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Environmental Water Needs and Impacts of Irrigated Agriculture in River Basins

A Framework for a New Research Program

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International Water Management Institute

FUTURE HARVEST
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Abstract

The intention of this paper is to develop a framework for a new IWMI research program on environmental water requirements of aquatic ecosystems and environmental aspects associated with irrigated agriculture in river basins and wetlands. The program will be implemented primarily in the context of developing countries, but the paper also examines research questions, which are of general importance for eco-hydrology and environmental water resources management. At the same time, it does not purport to be a comprehensive coverage of the environmental water research field but is designed primarily for attention of specialists dealing with wetlands, water resources management and sustainable agricultural development within sister CGIAR centers and other similar international agencies. It is envisaged that some ideas for future research presented in the paper will also be of interest to hydrologists and ecologists engaged in developing the concepts of environmental water requirements of aquatic ecosystems. The introduction of the paper sets up the purpose of the document. This is followed by a description of a framework, which links different levels of water resources use and conservation of natural aquatic systems with various management interventions. The main focus areas of the proposed research are then discussed. They include estimating water requirements of aquatic ecosystems, evaluating scenarios of development and impacts of irrigated agriculture on rivers and wetlands, allocating water with the consideration of environmental thresholds, etc. The paper also discusses possible research activities, which are associated with these focus areas and presents examples of specific research projects that could be pursued internally or in partnership with other national and international institutions.

Introduction

Malin Falkenmark calls “the inability to link environmental security, water security and food security” the greatest water problem of our time (Falkenmark 2001). The trade-off between freshwater for basic human needs, food production and maintenance of the freshwater ecosystem is already on the agenda in many countries of the world, particularly those with limited freshwater resources. The International Water Management Institute (IWMI) is at the forefront of research that brings “more crop per drop.” At the same time, it promotes a worldwide Dialogue on Water for Food and Environment and develops new research initiatives specifically focusing on environmental water needs and environmental aspects of agricultural development in river basins.

The purpose of this document is threefold:

- To illustrate the place and importance of environmental water requirements in the context of water resources management in river basins.

- To attract more attention of the agricultural research community to problems associated with environmental water management in river basins and ecological aspects of agricultural development. While general awareness of these problems certainly exists, their range, technical aspects and associated complexities are frequently underestimated.

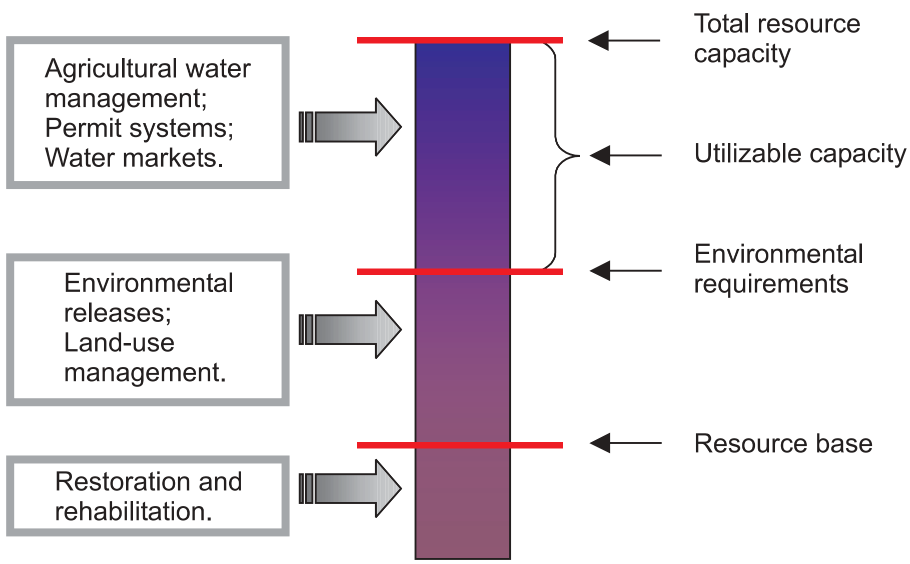
- To develop a layout of an internal research program on environmental water requirements and management in river basins, which could be used as a basis for developing full research proposals, for further identification of research needs and priorities (particularly in the context of developing countries), as well as for establishing research partnerships.

