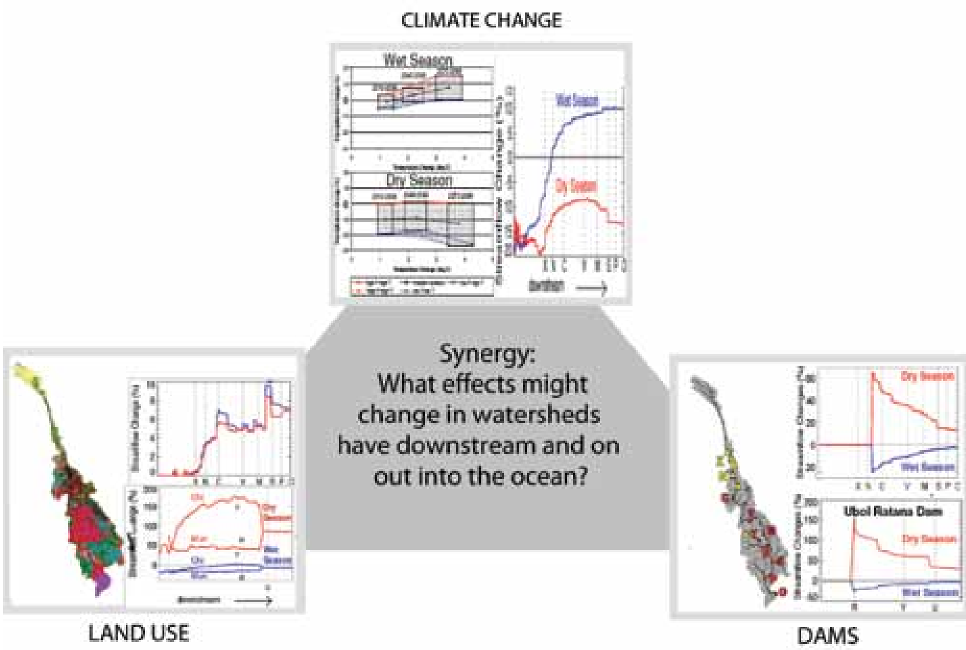


immediate and acute impact would be physical barriers for fish migration.

An additional consequence of reservoirs on the Mekong and other tropical river basins is the potential for the production of greenhouse gases (GHG), especially methane. As noted by the report of the World Commission on Dams (2000), hydropower cannot, *a priori*, be automatically assumed to be a cleaner technology than thermal alternatives with respect to GHG emissions. Case-by-case research is needed to make this claim. The organic carbon/gas dynamics of the Mekong are very "active," fed by terrestrial inputs as well as *in situ* production. The implication is that a cascade of reservoirs could be expected to have a very significant GHG footprint.

Finally, the critical question that must be asked is: What are the cumulative impacts of land use change, reservoir construction, and climate change (Figure 9)? The answer to this question represents the ultimate cross-sector analysis, not only for the Mekong, but across regions.

Figure 9. Synergistic, Cumulative Impacts from Land Use, Dams, and Climate Change for the Mekong (and Elsewhere)



Source: Adapted from Costa-Cabral et al. (2007).

A Foundation for Multi-sector Integration of Information

As such, these targets represent a very complex set of intersecting issues of scale, cross-sector science and technology, education, politics, and economics. One of the most significant challenges for evaluating past performances and establishing the basis for future decisions is how to undertake a quantitative analysis of the multiple complex pathways and trade-offs involved in a policy project, from small farms to regional implications. A template for decision makers to rigorously consider alternative scenarios could play an important role in making complex environmental and economic decisions. This requires an accurate understanding of linkages between water and multiple allocations, with the ability to carry out quantitative forecasts of the individual and combined impacts of demand. Once that information is available, it would then be necessary to evaluate the trade-offs among sectors in order to establish future policy interventions and financial investments.

To do this, information from multiple sources must converge, it must be organized and evaluated (preferably according to organizing ecosystem principles), and it must be disseminated. A baseline assessment of current and past environmental conditions (to establish both the extent and processes of change) of a basin provides the foundation from which to build. A baseline allows the analysis of future scenarios as well as monitoring the evolution of key system variables.

Establishing such a process is not a trivial task, for several reasons. First, the information required comes from multiple sources, from individual rain gauges to statistics on rice yield and fisheries. It also comes from multiple disciplines, which presents problems even with communication between specialists. Existing data are not always readily obtainable, sometimes for institutional reasons. New field measurements, especially holistic and cross-boundaries, are challenging. Second, handling such diverse data and executing models is not straight-forward. There are very real problems in converting data streams into useful information that goes beyond a database. Third, perhaps most challenging is how to get the information into the hands of users, from specialists to local and regional decision makers, and to the local farmers or fishermen. Finally, few, if any, institutions in the world have sufficient in-house expertise to execute all parts of such a process.

The information and decision issues confronting a basin are challenging but not unique. There is now broader recognition of the need for more holistic views. Advances in the science of how to analyze complex systems is evolving, as are sensors (on the ground and in orbit), and computers that facilitate the acquisition and processing of information. Knowledge about the process of organizing complex information (sometimes known as "cyber-informatics") is also evolving rapidly.

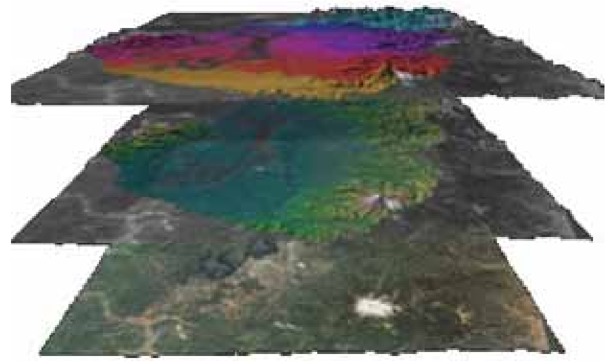
In this spirit, it may be useful to think of a virtual river basin (VRB) as both a metaphor and a practical engine for organizing and processing the information and decision needs for a basin (Figure 10). A virtual river basin can be thought of as the common environment for the overall information sources describing a basin, organized in a highly systematic fashion, to facilitate analyses, and to "visualize" outcomes. Information organized according to landscape principles (below) can serve multiple purposes, with specific targets for information identified and prioritized. The intersection of biophysical processes and environmental stressors can be seen in a geospatially-explicit fashion. Careful attention must be paid to how the information is organized, displayed, and distributed.

Organizing Principle for the VRB: The Movement of Water Across and Down a River Network

The theoretical structure for a VRB is to track the overall pathways and processes of water as it moves from the atmosphere to and through the landscape and down river channels, through reservoirs and lakes, to the sea, on a geospatially-explicit, multi-temporal basis (as described, below). The knowledge necessary to track water includes an understanding and mobilization of information for all aspects of the landscape, including agriculture practices, land cover, topography, soils, fisheries, infrastructure, and human interactions.

The robust framework for tracking water to be enacted for a VRB is the emergence of a new generation of earth system science, based on rapidly evolving capabilities for addressing global change issues. This involves use of satellites, new generations of dynamic models, field measurements focused by model requirements covering wide areas, and, especially, a focus on "integrated systems."

Figure 10. A Schematic of a Virtual River Basin, from Topography (Bottom) to Land Cover Attributes (Middle) to Political Boundaries (Top).



Each data "layer" is a "model" in its own right, of interest to diverse parties. The "summation" provides not only within- but cross-sector integration.

Fundamental to these is a new class of hydrology models, which can also be regarded as overall landscape models because of the processes (and data layers) they represent. A key aspect of these models is that they are geospatially explicit, fully distributed, recognize the spatial heterogeneity of the watershed, and are process-based. Because these models can, and must, meld information from multiple sources, they can be functional in specific regions where local data are relatively sparse.

The Information Structure

At the core of a virtual river basin is a dynamic information framework (DIF) that can provide a consistent theoretical basis and the overall capability of integrating across sectors. "Dynamic" refers to the fact that the landscape is evolving; that is, that we must look not only at the present, but also at the past and, especially, the future. Information is not static. "Information" means that more than just data needs to be considered; that is, what products must be developed from the data? "Framework" means that an overall set of information must be logically arranged and communicated within a flexible environment. The ability to interact with and communicate the results of a DIF is critical.

Essentially, a DIF is a numeric and quantitative "commons" that builds on the legacy of knowledge from experience, with the goal of harmonizing watershed function for multiple users. The goal is to provide an instrument for a (quantitative) analysis of complex interdependent problems. The process of creating the model provides an integration of data from multiple sources (of interest to many). The framework provides a way to interpolate sparse data, as well as the basis for cross-scale/upscaling analyses, and the foundation for building "scenarios."

The specific components of the DIF include:

- Base data layers;
- Directed data layers, focused on synthetic objectives;
- Geospatially-explicit, process-based, cross-sector simulation models (requiring data from the directed data layers). A modular structure allows ready swapping of models (while focusing on getting work done);
- Facilitated input/output (including visualizations);
- Decision support system and scenario testing capabilities.

The framework should be cross scale, allowing accurate representation of large regions and far-field effects, while being able to "zoom in" to a specific site of a project. While flexibility is highly desirable, hence the term "framework," emphasis must be given to "getting the job done."

A Cyber Infrastructure

The computational and data organizational issues represented in executing the DIF are not trivial, but they are manageable. Figure 11 shows the sequence of issues to be resolved, from the details of metadata and data storage, to facilitated access. It is useful to think in terms of mobilizing the data from archives (and its attendant issues) to "data streams," which focus on specific outcomes, as represented by the modules. The actual execution of moving data from archives to something useful is expedited by including data services for processing the data into usable forms. Given the complexity of outcomes, experience has shown that attention to providing visually compelling data products is very important for effective communication, not only with decision and policy makers, but also with the public at large. Underlying the technical details are the issues of dealing with (1) ownership of and access to primary data, (2) where systems reside (national, ministry, agency), (3) accessing and using core information from multiple locations for inclusion in analysis, synthesis, and outputs, and (4) the communication of scenarios and likely outcomes.

Figure 11. The "Cyber Infrastructure" to Support a DIF

Including databases, data archives, data services, models, and "visualization servers".

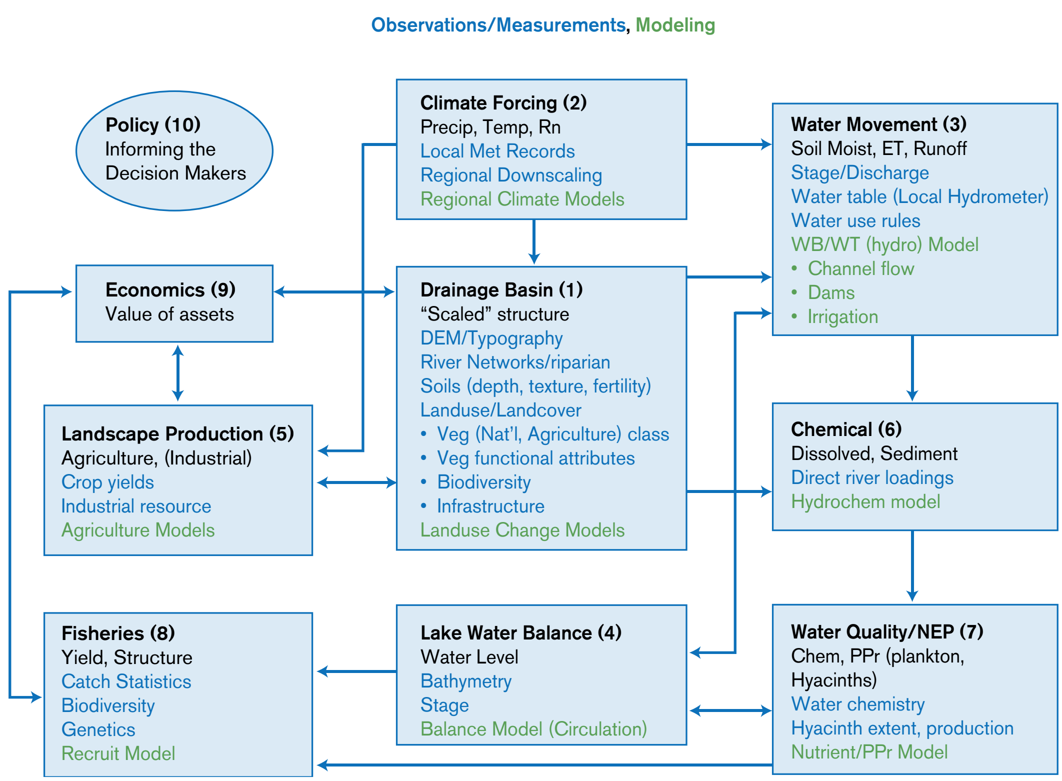
A Prototype Virtual River Basin

As a means to start the discussion on developing a virtual river basin, consider the conceptual framework shown in Figure 12. The construct is that each module of the framework represents internally consistent data and information, and that exchanges between each module occur sequentially. The information is derived from direct measurements and observations, and from modeling to interpret that information.

The first set of modules establishes the basic structure and dynamics of the basin. The drainage basin (Module 1) establishes basic attributes of the landscape, including topography, soils, land use, and land cover. The climate forcing (Module 2) "drives" the landscape (including Tonle Sap) with precipitation, temperature, and winds. Climate can be derived from surface observations (including telemetry back to a home base), satellites, and climate models. The water movement (hydrology, Module 3) then proceeds as the product of the climate acting across the templates of the landscape. Such models can then be used with or "coupled" to other models (for example, for climate or hydropower or carbon exchange with the atmosphere) and used to evaluate the impacts of land use change, irrigation, dams, and climate change on the hydrologic cycle. The lake water balance (Module 4) is the product of water inputs (from Module 3), outflows, and bathymetry.

The second set of modules addresses the production basis of the basin, building on its basic "physics". The Landscape Production (Module 5) represents primary production by land cover (including natural vegetation and agriculture), and secondary production (including livestock), responding to the structure of the drainage basin, and climate forcing (including changes in climate). Coupled to the hydrology models, net ecosystem (carbon) production can be calculated. Specific agriculture crops can be represented at progressively finer resolution ("downscaling") with data from multiple sources and models. The chemical loading (Module 6) is the input of chemicals (nutrients, toxics), as the product of hydrology and drainage basin properties. Lake water quality and net ecosystem production (NEP,

Figure 12. A Schematic for the Execution of a River Basin/Coastal Dynamic Information Framework



Module 7) is then driven by the loading and water balance. The all-important fishery (Module 8) responds to external fishing pressure and NEP.