It is also expected that interested researchers, primarily within IWMI and CGIAR, may assess the suitability of some of these concepts against their interests and capabilities. The document is focused primarily on technical issues but it is envisaged that addressing them will have a direct effect on policy development and decision making.

The document suggests a general framework, which intends to link research on agricultural water management with that on environmental water requirements of aquatic ecosystems. It further explores the major possible focus areas, which could be pursued independently or in partnership with external research groups and also suggests a few groups of relevant research activities. This separation is rather arbitrary but, in general terms, the first is intended to suggest what should be done while the second is intended to determine how it may be done. Multiple boxes contain descriptions of specific research problems or potential research projects.

In very general terms, the relationships between different levels of water resources use and conservation of aquatic environment, on the one hand, and appropriate policies and management measures on the other are illustrated by figure 1. Thresholds of water resources use and conservation are shown on the right-hand side of this diagram, while examples of management measures applicable at or between different thresholds are presented in boxes on the left-hand side of the diagram. A brief explanation and interpretation of various components of this diagram are given below.

Figure 1. Thresholds of water resources use and conservation with examples of corresponding management measures.



Every aquatic ecosystem (river, wetland, aquifer, etc.) may be characterized by its *total resource capacity* (figure 1). For a river catchment, this capacity may be represented by its Mean Annual Runoff (MAR), which reflects the natural (undisturbed, predevelopment) catchment conditions. For lakes and certain types of wetlands, this capacity may be represented by the mean annual volume of water in a lake (wetland). The concept of total resource capacity is, in fact, equally applicable at the scale of a specific aquatic ecosystem, and at the scale of a country, geographical region or the entire world.

Every aquatic ecosystem requires a certain amount of water to maintain its ecological integrity. The question "How much water does a river (wetland, estuary, etc.) need?" is a subject for ongoing debate and intensive research in the world, particularly over the last two decades. This research has already had a significant impact on environmental policy development in many countries, especially those with arid climates and/or limited water resources (Australia, South Africa). The impact of this research worldwide is continuously increasing. In very broad terms, *environmental water requirements* of an aquatic ecosystem may be defined as the quality and quantity of water for protection of the structure and functioning of an ecosystem in order to ensure ecologically sustainable development and utilization of water resources. Environmental water requirements may have different thresholds, associated with different levels of possible ecosystem degradation. The lowest of these may be called a *resource base* (figure 1)—an ecological threshold, below which an aquatic ecosystem experiences severe, often, irreversible changes.

The difference between total resource capacity and environmental water requirements represents *utilizable capacity* of the resource (figure 1). It is ideally only this portion of water, which could be put to multiple use and which multiple users, including agriculture, should compete for. It is here that such measures and programs as user registration, development of *permit systems, water markets, better management of agricultural water* for increased productivity and efficiency, etc. are of vital importance.

Environmental water requirements have to be established using available scientific knowledge and experimental evidence. Research into eco-hydrology and aquatic ecology has resulted in a number of estimation methodologies, detailed descriptions of which may be found in many comprehensive reviews (Tharme 1996; Durban et al. 1998). The methodologies have been developed for different types of aquatic ecosystems, such as rivers, aquifers, estuaries and wetlands. The existing methods range from quick and simple assessments, where environmental water thresholds are defined in terms of the status of aquatic habitat and expressed as a percent of MAR (Tennant 1976) to comprehensive assessments, which may take as long as a year or two to complete (King et al. 2000). The simpler methods are largely based on available hydrological information whereas detailed ones require collection of significant amounts of ecological data.

Environmental water requirements should not be understood as just “water for bugs” or “water for fish” or the like. Most of the promising currently available techniques pay attention to multiple aspects of ecosystem functioning and services, including maintenance of the geomorphology of river channel and floodplain, fish and bird diversity, aquatic vegetation, water quality, recreational water use, etc. At the same time, even water requirements of any of these components individually have a very clear social and economic content. For example, maintenance of certain flows in rivers may be directly associated with river fisheries, which sustain food security and livelihoods of millions of poor people in developing countries.

It is also important to note that environmental water requirements are now often considered to have priority over other water uses. The emphasis is gradually shifting from “a river is also a water user” type of attitude to the “water in a river is a resource for multiple uses and has to have an untouchable reserve.” In some countries (e.g., South Africa) this principle has received the status of a national water policy and is currently being implemented. This certainly has very important implications for future development of irrigated agriculture and management of agricultural water already in use.

In reality, in many river basins over the world, environmental water requirements have never been estimated or set. Water resources use in many catchments and countries has already reached levels that are hardly compatible with environmental thresholds, even if the latter are set as low as the resource base. If a water resource is overutilized to that level and/or severely degraded, the *rehabilitation/restoration measures* may be applied, where feasible (figure 1). If the resource is utilized to the levels above the resource base, but below the established or perceived healthy environmental thresholds, it is necessary to implement management measures, which ensure that no further degradation will occur in this aquatic ecosystem. This could be a *plan of environmental flow releases* (in case of a regulated river) *or a land-use management plan*, which ensures that the effects of streamflow reduction activities upstream are minimized, etc. (figure 1).

Figure 1 rather represents a framework for understanding the context in which environment and irrigated agriculture are likely to coexist in the future. The differentiation between management interventions on the basis of where they apply is certainly rather arbitrary. For example, restoration/ rehabilitation measures may need to be and are applied also at much lower levels of resources use and, therefore, above the resources base. Also, operating rules for environmental release are necessary to ensure that environmental water requirements downstream (if they are set) are actually met; consequently, this management intervention "operates" in the section of utilizable capacity as well. Therefore, figure 1 is not intended to be comprehensive and is presented here to set a general framework for further discussion in this document.

Possible Focus Areas of Research on Environmental Aspects of Irrigated Agriculture in River Basins

Each element of the framework discussed above has a number of associated research issues. These issues are grouped below into major focus research areas, which could be pursued by IWMI, independently or in partnership with other research institutions.

Environmental Water Requirements of Aquatic Ecosystems: Concept Development

This focus area relates to the development of methods for scientific estimation of the threshold of environmental requirements shown in figure 1. This research has been developing rapidly in the last decades and as already mentioned above, a number of methods of different complexity, information requirements and purposes have been suggested. But multiple research gaps will still need to be filled. Two important considerations pertain to this area of research, particularly from IWMI's perspective.

- The existing methods to estimate environmental water requirements have all been developed in countries and for countries that possess a reasonable hydrological expertise and information, a track record of research in aquatic ecology and an understanding of the necessity to protect aquatic ecosystems. Most of the developing countries in Asia and Africa are forced to develop their irrigated agriculture to alleviate hunger and poverty. To this end they had little exposure to such methods and made little or no use of them at the policy level. The consequence of this is that available resources are, often, being developed to the levels of severe degradation and total utilization. There are cases when such methods are required in the developing world, for example, when environmental flows need to be determined for national parks to ensure the continuous income from tourism. In such cases, however, only crude environmental flow methodologies are likely to apply, as information available will still be limited. Consequently, *it is necessary to focus on developing methods, which are parsimonious, in terms of required input information, and which could, therefore, be appropriate in the context of developing countries*.

- A number of important issues pertain to the coexistence of wetlands and agriculture. The existing methods for assessing water requirements of wetlands are the least developed to date, partially due to the complexity and diversity of wetland ecosystems. Much of the relevant wetland work has also been held up by the need for further wetland classification studies. In summary, *more focus is required on developing environmental flow methodologies for wetlands.*

Scenarios of Development and Impacts of Irrigated Agriculture on Aquatic Ecosystems

This area would include the evaluation of such impacts as upstream agricultural development, deforestation, water diversions, agricultural return flows, etc., on wetlands, river reaches and estuaries downstream (box 1). It should also focus on evaluating the impacts of more specific

Box 1. Impacts of Crops on Flood Hydrology.

Agriculture leads to changes in vegetation of floodplains, and this alters their hydraulic characteristics that, in turn, may lead to changes in the flood regime. Agricultural fields in a catchment or utilized wetlands may retard floods more than in less-dense vegetation, reducing downstream flood peaks. The reverse effect is also possible. Different crop types will also alter the water budget of the catchment and affect flow rates during periods of low flow. These effects may be studied on a catchment scale or on an individual field/wetland scale.