Finally, the third set of modules addresses how economics and policy interact with the "biosphere." The economics (Module 9) represents the economic consequences and feedbacks of the use of ecosystem goods and services. Policy (Module 10) represents the legislative intersection with the management of the basin, including polices from land tenure decisions to specific, nominally informed, legislation.

The concepts are equally relevant to progressively fined scales, down to individual projects. The construct allows upscaling as well as relating how an individual project or locale is "nested" in a larger region. The execution of an architecture such as the one sketched out here provides a framework for identifying specific field sampling requirements, from climate stations to suspended sediments to economics of resources. The framework can then serve as the organizing structure for the activities of the Mekong basin, including providing a basis for development of management scenarios. A basin baseline can be executed as organizing and analyzing the information required to bring each module "to life."

Applications to Existing World Bank Projects

The VRB/DIF construct is not an esoteric, theoretical exercise. It is a construct that is not only realistic at this point, but practical. It is currently being applied to, and developed from, emerging World Bank/GEF projects. The model and information framework was used to establish the baseline for the GEF–Zambezi Valley Market-Led Smallholder Development Project: Baseline Data on Land Use, Biodiversity, and Hydrology. Through consultation with the Lake Victoria Basin Commission (LVBC), and the national teams for Kenya, Uganda, and Tanzania, the framework elements for a Lake Victoria basin Dynamic Information Framework were created for the proposed IAD Lake Victoria Environmental Management Plan 2. VIC is the core model for the ongoing World Bank/GEF project on the China 3H Basin project Mainstreaming Adaptation to Climate Change into Water Resources Management and Rural Development. It is being setup in Bhutan for the project Distributed Hydrology Modeling and DrukDIF Design and Development. The work was presented to World Bank Water Week, in February 2007 (Quantitative Approaches to Optimizing Water, Land and Biodiversity Management) and the World Bank Sustainable Development Network (SDN) in February 2008 (Watershed and Basin Management–Integrated Approaches across the SDN Practice).

Lessons Learned and Future Directions

It would be ideal to implement integrated water resources management along the continuum from land to ocean, as a systematic process for the sustainable development, allocation and monitoring of water resource use in the context of social, economic, and environmental objectives. At its simplest, integrated water resources management is a logical and intuitively appealing concept. Its basis is that the many different uses of finite water resources are interdependent. High irrigation demands and polluted drainage flows from agriculture mean less freshwater for drinking or industrial use; contaminated municipal and industrial wastewater pollutes rivers and threatens ecosystems; if water has to be left in a river to protect fisheries and ecosystems, less can be diverted to grow crops; and so on. There are many more examples of the basic theme that, in a rapidly changing environment, unregulated use of scarce water resources is wasteful and inherently unsustainable.

Relative to such goals, the analysis of the World Bank project portfolio makes several points. The projects deal most directly with immediate services to be provided (water supply, irrigation, etc). The projects dealing with the consequences of (sudden) change, such as floods or droughts, are considerably fewer. While clearly the sectors within each one of the major categories are highly related to each other, in an ecosystem/water cycle sense, there was surprisingly little overlap between them. Overall, this suggests the need for enhanced multi-sector cross-over and integration, and the need to pay more attention to the emerging ideas of "ecosystem goods and services."

A template for how to undertake integration and consider services is provided by the broad-brush analysis of land-ocean fluxes, summarizing the net transport of dissolved and particulate materials from land to and through fluvial systems to the sea. While the general patterns of fluxes are clear, there are (perhaps surprisingly) large uncertainties in the magnitudes of specific fluxes, which could ultimately impact the ability to quantitatively determine possible outcomes of management actions. Part of the problem is scarcity of reliable measurement campaigns. A substantial investment in improved measurements systems is needed.

This template provides a basis for region-specific analyses and case studies, from hydropower to sea-level rise. Sediments coming off hill slopes impact coral reefs as well as streams. The Mekong case study shows how interconnected apparently separate sectors are. Decisions must consider the simultaneous and multiple interactions of land use, reservoirs, and climate change. In many coastal regions, these effects then propagate on local coastal change, exacerbated by sea level rise. Combined with the issues of greenhouse gases from reservoirs, mudflats and deltas, the land-to-ocean carbon cycle should be considered as part of global carbon trading.

The problem is, how does the development community deal with such complex, cross-over issues? New opportunities are emerging for nature-based adaptation in the coastal zone and new investments to secure coastal ecosystem services through better management, restoration, good governance, and so forth, as cost-effective adaptation strategies and alternatives to hard engineering (including flexible/adaptive infrastructure, source control) solutions in some cases. Incorporation of the concept of "ecosystem goods and services" should be a key part of the agenda. These become cost-effective ways of addressing global change issues, including building resilience into linked natural-human coastal ecosystems, and accommodating future conditions (whatever they may be).

Choi (2004) suggests the following five steps:

- Set realistic and dynamic goals for future environments, rather than static goals based on the past.
- Assume multiple possible trajectories acknowledging the unpredictable nature of ecological communities and ecosystems.
- Take an ecosystem or landscape approach (instead of an ad hoc approach) for both function and structure.
- Evaluate the restoration progress with explicit, quantitative criteria.
- Maintain long-term monitoring of restoration outcomes.

What is the best way to incorporate the necessary technologies to achieve these goals? Market-based incentive systems provide rewards in the hope of promoting sustainable land and water stewardship in catchments and basins. They generally work on the concept that enhanced resources management in upper catchments results in both productivity increases and ecosystem services that can benefit stakeholders in the lower catchments and coastal regions. In most incentive-based systems, the beneficiaries are charged an appropriate amount that is then equitably shared among the land users in the upper catchment. To be successful, the volume and quality of water flows and associated benefits (for example, vegetation biomass and soil cover, reduced erosion, and added food and fiber production) provided by good land and natural resources stewardship must be identified and reliably quantified.

Creating an appropriate decision-making framework and institutional support structure that can be accessed by all stakeholders is a critical step in the process. Key to being able to execute objectives is to be able to acquire, integrate, and process the multiple sources of information required to do this. The Virtual River Basin/DIF concepts advanced here represent significant and practical advances towards providing such a framework. The capabilities now being provided through earth system sciences, with its use of geospatial information from satellites combined with ground measurements, internet-accessible databases, and dynamic process-based models provide a new generation of tools. The capabilities for advanced visualization not only make it easier for the practitioner to understand his/her own results, but to convey them to a much broader audience, including decision makers.

It must be made clear that the capabilities to do this are now eminently feasible and tractable. Perhaps the main issue is to evaluate how best to overcome institutional constraints to adapting to new directions. The resource agencies and ministries of host governments are obviously important. The role of transboundary organizations, such as the Mekong River Commission and Nile Basin Initiative, could be enhanced.

Working as partners with current Work Bank Staff, the Hydrology Expert Facility (HEF) is timely and particularly well-suited to act as a catalyst in moving such an agenda forward. Applications could cover a diverse portfolio of Bank projects, from regions of melting glaciers to coral reefs affected by sediments. An important starting point would be to simply insure that the basics of hydrology are understood and applied (for example, that trees don't "produce" water). Then, the more advanced technologies discussed above, and represented by the HEF members, could be brought to bear on specific projects.

References

Aumont, O., J. C. Orr, P. Monfray, W. Ludwig, P. Amiotte-Suchet, and J.-L. Probst. 2001. Riverine-driven interhemispheric transport of carbon. Global Biogeochemical Cycles 15:393–406.

Bellwood, D.R., Hughes, T.P., 2001. Regional-scale assembly rules and biodiversity of coral reefs. Science, 292, 1532–1534

Bishop, A. N., A. T. Kearsley, and R. L. Patience. 1992. Analysis of sedimentary organic materials by scanning electron microscopy: The application of backscattered electron imagery and light element X-ray microanalysis. Organic Geochemistry 18:431–446.

Chen, C-T. A. 2004. Exchanges of carbon in the coastal seas. In: C. B. Field and M. R. Raupach (eds.) The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World. Island Press, Washington, D.C 526p.

Choi, Y.D., 2004. Theories for ecological restoration in changing environment: towards "futuristic" restoration. Ecol. Restor. 19, 75–81

Cole, J. J., and N. F. Caraco. 2001. Carbon in catchments: Connecting terrestrial carbon losses with aquatic metabolism. Marine and Freshwater Research 52 (1): 101–110.

Costa-Cabral, M. C., J. E. Richey, G. Goteti, D. P. Lettenmaier, C. Feldkötter, and A. Snidvongs (2007). Landscape structure and use, climate, and water movement in the Mekong River Basin. *Hydrological Processes*, vol 22, No. 12, pp1731–1746.

Day, J.W. et al. 2007. Delta: Lessons from Hurricanes Katrina and Rita. Science, 315, 1670–1684

Degens, E. T. 1982. Riverine carbon: An overview. In Transport of carbon and minerals in major world rivers, Part 1, edited by E. T. Degens. SCOPE/UNEP Sonderbd. Mitteilungen aus dem Geologisch-Palaontologischen Institut der Universitat Hamburg 52, 1–12.

Degens, E. T., S. Kempe, and J. E. Richey. 1991. Biogeochemistry of major world rivers. New York: John Wiley and Sons.

Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan. 2007. The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis World Bank Policy Research Working Paper 4136, February 2007

Doten, C., L.C. Bowling, J.S. Lanini, E. Maurer, and D.P. Lettenmaier (2006). A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous. Water Res Research. 42, W04417, doi:10.1029/2004WR003829,

Dunne, T, L. A. K. Mertes, R. H. Meade, J. E. Richey, and B. R. Forsberg. 1998. Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil. Geology Society of America Bulletin 110 (4): 450–467.

Hedges, J. I., and R. G. Keil. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. Marine Chemistry 49:81–115.

Hedges, J. I., J. R. Ertel, P. D. Quay, P. M. Grootes, J. E. Richey, A. H. Devol, G. W. Far-well, F. W. Schmitt, and E. Salati. 1986. Organic carbon-14 in the Amazon River system. Science 231:1129–1131.

Hedges, J. I., P. G. Hatcher, J. R. Ertel, and K. J. Meyers-Schulte. 1992. A comparison of dissolved humic substances from seawater with Amazon River counterparts by i3C¬NMR spectrometry. Geochimica et Cosmochimica Acta 56:1753–1757.

Hedges, J. I., G. L. Cowie, J. E. Richey, P. D. Quay, R. Benner, and M. Strom. 1994. Origins and processing of organic matter in the Amazon River as indicated by carbohydrates and amino acids. Limnology and Oceangraphy 39 (4): 743–761.

Hedges, J. I., R. G. Keil, and R Benner. 1997. What happens to land-derived organic matter in the ocean? Organic Geochemistry 27:195–212.

Ittekkot, V., and B. Hawke. 1990. The terrestrial link in the removal of organic carbon in the sea. Pp. 318–325 in Facets of modern biogeochemistry, edited by V. Ittekkot, S.Kempe, W. Michaelis, and A. Spitzy. Heidelberg: Springer-Verlag.

Ittekkot, V., and R. W. P. M. Laane. 1991. Fate of riverine particulate organic matter. Pp. 233–243 in Biogeochemistry of major world rivers, edited by E. T. Degens, S. Kempe, and J. E. Richey. New York: John Wiley and Sons.

Jones, J. B., E. H. Stanley, and P. J. Mulholland. 2003. Long-term decline in carbon dioxide supersaturation in rivers across the contiguous United States. Geophysical Research Letters 30:2-1-2-4.

Kao, S. J., and K.-K. Liu. 2002. Exacerbation of erosion induced by human perturbation in a typical Oceania watershed: Insight from 45 years of hydrological records from the Lanyang-Hsi River, northeastern Taiwan. Global Biogeochemical Cycles 16:1–7. Keil, MG., D. B. Montlucon, F. G. Prahl, and J. I. Hedges. 1994. Sorptive preservation of labile organic matter in marine sediments. Nature 370:549–552.

Keil, R. G., L. M. Mayer, P. D. Quay, J. E. Richey, and J. I. Hedges. 1997. Losses of organic matter from riverine particles in deltas. Geochimica et Cosmochimica Acta 61 (7): 1507–1511

Likens, G., F. Mackenzie, J. Richey, J. Sedell, and K. Turekian, eds. 1981. Flux of organic carbon by rivers to the oceans. National Research Council/DOE Conf-009140.Washington,U.S. Department of Energy.

Ludwig, W. 2001. The age of river carbon. Nature 409:466–467.

Ludwig, W, J. L. Probst, and S. Kempe. 1996. Predicting the oceanic input of organic carbon by continental erosion. Global Biogochemical Cycles 10 (1): 23–41.

McCready, S., Birch, G.F., Long, E., Spyrakis, G., Greely, C.R., 2006. Predictive abilities of numerical sediment quality guidelines in Sydney Harbour, Australia, and vicinity. Environmental International, 32, 638–649

Mayer, L. M. 1994. Adsorptive control of organic carbon accumulation in continental shelf sediments. Geochimica et Cosmochimica Acta 58:1271–1284.

Meade, R. H., T. R. Yuzyk, and T. J. Day. 1990. Movement and storage of sediment in rivers of the United States and Canada. Pp. 255–280 in Surface water hydrology, edited by M. G. Wolman and H. C. Riggs. Boulder, CO: The Geology of North America, Geological Society of America.

Meybeck, M. 1982. Carbon, nitrogen and phosphorus transport by world rivers. American Journal of Science 282:401–425. 1991. C, N, P, and S in rivers: From sources to global inputs. In Interactions of C,N, P and S. Biogeochemical rycles, edited by R. Wollast, E. T. MacKenzie, and L. Chou. Berlin: Springer Verlag.

Milliman, J. D., and J. P. M. Syvitski. 1992. Geomorphic tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. Journal of Geology100 (5): 525–544.

Milliman, J. D., K. L. Farnswortha, and C. S. Albertin. 1999. Flux and fate of fluvial sediments leaving large islands in the East Indies. Journal of Sea Research 41:97–107. Raymond, P. A., and J. E. Bauer. 2001. Riverine export of aged terrestrial organic matter to the North Atlantic Ocean. Nature 409:497–500.

Raymond, P. A., and J. J. Cole. 2003. Increase in the export of alkalinity from North America's largest river. Science 301:88–91.