The study objectives may include a) measuring the effect of crops in a selected catchment on peak flows and the shape of flood hydrographs, b) determining streamflow reductions associated with progressive agricultural development over time, and c) determining the total evaporative loss (water use) of the alternative vegetation cover types in a catchment: crops and predevelopment indigenous vegetation.

Aerial photographs and remote-sensing images for selected study catchment(s) may help to capture evidence of agricultural development. Available flow records should be analyzed in terms of flood peaks and rising and falling limbs of flood hydrographs for evidence of the hydrological impacts of change in the vegetation cover. Analysis of rainfall data will also be required to factor out the influence of differences in rainfall events on the flood hydrograph. In addition, total runoff over time may be analyzed to identify whether agricultural development had any impact on runoff volumes. Comparison of the water-use efficiencies of "natural" vegetation and crops is an important component of research. The results of such comparison may be linked to the analyses of flow records.

Such studies could develop recommendations for rehabilitation of a river, which would include restoring parts of a flood plain to its original vegetation cover, or recommend the types of crops that have the lowest impact on the natural flood pattern.

agricultural trends and practices on the functioning of aquatic ecosystems. Such practices may include *paal* (local rainfall harvesting and groundwater recharge) systems in India (S. Badiger, personal communication), replacement of paddy fields by prawn farming in southeastern Asia (O. Briet, personal communication), etc. It may also focus on impacts caused by various upstream catchment changes on both agricultural development and the state of aquatic ecosystems downstream (box 2).

The impacts and future development scenarios may be evaluated using available mathematical models and observed flow records (e.g., upstream and downstream of the impact zone, before and after the impact). They may be evaluated quantitatively both in terms of quantity (or quality) of water (flow) reduced (or increased), and in economic terms. The latter should add value to the impact and scenario assessment and make the implications of water resources and catchment development clear to policy makers.

Box 2. Impact of Upstream Catchment Development on Coastal Lagoons.

Temporarily open coastal wetland systems exist in many countries and are the subject for developing environmental research in countries like South Africa and Australia. Some of the coastal lagoons in Sri Lanka also fall in this category. Often, such coastal wetlands have high recreational and/or conservational value, important fisheries resources and are sensitive to fluctuations of freshwater inflow from their feeding catchments. They are temporarily blocked off from the sea for varying lengths of time by a sand bar. The lengths of the closed and open phases are determined by the interaction of river runoff, evaporation, seepage and wave action in the region of the estuarine mouth. The condition of an estuarine mouth and its temporal variability are important factors governing the structure and functioning of the estuarine resident biotic community. These factors need to be quantified as done in the hydrological regime.

For the majority of such wetlands and estuaries, no data are available on hydrological or the estuarine mouth condition. However, these data are the key to formulation of wise and informed management practices. A simple approach for generating such data from observed rainfall data is possible and may be similar to one suggested by Smakhtin and Masse (2000). An estuary or a coastal wetland may then be simulated as a reservoir with a spillway. The generated inflows may be routed through a reservoir and the estuarine mouth is considered open on days when the spillage from the "reservoir" occurs and closed on days with no spillage.

A further development of a reservoir concept may lead to the development of a general model, which would describe the entire estuarine "cycle" including breaching, emptying, bar-building, constriction, closure and water backing up. Such a model, while remaining a simple tool, may simulate water levels, salinity and volumes, and may serve as the basis for scenario testing and management decisions.

Such a model would allow the impacts of reduced inflows (e.g., due to upstream agricultural development) on estuarine mouth conditions, salinity, etc., to be examined and would provide a link with research on freshwater requirements of near-shore and estuarine fisheries.

Environmental Water Requirements and Water Allocation in River Catchments

Although water allocation practices are very often influenced by political decisions, technical tools and methods are useful, for example, at the stage of evaluation of allocation scenarios and consequences of reallocating water within and between water-use sectors.

In technical terms, water allocation in the conditions of limited water availability and multiple and competing water uses is an optimization problem. It seeks to find an optimal distribution of water, subject to a number of constraints, which may include flow variability in a river, assurance of supply of different users, economic value of water, etc. (box 3).

Box 3. Optimization Modeling of Water Allocation: The Case of an Unregulated Perennial River.