Richey, J. E., J. I. Hedges, A. H. Devol, P. D. Quay, R. Victoria, L. Martinelli, and B. R. Forsberg. 1990. Biogeochemistry of carbon in the Amazon River. Limnology and Oceanography 35:352–371.

Richey, J. E., J. M. Melack, A. A. K. Aufdenkampe, V. M. Ballester, and L. Hess. 2002. Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO2. Nature 416:617–620.

Richey, J.E. 2004. Pathways of Atmospheric CO2 through Fluvial Systems. Pp. 329–340. In: C. B. Field and M. R. Raupach (eds.) The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World. Island Press, Washington, D.C 526p.

Richey, J.E. 2005. Global River Carbon Biogeochemistry. (in. M. Anderson, Ed.) Encyclopedia of Hydrological Sciences Part 15. Global Hydrology. John Wiley & Sons, Ltd DOI:10.1002/0470848944.hsa191

Richey, J.E., and E. Fernandes. (2007). Towards Integrated Regional Models of Transboundary River Basins in Southeast Asia: Lessons Launched from Waters and Watersheds. Journal of Contemporary Water Research & Education. 136: 28–36.

Sarmiento, J. L., and E. T. Sundquist. 1992. Revised budget for the oceanic uptake of anthropogenic carbon-dioxide. Nature 356 (6370): 589–593.

Schlesinger, W. H., and J. M. Melack. 1981. Transport of organic carbon in the world's rivers. Tellus 33:172–187.

Smith, S. V., W. H. Renwick, R. W. Buddemeier, and C. J. Crossland. 2001. Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. Global Biogeochemical Cycles 15 (3): 697–707.

Stallard, R. F. 1998. Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles 12:231–257. Stanley, D.J., and Warne, A.G., 1998. Nile Delta in its destruction phase. Journal of Coastal Research, 14(3), 794–825

Takeuchi, K., H. Ishidaira, H. Sawada, and T. Masumoto. 2008. Special Issue: Studies on the Mekong River Basin—Modelling of Hydrology and Water Resources. Hydrological Processes 22.

Tong, P., Y. Auda, J. Populus, M. Aizpuru, A. al Habshi, and F. Blasco. 2004. Assessment from space of mangroves evolution in the Mekong Delta, in relation to extensive shrimp farming. Int. J. Remote Sensing 25: 4795–4812.

Ver, L. M., E T. Mackenzie, and A. Lerman. 1999. Biogeochemical responses of the car-bon cycle to natural and human perturbations: Past, present and future. American Jour¬nal of Science 299:762–801.

Vorosmarty, C. J., K. Sharma, B. Fekete, A. H. Copeland, J. Holden, J. Marble, and J. A. Lough. 1997. The storage and aging of continental runoff in large reservoir systems of the world. Ambio 26:210–219.

Vorosmarty, C. J., M. Meybeck, B. Fekete, K. Sharma, P. Green, and J. Syvitski. 2003. Anthropogenic sediment retention: Major global impact from registered river impound¬ments. Global and Planetary Change 39:169–190.

World Commission on Dams. 2000. Dams and development: A new framework for decision-making. London: Earthscan.

6. Managing the Real Water Consumer: Evapotranspiration

Peter Droogers
Walter Immerzeel
Future Water, The Netherlands

Abstract

While water related problems are diverse and location specific, water shortage is frequently the most pressing issue in many developing countries. A central challenge for the next decades is the increasing international and inter-sector competition for scarce water, in the context of growing demand for food and uncertain impacts of climate change.

This paper discusses the role of agriculture as one of the main causes of water-related problems, as well as the importance of evapotranspiration as the dominant water consumer. Experiences in China and Egypt serve as examples for a discussion of methodologies to support policy makers and water administrators and assist them in managing evapotranspiration.

Several models, ranging from those that are completely physically-based to conceptual allocation models, are discussed as policy support tools, some of which may prove to be too complex for practical applications. The paper advocates the inclusion of a combination of remote sensing and simulation models in policy support tools and introduces the concept of scenario-based modeling as a better alternative to support policy makers.

Introduction

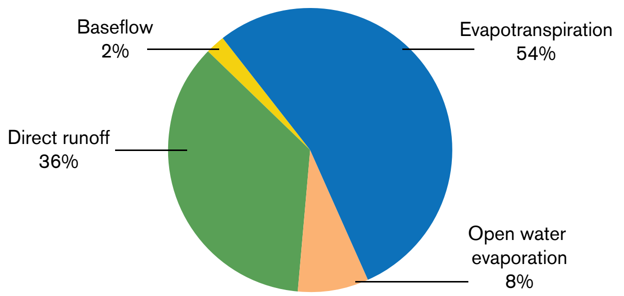
Water to sustain food production plays a key role in efforts to reach the Millennium Development Goals. Access to water and irrigation is a major determinant of land productivity and the stability of yields.

However, in sub-Saharan Africa, only 4 percent of the area in production is under irrigation, compared with 39 percent in South Asia and 29 percent in East Asia. Investments in improving the productivity of water in agriculture are becoming increasingly critical. Climate change and reduced glacial runoff are raising uncertainties in agriculture at the same that growing water scarcity and the rising costs of large-scale irrigation schemes are creating opportunities for enhancing productivity that should be explored.

Agriculture, and more specifically irrigated agriculture, is often regarded as one of the main causes of water related problems. The 2008 *World Development Report* claims: "Agriculture is by far the largest user of water, contributing to water scarcity." The very same report also concludes that "Without irrigation, the increases in yields and output that have fed the world's growing population and stabilized food production would not have been possible." In general, irrigated land productivity is more than double that of rainfed land and evapotranspiration is the main consumer of water (see Figure 1).

However, increasing complexity, and insufficient knowledge and tools to evaluate the consequences of alternative interventions constrain the ability of policy makers and planners to make appropriate decisions. Furthermore, important misconceptions often underlie strategies proposed to address these problems.

Figure 1. Global Water Use for Land



Source: Shiklomanov 1999

Evapotranspiration

This section discusses the concept of evapotranspiration and the tools available to policy makers.

Concepts

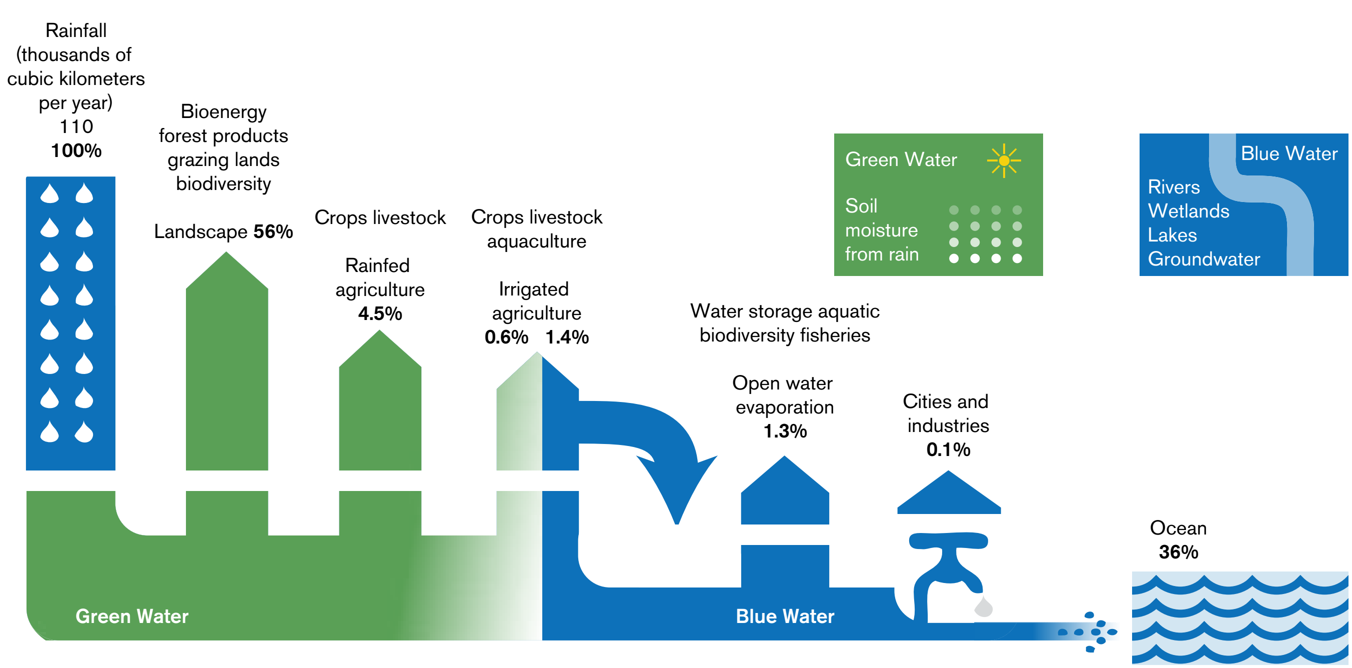
A persistent misconception is that irrigated agriculture is the main consumer of water (Figure 2). This misconception is mainly based on a combination of ambiguous terminology and undefined domains. Regarding terminology, it is often unclear what is meant by "consumers," "users," "efficiencies," "losses," and other such terms. This has led to confusing policies, especially in irrigation science (Allen et al. 2005; Seckler et al. 2002; Molden 2007; Perry 2008; Droogers et al. 2000).

For example, irrigation science has traditionally focused on improving "efficiency" while completely ignoring what happens with the "non-efficient" water. In many cases this "non-efficient" water is reused by downstream users, pumped from the groundwater, serves to reduce salt intrusion, or contributes to wetlands. It is quite common that a substantial amount of these "losses" is beneficial to the poorest in a region. From a discussion of these efficiency concepts, Perry (2007) showed that the following conclusions may be drawn:

- high efficiency reflects low losses;
- losses are a non-recoverable waste of resources;
- reductions in ''losses'' will mean that more of the input is available for alternative uses;
- high efficiency is ''good.''

The concept of "irrigation in the basin" has been promoted and partly put into practice over the last decade to overcome the misconceptions that arise from considering only the irrigation domain (Seckler 1996; Kite and Droogers

Figure 2. Global Water Use



Source: Molden 2007.

1999). This line of thinking is also reflected in the first of eight recommendations in the Comprehensive Assessment of Water Management in Agriculture (Molden 2007):

> Change the way we think about water and agriculture. Thinking differently about water is essential for achieving our triple goal of ensuring food security, reducing poverty, and conserving ecosystems. Instead of a narrow focus on rivers and groundwater, view rain as the ultimate source of water that can be managed. (Policy action #1).

The basic concept put forward in this policy action is that regardless of the policies that are put into place, the ultimate restriction is always the total rainfall in a basin (provided that no inter-basin transfer occurs). Acknowledging that rainfall is the only source of water, it could be claimed that there is effectively only one ultimate consumer of water: evapotranspiration. In other words, in the same way that rain can be regarded as the ultimate source of water on the supply side of the hydrological equation, it could said that evapotranspiration is the only term on the consumer side.

This simple fact has tremendous impact on policies. In situations where the non-evaporated components of irrigation diversions return to the fresh water resource for reuse by others, conservation programs may not stretch water supplies or “save” water in the region, especially in the long term. Water conservation programs should fundamentally be evaluated against the general principle that the only real loss of water from an irrigation project is by the process of evaporation from open water surfaces, evaporation from soil and wet foliage, transpiration from vegetation, and flows into saline sinks. In fact, one should go back to the fundamental hydrologic concepts that were already recognized by the early Greek philosophers, and mathematically underpinned in the 18th century by Bernoulli and Chezy, among others (Hubart 2008).

The term evapotranspiration (ET) relates to three components: (1) interception evaporation, (2) soil evaporation, and (3) crop transpiration. The interception evaporation for agricultural crops is often around 10 percent of total ET, while for forests this can range as high as 80 percent to 90 percent, depending on prevailing climate conditions. Soil evaporation can be a substantial amount of total ET, especially at the time of crop emergence when leaf cover is very limited. Crop transpiration is, in fact, the only term that can be considered as a productive use, since it supports vegetation growth. However, it is important to note that less than one percent of the transpired water is actually retained by the vegetation. Carbon dioxide is the only carbon source for plants and in order to obtain it, plants have to open their stomata. Water diffuses outwards during this process, and it could be claimed that plants have to transpire water to obtain the required carbon. In addition, plants might also transpire some water to maintain their internal temperature.

Ignoring ET and simply reducing water diversions almost always results in a reduction in return flow back to the resource. Therefore, the quantity of net consumption by an irrigation system may be largely unchanged by a conservation program. To effectively create “new” water in a regional context, unless directly upstream of a salt sink, a conservation program must in some way reduce ET or improve return flow quality, and not simply reduce diversions. Reduction of crop ET will almost always reduce crop yields, unless evaporation from the soil is reduced without reducing plant transpiration.

In fact, the performance of an irrigated area can only be evaluated by examining the irrigation water when it leaves the defined boundaries of interest. The applied irrigation water can be placed into five categories (Clemmens and Allen 2005):

1. Water consumed by the crop within the area under consideration for beneficial purposes.
2. Water consumed within the area under consideration but not beneficially.
3. Water that leaves the boundaries of the area under consideration, but is recovered and reused by the same party or by a “downstream” party.
4. Water that leaves the boundaries of the area under consideration, but is either not recovered or not reusable.
5. Water that is in storage within the area under consideration.

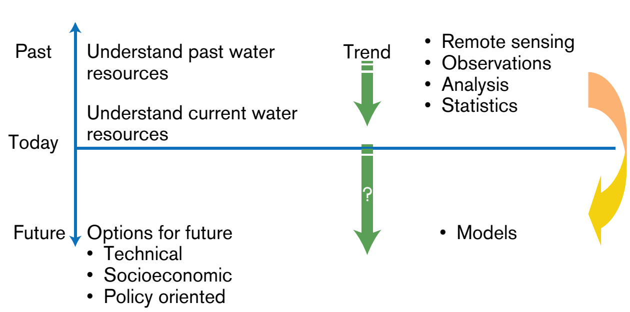
In practice, much emphasis in irrigation engineering has been on category 3 using the concept of efficiencies, while categories 2 and 4 are those that deserve greater recognition by policy makers and water managers.

A similar approach based on the diversion of water allocations was advocated by Perry (2007), who stated that all water that enters a certain domain (irrigation, streamflow, and rainfall) can be classified into one of four terms: beneficial consumption, non-beneficial consumption, recoverable fraction, and non-recoverable fraction.

1. *Beneficial consumption* is water evaporated or transpired for the intended purpose; for example, evaporation from a cooling tower, or transpiration from an irrigated crop.
2. *Non-beneficial consumption* is water evaporated or transpired for purposes other than the intended use; for example, evaporation from water surfaces, riparian vegetation, or waterlogged land.
3. *Recoverable fraction* is water that can be captured and reused; for example, flows to drains that return to the river system, percolation from irrigated fields to aquifers, or return flows from sewerage systems.
4. *Non-recoverable fraction* is water that is lost to further use; for example, flows to saline groundwater sinks, deep aquifers that are not economically exploitable, or flows to the sea.

Based on these discussions, it is clear that only by considering the basic concepts of hydrology and continuity of mass can proper intervention options be explored. When water is scarce, key areas of attention would be to reduce non-beneficial consumption, and to reduce non-recoverable flows to the extent that proper hydrological analysis shows that no unintended consequences of such reductions occur. Based on this conclusion, it is essential that all terms of the water balance should be known.

Figure 3. The Concept of Using Policy Oriented Supporting Tools



Policy Support Tools

From the previous section it is clear that a focus on ET is not only justified, but also required to understand water-related issues and improve water management. The concept of ET management requires innovative and policy-oriented supporting tools. Figure 3 provides a conceptual framework highlighting that a clear distinction should be made between understanding and monitoring the past and the current situation on the one hand, and pro-active planning using modeling tools, on the other hand.

In terms of monitoring ET, special emphasis should be placed on remote sensing. One could safely claim that remote sensing is the only tool available nowadays to monitor ET over large areas.

Over the last decades, various ET algorithms have been developed to make use of remote sensing data acquired by sensors on airborne and satellite platforms. The reported estimation accuracy of various methods varied from 67 percent to 97 percent for daily ET, and greater than 94 percent for seasonal ET, indicating that these methods have the potential to estimate regional ET accurately (Gowda et al. 2008). Only in the last decade have these tools made the transition from research to application. In particular, the SEBAL approach, introduced in 1998 (Bastiaanssen et al. 1998), and some successors (SEBS: Su 2002; METRIC: Allen et al. 2007), have been influential in promoting acceptance of these remote sensing approaches into operational and strategic decision support systems.

All policy should be based on comparing different options (interventions) for the future, and requires appropriate planning tools in the form of simulation models (Droogers and Kite 1999). Over the last decades, models have been used successfully to support policy making by first improving the understanding of processes, and then by conducting scenario analyses. The main reason for the success of models in promoting the understanding of processes is that they can provide output over an unlimited time-scale, at an unlimited spatial resolution, and for sub-processes that are difficult to observe (for example, Droogers and Bastiaanssen 2002). The most important benefit of applying models, however, is their use to explore different scenarios. These scenarios can capture aspects of the water management system that cannot directly be influenced, such as population growth and climate change (Droogers and Aerts 2005). These model outputs are often referred to as projections. In contrast, management scenarios or interventions can be simulated where water managers and policy makers can make decisions that will have a direct impact. Examples of the latter are changes in reservoir operation rules, water allocation among sectors, investment in infrastructure such as water treatment or desalinization plants, and agricultural/irrigation practices.

A huge number of hydrological models exist, and applications are growing rapidly. The number of pages on the Internet including "hydrological model" is over 300,000 (Google, November 2008). Using the same search engine with "water resources model" results in 13 million pages. Therefore, a critical question for hydrological model studies is related to the selection of the most appropriate model. One of the most important issues to consider is the spatial scale to be incorporated in the study and how much physical detail needs to be included. Figure 4 illustrates the negative correlation between the physical detail of a model and the spatial scale of the application. This figure also indicates the position of commonly used models in this continuum.

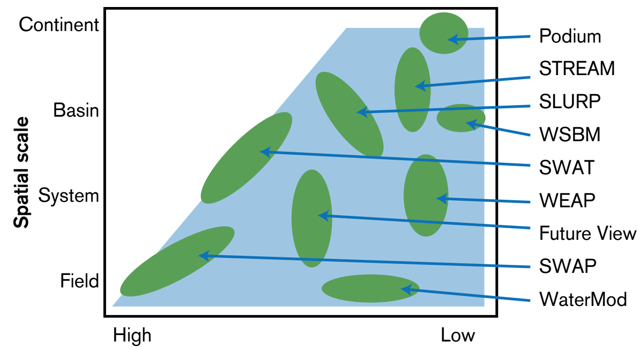
Examples

Several projects started over the last years take ET into consideration as a key component of the overall objective to improve water management. Three of these projects will be summarized in the following sections. They are China's Hai basin, Egypt's Nile basin, and a hypothetical basin derived from a real situation in northern Africa.

China's Hai Basin

The Hai basin in the People's Republic of China is experiencing groundwater overdraft, resulting in dropping groundwater levels and water shortages. The water balance shows a non-sustainable situation, with more water leaving the basin than entering it. Outflow from rivers in the Hai basin barely reach the Bohai Sea, and most of the water leaves the area through evapotranspiration.

Figure 4. Spatial and Physical Detail of Hydrological Models



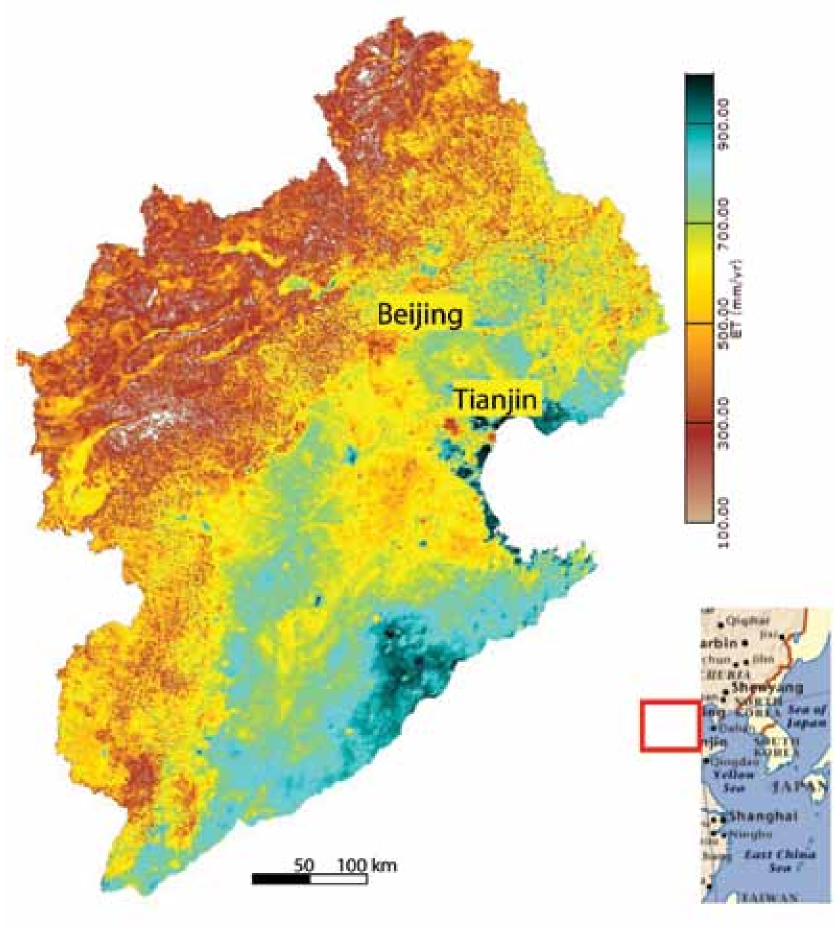
Although much information is available on agricultural water allocation to individual fields, information on real water consumption (actual ET) is lacking. Moreover, water consumption at the basin scale is essentially unknown. The aim of the GEF World Bank project "Hai Basin Integrated Water and Environment Management Project" is to manage ET to restore groundwater levels and maintain outflow to the Bohai Sea (Bastiaanssen et al. 2008).

In this project, ET from the Hai basin is calculated using remote sensing measurements. Based on these observations, allocation plans for each county are under development. Future scenarios to reduce evapotranspiration are being explored by using various modeling tools. A typical example of some of the policy-supporting tools is the basin-wide water consumption map shown in Figure 5. This map has been aggregated per county and is currently used to define water quotas. An innovative aspect is that these quotas will not be based on allocations, but on real water consumption (actual ET). A major advantage of this approach is that allocations that yield return flows to downstream counties are not considered as consumption.

Various modeling tools have been set up to support county water managers in the development of plans to reduce ET. Figure 6 shows an example of exploring the impact of an intervention. This example shows the impacts on ET and groundwater of reducing irrigation by 50 percent.

The Hai basin project was ongoing in 2008, but the uptake of the concept of ET management is impressive. Chinese policy makers and water managers have developed their

Figure 5: Actual Annual Evapotranspiration (2002) for the Hai Basin



own remote sensing applications and suite of models to focus on real consumption rather than on allocations.

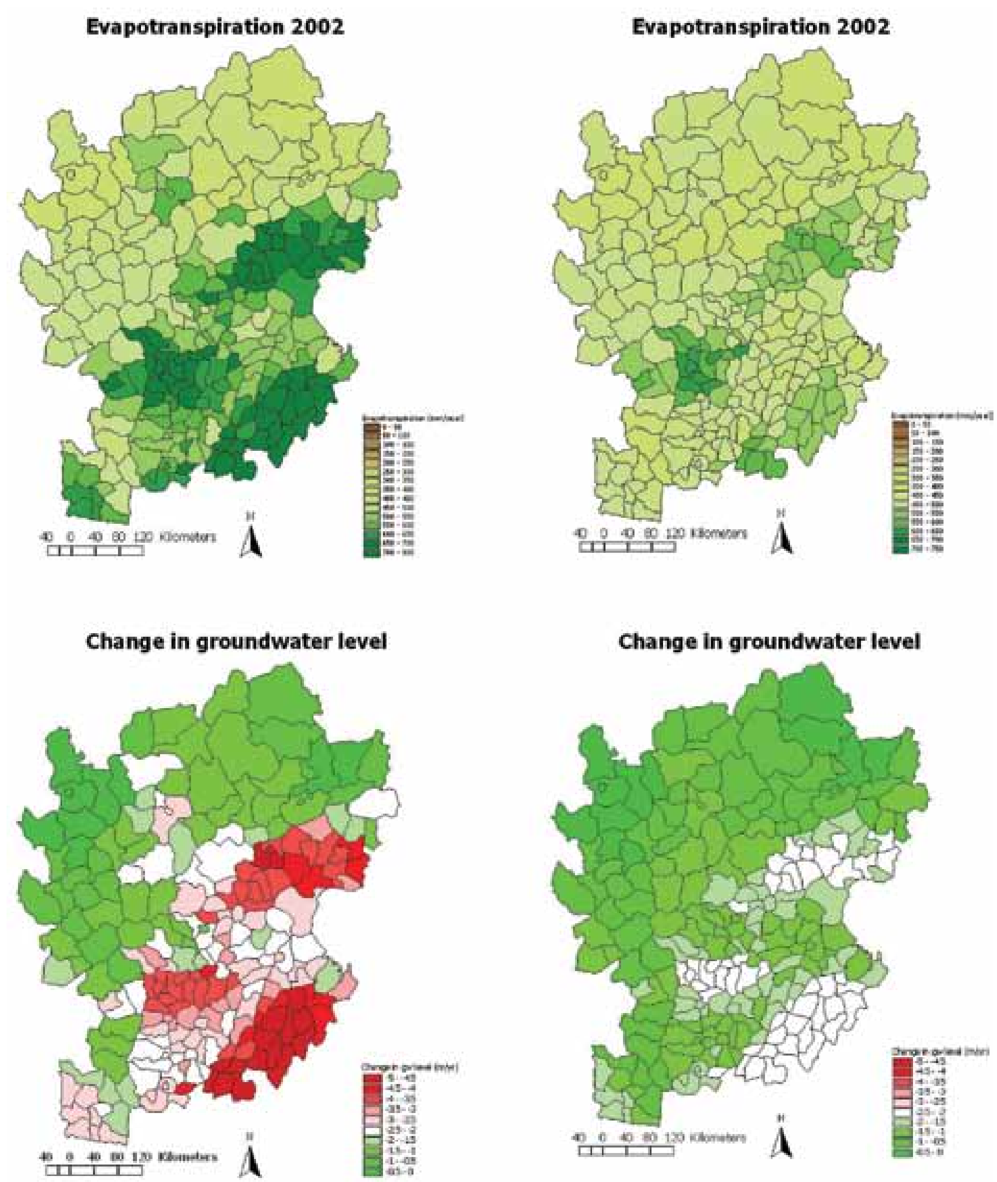
Egypt's Nile Basin

Debates on the actual water balance of the Egyptian part of the Nile basin have persisted over decades. The political sensitivity of the Nile Water Agreements of 1959 has made it virtually impossible to obtain realistic numbers on actual consumption. The agreed 55.5 km^3 entitlement is often equated to the total amount of water consumed. However, expansion of irrigated areas, large amounts of uncommitted flows to the sea, and water savings attempts have made the situation even more confusing. The main problem is that no information at all on real water consumption (actual ET) has been available.

A recent study (Droogers et al. 2008b) combined various completed studies focusing on the main question: How much water is actually used in contrast to the amount of water that is allocated? The cornerstone of the analysis was remotely-sensed ET estimates of the Nile (Bastiaanssen et al. 2003; Noordman and Pelgrum 2004).

Figure 7 shows the actual ET over the entire Nile Basin in Egypt for one particular year (2007). By using comparable information from other years, the long-term actual ET for irrigated lands is estimated at 32 km^3 y-1, while ET from non-irrigated areas (mainly from seepage) is about 8 km^3 y-1. Actual water allocations over the last decade, as recorded at Aswan, are higher than the 55.5 km^3 entitlement, and are on average 68 km^3 per year. Table 1 shows water balances for the entire Nile basin based on these figures and including some other data sources. The study showed that focusing on real water consumption, based on unbiased non-political estimates from remote sensing, provides decision makers

Figure 6: Scenario Analysis Applicable to Counties in the Hai Basin, China



Impact of Reducing Irrigation by 50 Percent (right) Compared to the Current Situation (left) on ET (top) and Groundwater (bottom)

with the necessary information to discuss the Nile water resources.