The goals of national or local policies on water allocation may include maintenance of ecological flows, protection of established rights, poverty alleviation, increased agricultural production, etc. Water authorities in a catchment or a country as well as water users themselves may benefit from understanding the trade-offs that result from competing objectives and constraints, especially if available water resources are limited, which is very often the case.

The task of optimally allocating water resources in a river basin may be approached using optimization methods, with certain constraints (e.g., Jacobs and Vogel 1998). The optimization problem may be formulated to maximize the objective function, subject to restrictions associated with streamflow variability, individual withdrawal requirements, a priori established ecological flow requirements and required assurances of supply. One measure, which could, in a simple way, present these complexities, is a flow duration curve (FDC), which is a cumulative distribution of streamflow discharges or volumes. An FDC-based allocation "model" will also implicitly take into account spatial distribution of withdrawals in a catchment. Some streamflow reductions (e.g., caused by forestry or dryland farming) do not have a specific reliability (assurance) of supply and, therefore, methods must be developed to account for the impacts of such activities on the overall shape of the FDC.

The important additional constraint, which could be introduced into the allocation "model" in cases where it is feasible, relates to the economic value of water. Marginal net benefit curves for each withdrawal may be incorporated into the analysis. This should help not only to explore the effects of streamflow variability on the optimal allocation but also to allow economic aspects of allocation to be accounted for.

This problem may pertain to different scales, from a release policy at some specific individual dam to a permit system at the scale of the entire catchment (large or small, regulated or unregulated). If one of the intentions of water allocation policy is to meet the established environmental water requirements, then optimization methods should operate in the area of the capacity of utilizable water resources (figure 1) with environmental flow requirements as a constraint.

Rehabilitation of Aquatic Ecosystems

The research in this area related mostly to the identification and understanding of the physiographic processes and environmental functions, which have been destroyed or modified by agricultural development or other human activities in river catchments. It also related to the identification and implementation of appropriate engineering or management measures, which help to reactivate lost or modified ecosystem functions and processes (e.g., Petts and Calow 1998). Such research is normally very case-specific. Rehabilitation and restoration of aquatic ecosystems come into the agenda when the ecosystem shows clear signs of degradation. This would mean that the levels of water utilization have exceeded the utilizable capacity of the ecosystem (figure 1).

It is important to note that development of ecosystem health indicators and reporting on the state of the water environment in developing countries, as well as rehabilitation of wetlands and rivers, represent enormous fields of current research. At the same time, they have not received much attention as yet in the context of the developing world.

Proposed Research Activities

The main focus areas of research outlined above involve a variety of research activities associated with them. Some of these activities are briefly explored below in no particular order.

Information Management and Analysis

This would primarily include the ongoing development and updating of web-based searchable databases of previous scientific experience. However, these would be "higher-level" databases than simple literature reviews, as they would aim at the analysis of quantitative statements from different sources rather than presenting just a sorted collection of references. The examples could be:

- A database of quantitative statements on hydrological functions of wetlands (or, in broader terms, of different aquatic ecosystems). In the context of inland wetlands, for example, it is commonly accepted that wetlands attenuate floods, sustain base flow during dry periods and can recharge aquifers. However, little is known about the quantitative side of these wetland functions (box 4). The systematic collection and analysis of available quantitative or even semiquantitative information (e.g., "yes" or "no" type statements) will serve as an additional tool in wetland research, complementing and supporting other approaches like modeling or field surveying of wetland ecosystems.

- A database of qualitative and quantitative statements pertaining to ecological consequences of changes in the river flow regime or wetland water balance. This would contribute to the quantification of complex eco-hydrological processes in aquatic ecosystems (box 5).

- A database that would provide systematic information on the known social services (e.g., fisheries, construction materials, medicines, etc.) provided by different types of aquatic ecosystems. Work in this field is in its infancy at present. This could be linked to a database of reported economical benefits associated with such natural dependencies.

- A database of the environmental flow methodologies being used or proposed for use in various countries. This could include such information as the nature of the methodology (habitat assessment, comprehensiveness, etc.), input-data requirements, strengths and deficiencies, recommendations and success of implementation and monitoring. A good starting point for this would be the already available hard copy reviews (e.g., Tharme 1996)

In database development, there should be more focus on information acquisition from developing countries of Africa and Asia. Unpublished reports and other similar "gray" literature may become an important source of information in this regard.