Scenario-Based Modeling

As indicated earlier in this paper, various modeling tools exist ranging from completely physically-based models to conceptual allocation models. Policy makers require models that have a focus on scenario analyses, rather than models that are too complex to use for practical applications. There are too many modeling studies where the final conclusion is that the model is able to mimic reality. Moreover, in many cases relative model accuracy (comparing model baseline with model scenario) is much higher than the actual accuracy (comparing model to observations) (for example, Bormann 2005; Droogers et al. 2008a).

Droogers and Perry (2008) demonstrate concepts of scenario analysis for a hypothetical basin, derived from a real situation in Northern Africa. The hypothetical basin comprises four catchment areas and two irrigation systems, one upstream and one downstream in the basin

Figure 7. Actual Evapotranspiration for 2007 in the Nile Delta Based on Remote Sensing

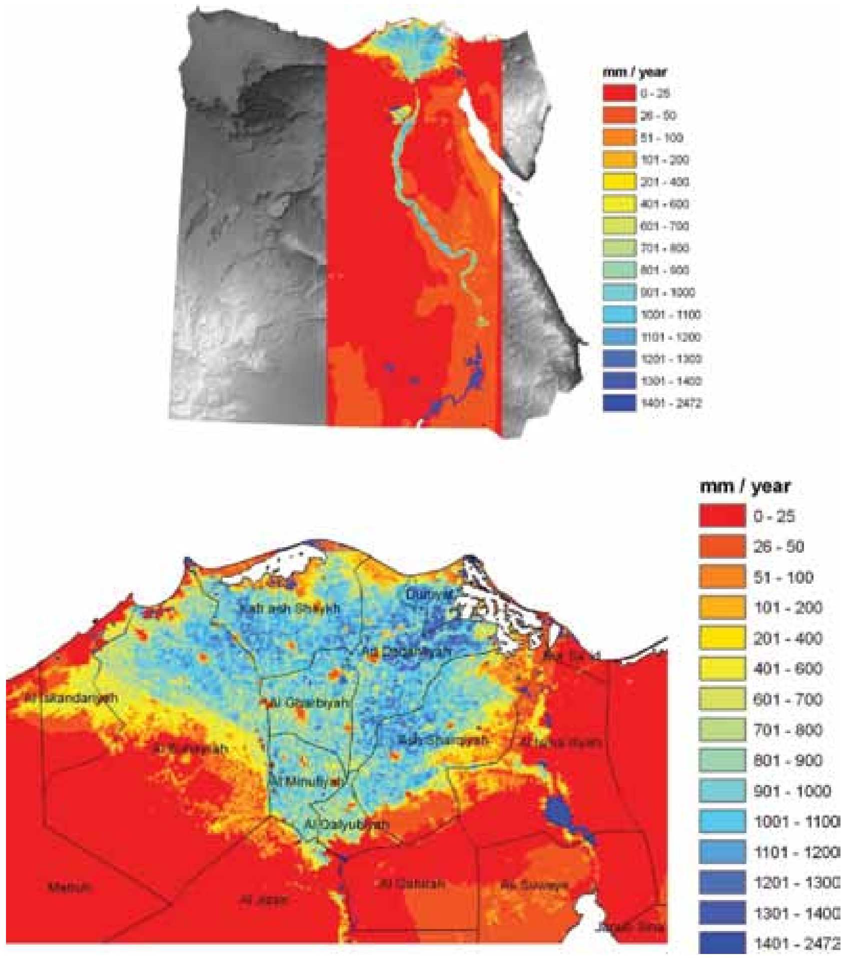


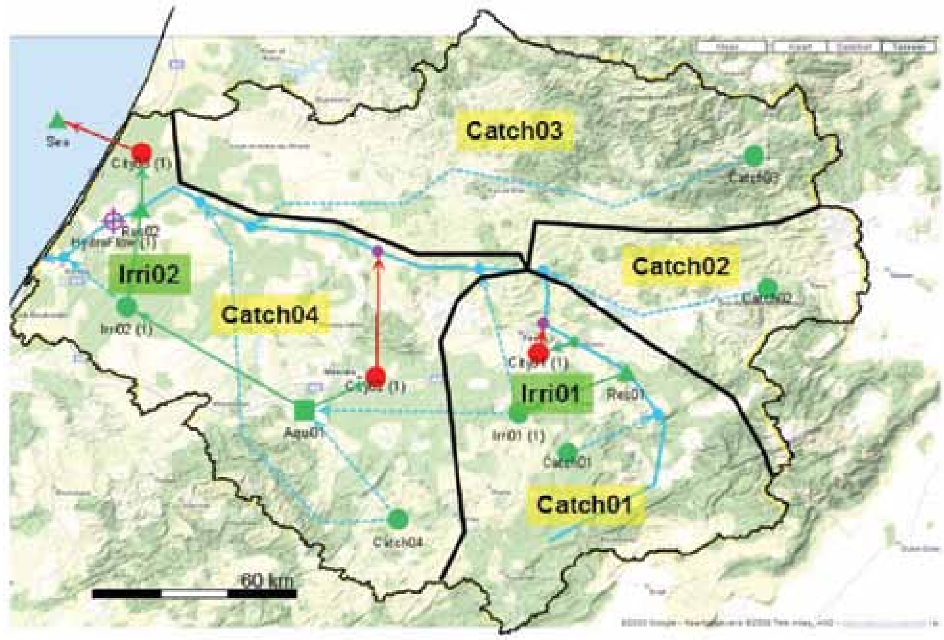
Table 1. Estimated Water Balances in the Nile Basin in Egypt (For a Representative Year Under Current Conditions)

In (km^3)		Out (km^3)	
Outflow Aswan	68.0	ET irrigation	32.0
Rainfall	0.5	ET other	8.0
		Industry/domestic	1.0
		ET seepage	2.3
		Outflow to sea (rest)	25.2
Total	**68.5**	**Total**	**68.5**

(Figure 8). Groundwater tables in the basin are dropping at alarming rates and interventions are discussed to improve the efficiency of the irrigation systems. The latter are based on observations that the efficiency, defined as the amount of water allocated to a system divided by the uptake of plants, is approximately 50 percent. Based on this number, it was concluded that a huge amount of water could be saved.

However, a first basin-wide analysis showed that by far the major consumers of water in the basin are forests and natural vegetation. Actual evapotranspiration from irrigated crops is about 20 percent of overall ET in the basin. Since managing ET from forests and natural vegetation is difficult, the focus here remains on irrigated agriculture. Note that managing non-irrigated water consumption has been under debate for reforestation projects, as in many cases these new forests consume more water by ET compared to the original vegetation (Calder 1999).

Figure 8. Hypothetical Basin Including the Four Catchment Areas



Considering only the irrigation sector, it is important to evaluate the different locations of the two irrigation systems in the basin. Irri01 is located upstream and outflow of this system might be reused downstream, while outflow of the downstream system is lost from the basin. The water balance of the two systems is depicted in Figure 9, indicating that about 50 percent of the incoming water (irrigation and rainfall) is consumed by ET. In terms of water saving programs, it is important to recognize three different outflow components:

- beneficial outflow: crop transpiration
- non-beneficial outflow: soil evaporation, drainage (downstream)
- reusable outflow: percolation (upstream), drainage (upstream)

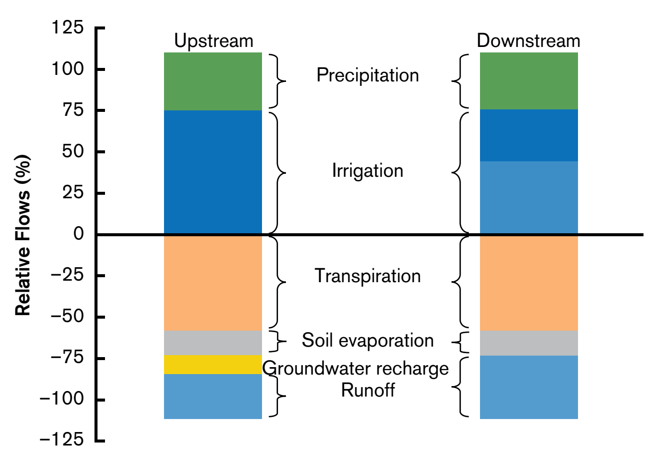
By estimating these three terms, different interventions for the upstream and the downstream irrigation systems can be assessed to obtain the real water saving.

The Way Forward

The main message conveyed in this paper is summarized by the following four points:

- Evapotranspiration should be considered as the main consumer of water, in the same way as rainfall is regarded as the only source of water.
- Irrigation should always be considered in a location-specific (basin) context.
- Remote sensing data can support policy making by evaluating current and past water consumption (ET).
- Simulation modeling supports policy making by evaluating different scenarios (interventions).

Figure 9. Water Balance of the Two Irrigation Systems

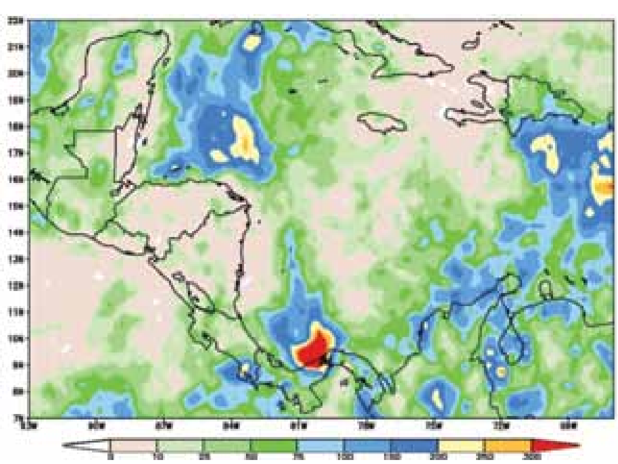


In practice this means that projects should include an evaluation of the full hydrological cycle considering the appropriate domain. The preferred domain in this respect is not the irrigation system but a hydrological (sub) basin. In cases where the entire basin is not considered, one should understand the upstream and downstream interactions of the domain under study.

Policy supporting tools should include a combination of remote sensing and simulation models. A somewhat unexplored subject is the role that remote sensing information can play in calibrating models (Immerzeel and Droogers 2008). Currently, model development has progressed to the extent that further development is hardly required for practical applications; the main challenges are in obtaining the data and information necessary as inputs to these models (Immerzeel et al. 2008). Typical examples of remote sensing products that have emerged recently to the benefit of user groups include (1) actual rainfall provided by the TRMM satellite, (2) actual ET information available on a near real-time basis, and (3) changes in groundwater observed from space using the GRACE satellite (Figures 10, 11, and 12).

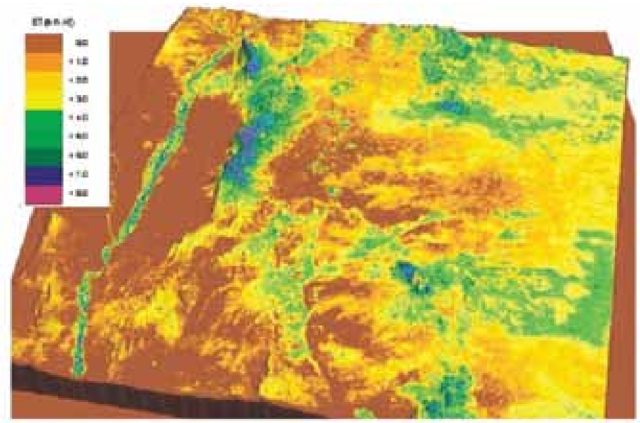
This information is essential to obtain realistic model outputs that can be used to explore the impact of interventions. A typical example of such an approach is the ongoing IFAD project in Kenya on Green Water Credits (Dent and Kauffman

Figure 10. Satellite-estimated Precipitation (TRMM) 22–28 October 2008



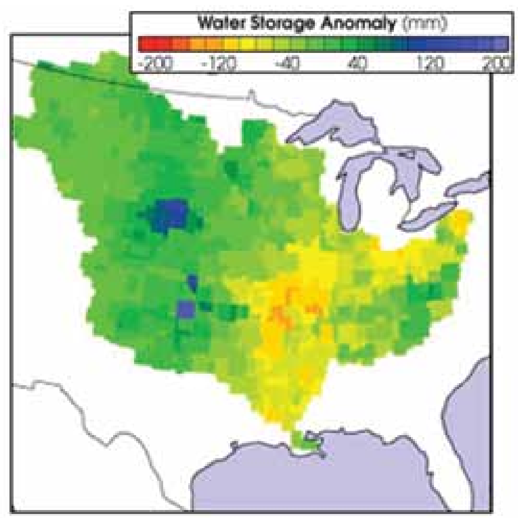
Source: http://trmm.gsfc.nasa.gov

Figure 11. Remote Sensing of Actual ET, Rio Grande, New Mexico, June 16, 2003



Source: Hong and Hendrickx, 2003

Figure 12. Typical Example of GRACE Results Showing Changes in Groundwater for the Mississippi Basin, July 2005



Source: Rodell et al., 2006

2008). By combining remotely sensed information and modeling tools, a much better understanding of the impact of certain interventions on all water related issues, including erosion, can be obtained (Figures 13 and 14). Finally, the phrase by Lord Kelvin “To measure is to know” can be expanded to “To measure ET is to know where to act.”

Figure 13. Scenario Analyses for the Tana Basin, Kenya. Spatial Variation of Increases in Actual Crop Transpiration Under the Enhance Water Productivity Scenario

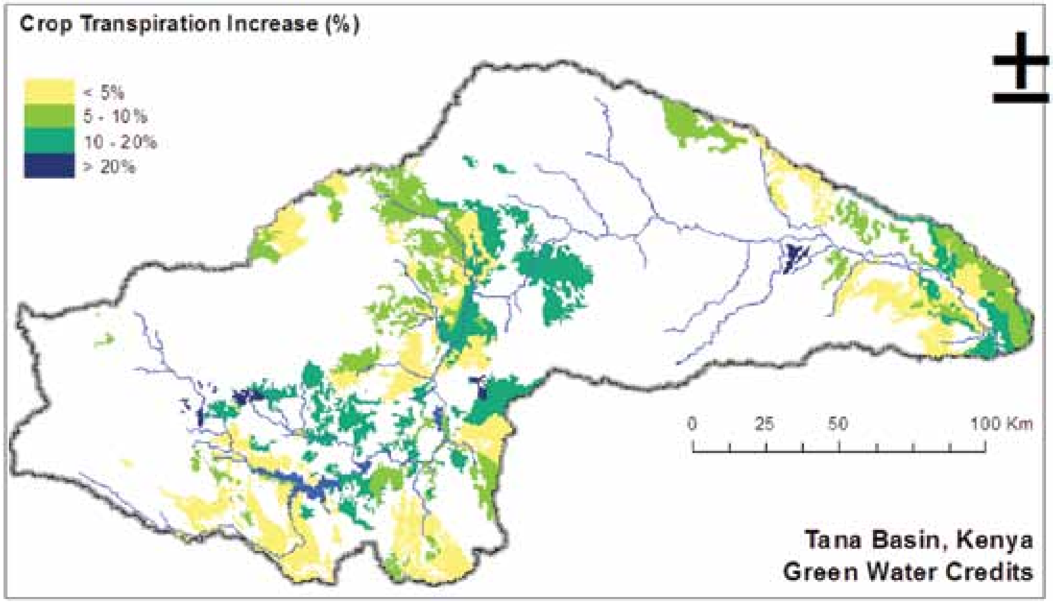
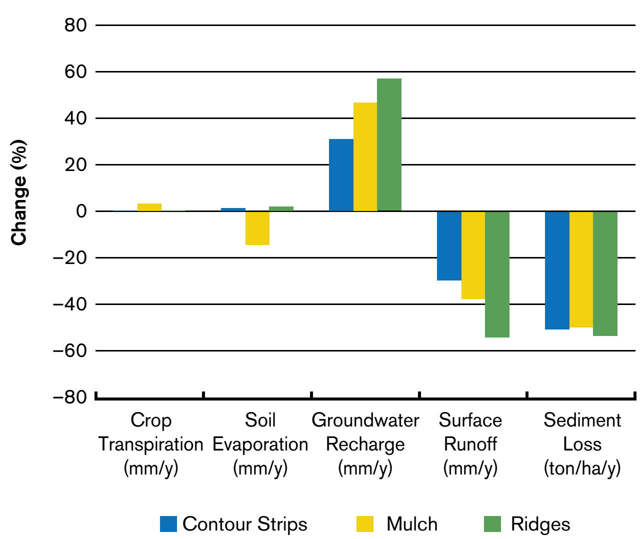


Figure 14. A Comparison of Three Water Management Scenarios in the Tana Basin, Kenya



References

Allen R.G., M. Tasumi, R. Trezza. 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)-Model. ASCE J Irrigation Drainage Eng. Vol. 133, No. 4, 380–394

Allen, R.G., A. J. Clemmens, L. S. Willardson. 2005. Agro-hydrology and irrigation efficiency. ICID Session on Agrohydrology and Efficiency.

Bastiaanssen W.G.M., M. Menenti, R.A. Feddes, A.A. Holtslang. 1998. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. J Hydrol 212–213:198–212

Bastiaanssen, W., E. Noordman, H. Pelgrum. 2003. Monitoring summer crops under changing irrigation practices: A Remote Sensing Study in the North-western Nile Delta for the Irrigation Improvement Project 1995–2002. Report WaterWatch.

Bastiaanssen, W.G.M., W. Bingfang, D. Olson, J. Liping. 2008. Real water savings and ET reduction: the Hai Basin paradigm, Water Front, World Water Council, Stockholm

Bormann, H. 2005. Evaluation of hydrological models for scenario analyses: signal-to-noise-ratio between scenario effects and model uncertainty. Advances in Geosciences, 5: 43–48.

Calder, I.R. 1999. The Blue Revolution, Land Use and Integrated Water Resources management. Earthscan, London, ISBN 1 85383 634 6.

Clemmens, A.J., R.G. Allen. 2005. Impact of agricultural water conservation on water availability. Proceedings of the EWRI World Water and Environmental Resources

Congress 2005: Impacts of Global Climate Change. May 15–19, 2005, Anchorage, Alaska, USA, 14 p.

Dent, D., S. Kauffman. 2008. Green Water Credits: proof of concepts. Report 7, ISRIC, Wageningen.

Droogers, P., A. Van Loon, W. Immerzeel. 2008a. Quantifying the impact of model inaccuracy in climate change impact assessment studies using an agro-hydrological model. Hydrology and Earth System Sciences 12: 1–10.

Droogers, P., C. Perry. 2008. Scenario Based Water Resources Model to Support Policy Making. FutureWater report (in press).

Droogers, P., C. Perry, W. Immerzeel. 2008b. Application of remote sensing in national water plans: Demonstration cases for Egypt, Saudi-Arabia and Tunisia. FutureWater report (in press).

Droogers, P., J. Aerts. 2005. Adaptation strategies to climate change and climate variability: a comparative study between seven contrasting river basins. Physics and Chemistry of the Earth 30: 339–346.

Droogers, P., W.G.M. Bastiaanssen. 2002. Irrigation performance using hydrological and remote sensing modeling. Journal of Irrigation and Drainage Engineering 128: 11–18.

Droogers, P., G. Kite, H. Murray-Rust. 2000. Use of simulation models to evaluate irrigation performance including water productivity. Irrigation Science 19: 139–145.

Droogers, P., G. Kite, 1999. Water productivity from integrated basin modeling. Irrigation and Drainage Systems 13: 275–290.

Gowda, P.H., J.L. Chavez, P.D. Colaizzi, S.R. Evett, T.A. Howell, J.A. Tolk. 2008. ET mapping for agricultural water management: present status and challenges. Irrig Sci 26:223–237

Hong, S.H., J.M.H. Hendrickx. 2003. Spatio-temporal distributions of evapotranspiration and root zone soil moisture in the Middle Rio Grand basin. Presentation at 3rd SAHRA meeting in Tucson, AZ.

Hubbart, Jason (Lead Author); Jim Kundell (Topic Editor). 2008. "History of hydrology." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). <http://www.eoearth.org/article/History_of_hydrology>

Immerzeel, W.W., P. Droogers. 2008. Calibration of a distributed hydrological model based on satellite evapotranspiration. Journal of Hydrology 349: 411–424.

Immerzeel, W.W., A. Gaur, S.J. Zwart. 2008, Integrating remote sensing and a process-based hydrological model to evaluate water use and productivity in a south Indian catchment. Agricultural Water Management 95: 11–24.

Kite, G.W., P. Droogers. 1999. Irrigation modeling in a basin context. Water Resources Development 15: 43–54.

Molden, D. (Ed). 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute.

Noordman, E., H. Pelgrum. 2004. Monitoring winter crops under changing irrigation practices: A Remote Sensing Study in the North-western Nile Delta for the Irrigation Improvement Project 1997/98–2002/03. Report WaterWatch.

Perry, C. 2007. Efficient Irrigation; Inefficient Communication; Flawed Recommendations. Irrigation and Drainage 56: 367–378

Perry, C. 2008. Efficient irrigation; inefficient communications; flawed recommendations? ICID/UEA international seminar—Towards a political ecology of irrigation & water use efficiency and productivity. 6th November 2008. East Anglia. UK

Rodell, M., J. Chen, H. Kato, J. Famiglietti, J. Nigro, C. Wilson. 2006. Be consistent with use of brackets for years. Estimating ground water storage changes in the Mississippi River basin (USA) using GRACE. Hydrogeology Journal doi:10.1007/s10040-006-0103-7

Seckler, David. 1996. The new era of water resources management: From "dry" to "wet" water savings. IWMI Research Report 1. Colombo, Sri Lanka: International Water Management Institute.

Seckler, D., D. Molden, R. Sakhivadivel. 2002. The concept of efficiency in water-resources management and policy. Appendix A. A Note on Transpiration. 2002. In J. W. Kijne, R. Barker and D. Molden, Water Productivity in Agriculture: Limits and Opportunities. CAB International, Wallingford, UK.

Shiklomanov, I.A. 1999. State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris).

Su, Z. 2002. The surface energy balance system (SEBS) for estimation of turbulent fluxes. Hydrol Earth Syst Sci 6:85–99

7. Addressing the Links between Hydrology and Watershed Climate, Soil, and Vegetation

Ignacio Rodríguez-Iturbe
Department of Civil and Environmental Engineering, Princeton University

Abstract

Among the greatest challenges facing sustainable development are those derived from climate change. These challenges are varied and also qualitatively different in character. In carrying out a realistic evaluation of the impact of climate change on ecosystems, it is not sufficient to merely account for changes in mean responses to climatic variability. Changes in the dynamics of less frequent and stronger rainfall events will have larger consequences for the assimilation process and survival of vegetation. An increase in the intensity of rainfall events also leads to other type of ecohydrological consequences especially related to soil erosion. As a result, farming activities are either dramatically reduced or supplanted by pastoral subsistence, constraining sustainable development. This paper focuses on those challenges where ecohydrology will contribute in a most decisive manner to the necessary understanding for their amelioration and management.

Introduction

To begin, it is worth quoting Brown (2006) at length because his words convey a clear picture of the reason why ecohydrologic factors are a central part of regional and global sustainable development.

> "The health of an economy cannot be separated from that of its natural support systems. More than half the world's people depend directly on croplands, rangelands, forests, and fisheries for their livelihoods. Many more depend on forest product industries, leather goods industries, cotton and woolen textile industries, and food processing industries for their jobs.
>
> A strategy for eradicating poverty will not succeed if an economy's environmental support systems are collapsing. If croplands are eroding and harvests are shrinking, if water tables are falling and wells are going dry, if rangelands are turning to desert and livestock are dying, if fisheries are collapsing, if forests are shrinking, and if rising temperatures are scorching crops, a poverty-eradication program—no matter how carefully crafted and well implemented—will not succeed."

It has been well documented (by Diamond [2005], among others) that the fundamental reasons that earlier civilizations declined were tied to the environment rather than directly to the economy. Ecohydrology plays a key role in sustainable development through environmental stewardship.

Ecohydrology is the science that studies the hydrologic dynamics responsible for ecological patterns and processes (Rodriguez-Iturbe 2000). As such, it takes place at the frontiers of environmental sciences where the historically distinct disciplines of biology and physical sciences converge. According to Hedin et al. (2002)," [T]his disciplinary convergence will, over the next several decades, transform our understanding of basic processes that control the stability and sustainability of natural environmental systems. The ensuing findings will have extraordinary implications for our abilities to predict and manage how humans impact the health of ecosystems across local, regional, and global scales. Such knowledge is a critical component of a safe, sustainable, and prosperous future."

Ecohydrologic Implications of Climate Change

It is universally accepted that the world has become warmer during the last 150 years. Moreover, there is ample evidence that global temperature fluctuations are correlated with the concentration of carbon dioxide in the atmosphere. Carbon dioxide and other gases absorb radiation in the infrared spectrum causing a greenhouse effect. Since the light from the sun contains energy in all wavelengths and the radiant heat from the earth is mainly in the infrared spectrum, more energy is kept than is left out, leading to an increase of the atmospheric temperature. This increase in temperature takes place at the global scale and presents large spatial fluctuations which then, directly and indirectly, have enormous ecohydrological impacts.

This paper groups the ecohydrologic impacts of climate change in two large categories that mainly relate to either precipitation or streamflow dynamics (obviously, there are strong linkages and correlations between them). Thus, the impact of temperature changes and the associated fluctuations in precipitation and streamflow in space and time are responsible for a very large number of different types of changes that directly or indirectly affect the sustainability of natural ecosystems. This paper focuses only on the most important ecohydrologic changes.

Precipitation Dynamics and Ecosystem Response

Henson (2006) noted that "[A]lthough it's natural to think of temperature first when we think of global warming, the impact of climate change on precipitation may be even more important in the long run for many places and many people."

The most important impacts arise because of the highly spatially varying fluctuations in rainfall as well as the temporal changes that take place in the seasonality of precipitation. This means that some places will become wetter and others will become drier, but even those places where average precipitation changes only very little are likely to experience serious impacts resulting from changes in the dynamics of the precipitation regime. In 2001, the Intergovernamental Panel on Climate Change reported an increase in precipitation (rainfall and snowfall) of between 5 percent and 10 percent across most mid and high latitudes of the Northern Hemisphere. Although there are regions that will experience decreased precipitation, the important point is that extremes will intensify. In other words, droughts will become longer and more oppressive and storms will be more frequent and intense. Some spectacular events of this type have already been widely reported, including devastating hurricanes like Katrina or droughts like those afflicting Sudan. While changes in many other ecosystems occur more subtly, their consequences are no less serious. There is growing evidence that predicted changes in rainfall regime because of climate change will reduce the primary productivity of ecosystems and induce shifts in community composition as well as loss of biodiversity. In water controlled ecosystems in particular, hydroclimatic variability together with soil and plant characteristics produce the soil moisture dynamics that largely control vegetation conditions. The most important characteristics of hydroclimatic variability are changes in temperature and in the frequency and intensity of precipitation events. Plant productivity is largely controlled by the pulsing and unpredictable nature of soil moisture dynamics, which is itself a result of the characteristic of the precipitation input and the transpiration of the vegetation (Rodríguez-Iturbe and Porporato 2004).

It is crucial to understand that accounting only for changes in mean responses to climatic variability is not sufficient for a realistic evaluation of the impact of climate change in ecosystems. It is necessary to account for changes in the stochasticity of the hydrologic forcing and its possible alterations in terms of frequency and amount of precipitation (Porporato, Daly and Rodríguez-Iturbe 2004). Such alterations are responsible for modifying soil moisture dynamics (that is, intensity, duration, and frequency) of periods of water stress and impaired plant assimilation (Rodríguez-Iturbe and Porporato 2004). An increase in atmospheric carbon dioxide may alone contribute to accelerate photosynthesis, but the accompanying effects of stomata being stimulated to close, the increase in plant respiration, the costs in water transpired, and the higher release of carbon by the bacteria and fungi in the soil, are also highly detrimental to the ecosystem. The matter of water is especially important since a depletion in soil moisture induces a reduction of the plant's water potential. This can, in turn, cause dehydratation, turgor loss, xylem cavitation, stomatal closure, and a reduction of photosynthesis (see, for example, Nilsen and Orcutt 1998). Soil moisture deficits result from the full dynamics, where the infiltration of water depends on the soil and precipitation characteristics as well as on the transpiration from the plant. Soil moisture is thus cause and consequence of plant transpiration. "Even maintaining the same total rainfall, an increase in the intensity of rainfall events, concomitant with a reduction in their frequency, will affect soil moisture dynamics and plant conditions in a manner that depends on the soil and plant physiological characteristics at the site" (Porporato, Daly and Rodríguez-Iturbe 2004).

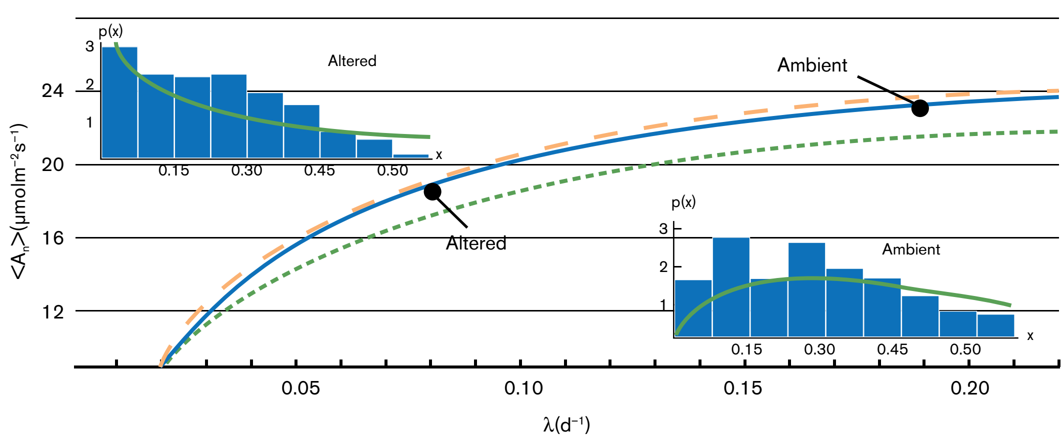
Figure 1 shows a comparison of the experimental results of Knapp et al. (2002) with the theoretical results obtained by Porporato et al. (2004) for the mean daily carbon assimilation rate as a function of the frequency of rainfall events for a constant total amount of precipitation during a growing season. The analysis corresponds to the response of a messic grassland to ambient rainfall pattern versus an artificially increased variability. There is a 20 percent decrease in net assimilation for the altered rainfall conditions when total rainfall was the same but concentrated in fewer events. The analysis also shows that in such a grassland ecosystem the impact on carbon assimilation of a decrease in total rainfall is more pronounced when the decrease is accompanied by a reduction in the frequency of rainfall events (Knapp et al. 2002, Porporato et al. 2004).

The scenario described in Figure 1 may become reality in many areas of the world as a consequence of climate change. Studies being carried out as part of the IPCC's 2007 assessment confirm that many parts of the world show an increase in the fraction of rainfall and snowfall that falls in the wettest 5 percent of all days with precipitation. A helpful manner to quantify such changes for ecohydrological purposes is to estimate the rate of occurrences of days with precipitation during different seasons, as well as the mean depth of precipitation per day during wet days. This is especially useful for the period of the growing season.

Figure 2 shows some results from Franz et al. (2008) for a rainfall station with the longest period of daily rainfall data in the Upper Ewaso Ngiro River basin in Kenya. The seasons analyzed correspond to those of the "long rains," which goes from the beginning of March to the end of May, and to the "short rains" that extend from October to December. In both cases, there is a statistically significant trend in the increase of the mean depth of rainfall during wet days, as well as a decreasing trend in the rate of occurrence of rainy days.

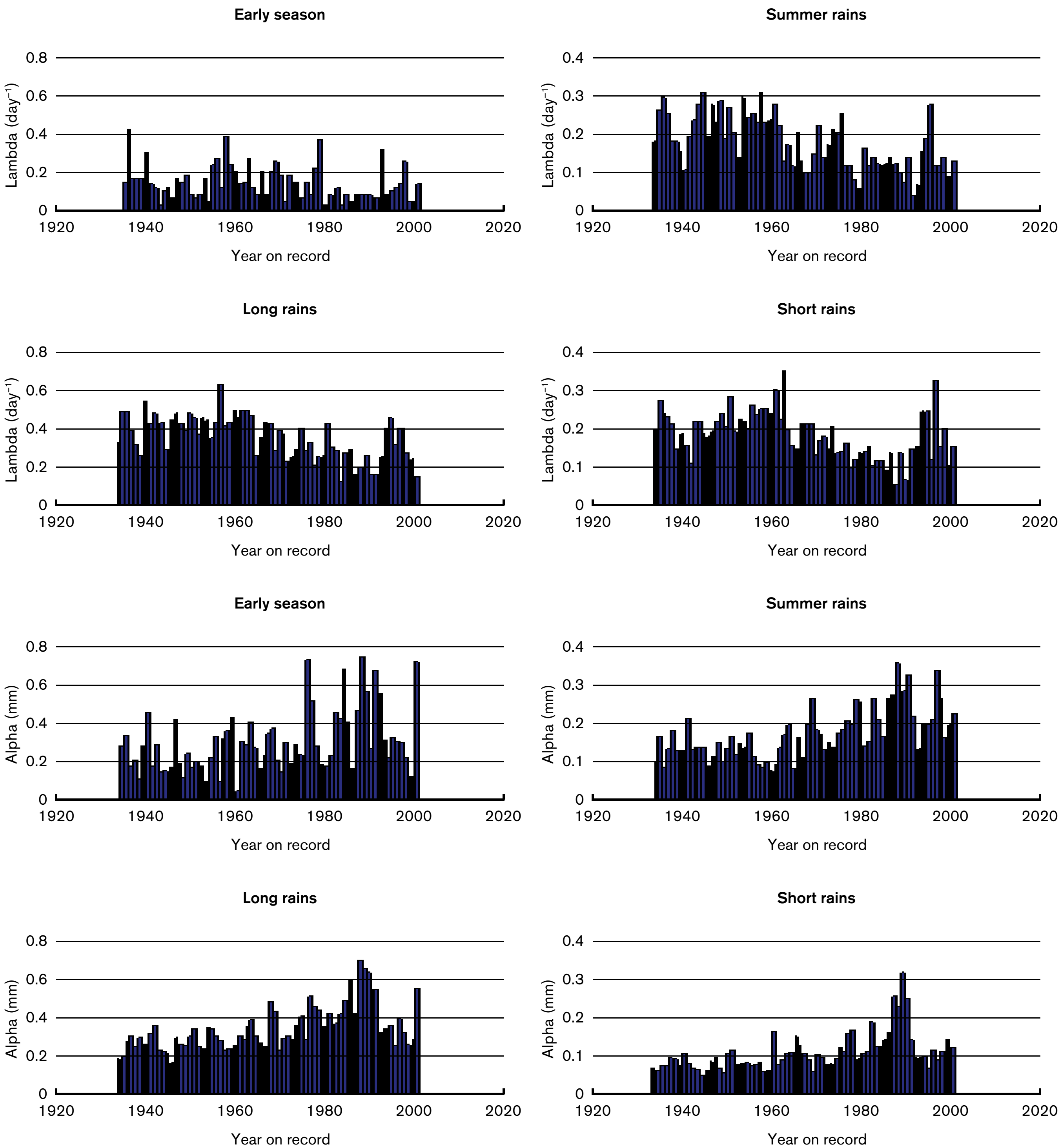
Caylor (2003) shows the mean value and coefficient of variation for the mean annual rainfall along the Kalahari transect in Africa, jointly with the structure of the tree vegetation found along the transect (see Figure 3). It is clear that the very strong gradients in rainfall are accompanied

Figure 1. Rainfall Dynamics Has Dramatic Impact on Net Assimilation



Source: Porporato et al. (2004)

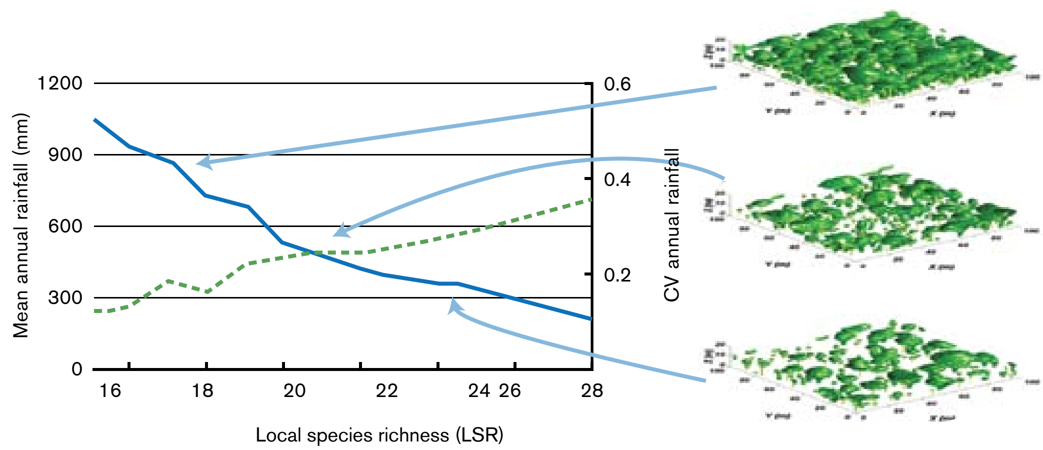
Figure 2. Jacobson Farm; 68 Years of Rainfall Data



Source: Franz et al (2008)

by interannual fluctuations around the average values, which are much stronger for the drier areas of the regional landscape. These interannual fluctuations, accompanied with the changes described above in the dynamics of the daily rainfall events, are key controls for the type of vegetation of the different subregions, as well as for their spatial structure. As mentioned before and described in Figure 1, changes in the dynamics regarding less

Figure 3. Annual Rainfall and Vegetation Characteristics along the Kalahari Transect



Source: Caylor (2003)

frequent and stronger rainfall events will have even larger consequences for the assimilation process and survival of vegetation when accompanied by a decrease in overall precipitation.

An increase in the intensity of the rainfall events also leads to other types of ecohydrological consequences, particularly in relation to soil erosion. For example, a report from the Food and Agricultural Organization (FAO 2002) as quoted in Brown (2006) found that: "Agriculture in Lesotho faces a catastrophic future, crop production is declining and could cease altogether over large tracts of the country if steps are not taken to reverse soil erosion, degradation, and the decline in soil fertility." Brown (2006) goes on to note that "[W]hether the land is in northern Syria, Lesotho, or elsewhere, the health of the people living on it cannot be separated from the health of the land itself. A large share of the world's 852 million hungry people lives on land with soils worn thin by erosion".

Soil erosion leads to loss of vegetation and desertification. Farming activities are either dramatically reduced or frequently supplanted by pastoral subsistence, which provides feedback for further vegetation loss. Thus, sustainable development becomes out of reach.

Soil is the medium in which plants grow and, in turn, plants protect the soil from erosion. Deforestation and soil erosion commonly go together; their impacts are multiple ranging from the occurrence of large disastrous floods to reduction of the recycling sources of moisture from inland regions to the atmosphere. These effects have been amply documented. An important example is the Yangtze River basin, where the flood control services of trees have been evaluated to be worth much more than their value as lumber. Another example is recycling of the evapotranspiration of the Amazonian forest, which constitutes an important fraction of the total rainfall over the inland part of this enormous river basin.

Fire is another specific aspect of great ecohydrological significance in relation to the impacts of climate change. Its frequency and intensity will also be greatly affected by climate change dynamics.

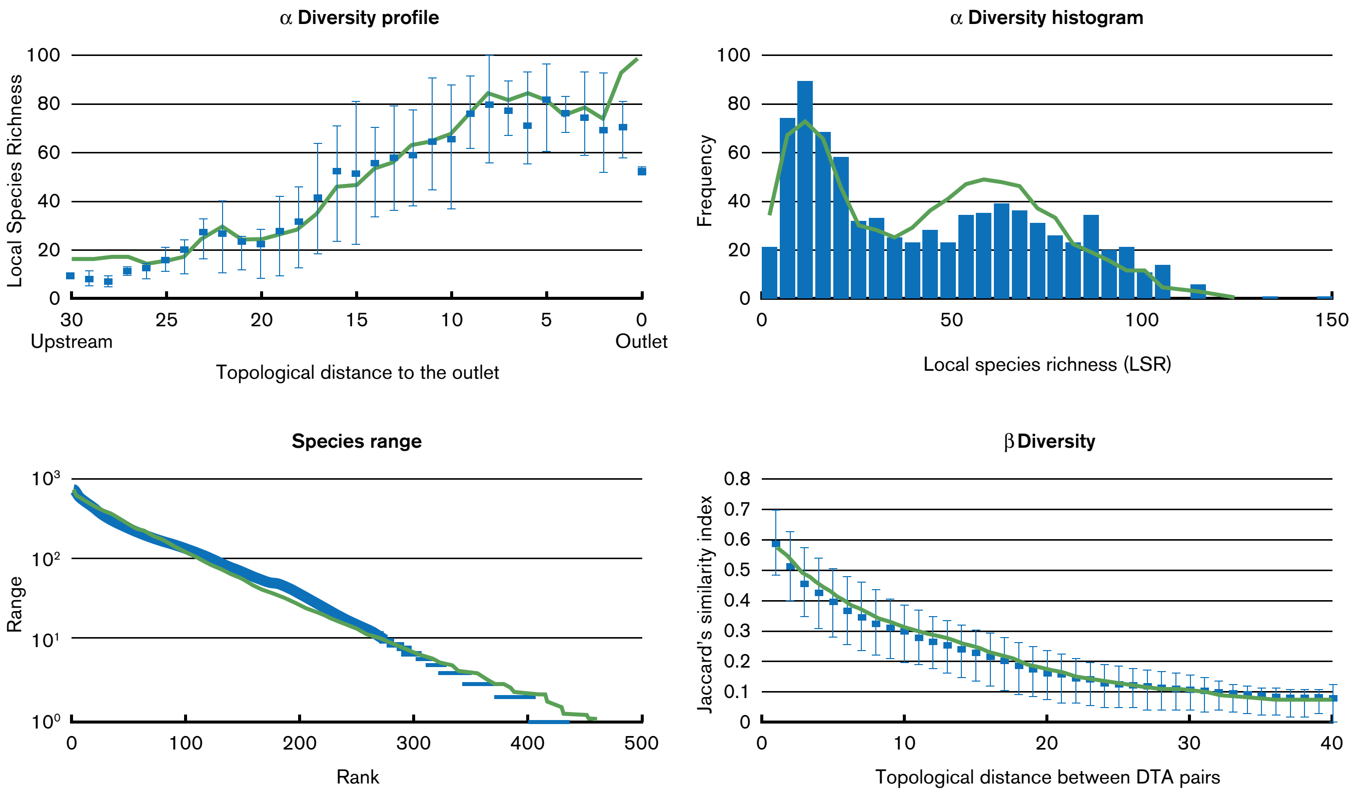
Hydrological Controls of Biodiversity and Impact of Climate Change

Biodiversity is crucially affected by hydrologic conditions both in savannas and in river basin ecosystems.

Muneepeerakul et al. (2008) have recently developed a very simple neutral model that is able to predict the main biodiversity features of both vegetation and fish communities in river basins. Figure 4 shows part of their results for the case of fish biodiversity in the Mississippi-Missouri river system (MMRS).

The local species richness (LSR) as well as the frequency distribution of LSR are extremely well reproduced by a

Figure 4. Data and Model Results of Fish Biodiversity in the Mississippi-Missouri River System



Source: Muneepeerakul et al. (2008)

model with only four parameters. Moreover, the rank-occupancy curve (where the occupancy is given by the number of direct tributary areas (DTAs) where the species is present) is also very well reproduced by the model. Muneepeerakul et al. (2008) measure the between community diversity (or how diversity changes spatially) through the Jaccard's similarity index (JSI), which the model (again) reproduces very well with respect to that found in the data.

Similar results are being presently obtained with an extensive analysis of species of vegetation existing in the MMRS. These results are of great relevance for the study of the possible impacts of climate change on the biodiversity characteristics of ecosystems. Thus, the controlling variables in the results of Munepeerakul et al. (2008) for the case of freshwater fish diversity are: (1) the habitat capacity of the different DTAs (which are a direct function of the freshwater runoff arising from the DTA), and (2) the network connectivity in the river system. Similarly, in the case of vegetation the habitat capacity is controlled by the amount of green water on the DTA.

The impacts of climate change and man-made alterations on the habitat capacity and/or network connectivity can be directly studied in the model of Muneepeerakul et al. (2008). Also, this type of approach allows the identification of crucially important subregions where changes of the previous type will bring the most impacting changes in the biodiversity of the system. This identification will then allow for the optimal organization and planning of conservation campaigns.

Ecohydrological Footprints

D'Odorico et al. (2008) have recently proposed the concept of ecohydrological footprints to quantitatively account for the human impacts on ecosystems resulting from anthropogenic disturbances of hydrologic processes.

The ecohydrological footprint will measure the change in a specific ecosystem function or service caused as result of human intervention on hydrologic drivers.

An example of ecohydrological footprints are the changes in carbon sequestration resulting from the changes in soil/water balance, which in turn result from land use or drainage projects. Another example is the changes in fish or vegetation biodiversity arising from the reduction of habitat capacity ensuing from the decrease of direct contributing runoff in different regions of a river basin (D'Odorico et al. 2008). These changes can be quantitatively measured via models like the one developed by Muneepeerakul et al (2008).

References

Brown,L.,R., Plan B 2.0,W.W. Norton, 365p.,2006

Caylor,K.,Structure and Function of Kalahari Transect Vegetation,Ph.D. Thesis,University of Virginia,2003

Diamond, J., Collapse: How Societies Choose to Fail or Succeed, Viking Press,575 p.,2005.

D'Odorico, P., Laio.,F., Ridolfi,L., Porporato,A., Rinaldo,A., and I.Rodriguez-Iturbe, Ecohydrological Footprints, in review, November 2008.

United Nations Food and Agriculture Organization (FAO),"FAO/WFP Crop and Food Assessment Mission to Lesotho Special Report". FAO, 2002. *www.fao.org*

Franz,T., Caylor,K., Nordbotten, J., Celia, M., and I.Rodriguez-Iturbe, Soil Moisture, Water Stress,and Vegetation Patterns in the Upper Ewaso Ngiro River Basin in Kenya, in review, November 2008.

Hedin,L., Chadwick,O., Schimel,J., and M.Torn, Linking Ecology, Biology, and Geoscience, Report to the National Science Foundation, 2002.

Henson, R., The Rough Guide to Climate Change, Penguin Group,341p.,2006.

IPCC (2001). Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change. Cambridge University Press.

Knapp,A.K.,P.A.Fay,J.M.Blair,S.L.Collins,M.D.Smith,J.D.,Carlisle,C.W.Harper,B.T.Danner,M.S.Lett,and J.K.McCarron. Rainfall Variability,Carbon Cycling,and Plant Species Diversity in a Messic Grassland,*Science*,298,2202–2205, 2002.

Muneepeerakul,R., E.Bertuzzo,H Lynch,W.Fagan, A.Rinaldo,and I.Rodriguez-Iturbe, Neutral Metacommunity Models Predict Fish Diversity Patterns in Mississippi-Missouri Basin,*Nature*,453,220–224, 2008

Porporato, A.,Daly E., and I.Rodriguez-Iturbe, Soil water balance and ecosystem response to climate change, American Naturalist, 164 (5),625–632, 2004.

Nilsen,E.T., and D.M.Orcutt, Physiology of Plants Under Stress; Abiotic Factors, New York,John Wiley,1998.

Rodriguez-Iturbe, I., Ecohydrology: a Hydrologic Perspective of Climate-Soil-Vegetation Dynamics, Water Resources Research,36,3–9, 2000.

Rodriguez-Iturbe,I., and A. Porporato, Ecohydrology of Water Controlled Ecosystems, Cambridge University Press,442p., 2004.

Comments of World Bank Discussants

The comments made by invited World Bank discussants are summarized in this section. These comments reflect the personal experience of the various discussants about the November 2008 workshop topics and presentations, and are included as part of the selected hydrology topics review.

Integrated Water Resources Management

Integrated water resources management (IWRM) is like a nice warm place where everybody would like to go, much like sustainable development and its different aspects. It is something that no one can disagree with, since no one dare say that "disintegrated" water resources management is desirable. However, some challenges can be identified in the main messages that came across from all the presentations.

First, IWRM needs to stop being a buzz word (still the case in many places). Integrated water resources management needs to be placed into operation and implemented. However, this in itself is challenging because IWRM implementation faces hurdles of information, institutions, and capacity. In addition, the effort requires integration across different spatial scales (all the way form a particular use, to a river basin or to the national level), across uses and sectors (especially in cross-sector themes like the environment), and across different institutions (which is probably the most challenging).

Second, there is a need for measurement. It is time to move from *estimation* to the *use* of the information that is available. Moreover, without a system of water rights in place and without appropriate measurements it is very difficult to manage water resources in terms of water use. This challenge needs addressing.

There is another part of water resources management that has not been mentioned; namely, water scarcity. Water scarcity refers to the balance between the supply of and demand for water, as well as water availability and use. Water use refers to how much water is actually being extracted and how much intake is accounted for by different uses. However, water use is seldom monitored or measured.

Within that context and in terms of water use, building and operating infrastructure is also a very important part of water resources management that faces many problems. For example, good plans are usually lacking, operation is not optimized, and multi-purpose operations for flood control, hydropower, water supply, and irrigation are also lacking. The problems facing infrastructure operation are in need of improvement and must be addressed.

The third challenge to IWRM has to do with the question of pollution discharge, something that is not handled very well. Little is usually known about the location of discharge points or how much pollutants they are discharging. Integrated water resource management requires that all the discharges be inventoried, characterized, and controlled.

Finally, there is a need to balance new challenges with old ones using modern approaches, (especially those that have been shown to work in other countries), and those approaches should be institutionalized. It may be in terms of managing existing climate variability or climate change challenges or just managing development challenges. This would include basic management challenges of different types. This could be accomplished with more cross-learning-type of efforts, so that cross-fertilization and learning across different regions becomes a reality.

Climate Variability and Change

The key words in the presentation about hydrology for water systems development and management under climate change were risk and uncertainty, linked to probability and hydro-economics. Uncertainty analysis is not used enough to help evaluate policy and project options and to understand vulnerability to extremes vis-à-vis climate change.

But the one issue that was highlighted in the presentations is the idea of non-stationarity. Especially useful is the typology of intrinsic non-stationarity, but also the non-stationarity issues having to do with measurement and purpose.

Regarding measurement non-stationary, it is clear that in many of the places where the Bank works, data are often an issue and how they are collected remains a challenge. While decades-worth of streamflow data have been collected, discontinuous jumps because of measurement unit errors (rather than because of change in hydrological processes) are still common. There are data inconsistencies as well as problems with how it is collected; in many places, the quality of the data is extremely low. But, the historical record (or whatever synthetic flow series are generated stochastically from the historical record) is all that is available.

Non-stationarity of purpose is more frequent in environments where political leadership changes very frequently. Institutional interests change, and in that environment it is difficult to narrow on the data to focus on future scenarios or converge on the futures of interest, when these may change frequently.

In this sense it may be worthwhile to seek opportunities for longer term institution building. Opportunities to build relationships with experts in the region and to work with bilateral and other regional organizations should be sought in order to gain a broader perspective from people and institutions with a longer term stake in a particular country or region.

Last but not least, it pays to be humble. As knowledge increases, it must be recognized that Bank clients have different perspectives about the Bank's engagement, whether as partners in sector work or potential lenders or even competitors.

Hydrologic Interaction

Hydrologic interactions are complex. The Bank has shown a general interest in learning more about those interactions as well as the various models that can assist in watershed management and planning for practitioners, for Bank clients, and for other stakeholders.

It was very interesting that one of the presentations began by outlining some of the driving forces for modeling that are based on legal or regulatory requirements. In many developing countries, this is a similar situation where a very strong legal or policy framework exists. However, the data are lacking, and so are the capacity, and the institutions to drive their implementation forward. A very important point was made; namely, that hydro information cuts across sciences, economics, policy, and regulation.

A modeling system is required that meets the needs of user of different scales, from a basin down to a sub-watershed or micro-watershed. However, it should be borne in mind that no single model can do it all.

Sedimentation is another issue that is worth exploring further. Sedimentation is good and bad; the question is: good and bad for whom? Clearly, sedimentation is bad for a reservoir operator, but for a farmer in a very productive floodplain, sedimentation is good. So there is a need to balance the interests of these different stakeholders and uses of sedimentation.

The Bank's low involvement in coastal environments is an issue. Attention is mainly focused on environmental flows and making sure there is enough water going down to coastal wetlands and mangrove forests, but the issue of the water's quality and chemical constituents needs to be explored further.

Finally, the biggest innovation on the issue of evapotranspiration may be the existence of all the technologies from satellites and other remote sensing equipment for Bank clients to use. There is a real opportunity to leapfrog knowledge instead of having to spend huge amounts on developing a database from scratch. Maybe some judicious mix of ground truth data plus satellite images would be the better approach in terms not only of continuity, but also of accuracy and of the types of decisions that many of the clients face.

Associated Changes in Climate and Land Use

The very good presentation on ecohydrology, climate, and ecosystem response made three very pertinent points. One was that the focus of the effects of climate change in water resources should be on precipitation and streamflow, rather than temperature. Another pertinent point was the need to have a better understanding of how precipitation could change over time, and the impacts this could have on biodiversity. Finally, the presentation noted that it is important to look at shifts in precipitation that will result in shorter but perhaps more intense periods of rainfall. This is very relevant to regions that have short, intense monsoon seasons. In watershed management it is important to capture the surface water and deal with groundwater to support people over the dry season.

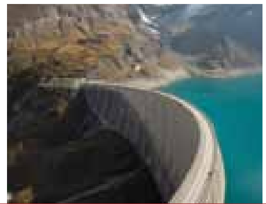
Talking about climate change that is going to affect the livelihood of people 20 or 30 years from today on an average basis seems like a big assumption in areas that are not even able to use what they are receiving on a daily basis. There is a need to do more to find ways to operationalize climate change consequences on water resources at appropriate spatial and temporal resolutions.

Selecting the right model has become a task in itself given the large number of such models in the field. No single model can solve all water resources problems. Model selection should be dictated by the problems at hand, availability of data and capacity of model users. The type of problems faced should lead to selection of the most appropriate models. Similarly, availability of data to calibrate the model and calibrate model parameters, and also the capacity of end users at the end of model development should help zero in on most appropriate models.

HEF

Hydrology Expert Facility

Hydrology and Water Resources Advisory Service



What we do

HEF assists in addressing complex hydrology and water resource management problems by providing short-term expertise on-demand

How we do it

Support is focused on specific issues, situations or problems in connection with the different stages of the Bank project cycle

HEF services

- **Operations support:** Expert advice for short assignments from a roster of more than 150 hydrologists/water resources experts
- **Expert panel:** High level 6 member panel for advisory role and application of cutting edge technology and approaches
- **Dissemination and learning:** Technical events in collaboration with thematic groups
- **Publications:** Publications include Mission Briefs and HEF Notes

Sample areas of support

- Integrated water resources development and management, including hydropower
- Watershed management modeling
- Hydro meteorological risk management
- Water quality, wastewater disposal alternatives and design of underwater outfalls

How to request HEF support

Task Team Leaders/members from the regions submit a short form describing the general characteristics of the assignment and its contribution to Bank business development

HEF in action: Some examples

Water Quality

Study of wastewater disposal alternatives in Rio de la Plata, Argentina; review and design of underwater outfalls in Baku Sea, Azerbaijan and Lake Titicaca, Bolivia.

Risk Management

Hydrologic analysis for regional and urban flood management in Ghana and Jakarta, Indonesia; strengthening of real-time hydrology forecast capabilities in Albania and Moldova.

Hydropower

Hydropower downstream impact analysis in India; water-energy linkage analysis in Central Asia.

CONTACT US

Gabrielle Puz
gpuz@worldbank.org
+ 1 (202) 473-9973

Luis Ernesto García
lgarcia@worldbank.org
+ 1 (202) 458-1897

Susanne Scheierling
sscheierling@worldbank.org
+ 1 (202) 473-7276

THE WORLD BANK

Water Sector Board

WATER PARTNERSHIP PROGRAM

http://intranet.worldbank.org/WBSITE/INTRANET/SECTORS/INTWAT/0,,contentMDK:21907421~menuPK:5317783~pagePK:210082~piPK:254376~theSitePK:4602115,00.html

WATER
PARTNERSHIP
PROGRAM

1818 H Street, NW
Washington, DC
202.123.4567
www.worldbank.org/water/wpp

THE WORLD BANK

bnwpp
Bank-Netherlands
Water Partnership Program