The collection of information may also be made participatory. On-line input of quantitative statements in some predefined format could be allowed on the website, where a database is maintained (e.g., IWMI website). Consequently, experts from all over the world could make their direct contributions to the development of databases. In a certain sense, such a website then becomes "internationally owned," and IWMI (or another organization) only provides site maintenance. This

Box 4. Quantifying Wetland Functions: A Database Approach.

The importance of conservation of wetlands is directly related to the value of functions that wetlands perform. The concept of a "function" is not well established in a hydrological community that is more familiar with process frameworks. However, it is well established within the wetland scientific community, dominated by ecologists. At the same time, there is no difficulty in connecting "processes" and "functions," at least in the context of a wetland research.

For example, wetland detention storage, vegetative resistance to flow, and flow transmission through soil stores are examples of hydrological processes (each operating within different components of a wetland ecosystem). An example of a relevant hydrological function, performed by the entire wetland complex as a result of complex interactions between these processes is flood attenuation. Other commonly cited examples of wetland hydrological functions, which may also accommodate other hydrological processes, include groundwater recharge and base flow maintenance (by storing precipitation and/or floodwater and releasing it later more evenly over time). There are also numerous non-hydrological (or "not only" hydrological) functions performed by wetlands, such as the purification of water, erosion control, etc. The explanation and description of wetland functions may be found in numerous textbooks, scientific publications and policy documents.

Despite the common agreement that wetlands do perform certain hydrological functions, the quantitative description of such functions is very limited. With regard to the flood-control function, for example, it is unclear to what extent different types of wetlands of different sizes and in different geographic regions affect flood attenuation, or which types of floods are being affected. Similar questions pertain to other wetland functions.

Many publications on wetland hydrology contain quantitatively based statements of wetland functions (in each of the above categories of functions). Statements may also be categorized by different types of wetlands. Relevant sources may be identified and the information collated and analyzed (A. Bullock, personal communication). This information may then be used a) to summarize the nature of past hydrological research in this specific field and identify gaps, b) to search for consistency of conclusions amongst single wetland types and single functions, and c) to compare the collated information against the information on water quantity functions and, on that basis, identify policy issues for wetland management.

could lead to the development of "communities of practice," an important element of knowledge management, particularly important in dynamic research areas, such as environmental water requirements of aquatic ecosystems. If successful, the participatory approach can, in principle, radically change the whole process of scientific database development and reviewing the state-of-the-art of research fields.

The databases should be searchable, so that one can extract values/statements, pertaining to certain research topics. Developing relevant databases could become an ongoing initiative. It may link well with other large-scale relevant international research initiatives.

Box 5. Quantifying Eco-Hydrological Links: A Database Approach.

Hydrological regimes may be characterized in terms of flow magnitude, frequency, duration, timing, and rate of change (e.g., Richter et al. 1997). Each of these groups has a number of specific flow measures and indices. All groups are interrelated: hydrologists often talk about 10-year floods, 10-day average minimum flow of a 2-year return period, the probability of flow being less than half of the daily average for longer than 30 days continuously (!), etc.

Attempts have been made in the past to relate the changes in hydrological characteristics with the ecology of rivers. Less so has been done for wetlands. In general, while it is widely accepted that changes in hydrology lead to changes in ecology, the quantitative side of the problem remains relatively poor. While the ecologists are building their quantitative resources through many case studies, it is important to review already available information on quantitative relationships, and categorize quantitative statements in different ways. This may lead to the development of "generic quantitative statements" describing how changes in frequency of floods, for example, affect the richness of fish species or how the increased duration of low-flow events affects certain habitat types, etc. Generic statements would be invaluable for further development of some methodologies for environmental water requirements, if they include a flow-response database on which ecological and social motivations for particular flows are founded.

Such databases might need to be developed in parallel (with cross-linking ability) for different components of aquatic ecosystems, e.g., vegetation, fish, overall biodiversity, etc., as vast literature sources exist for each such component.

It is quite possible that information for certain types of such databases will be qualitative or only semiquantitative at best. One of the difficulties will be the grouping of similar types of aquatic systems (river ecotyping, classifications of wetlands, etc.), without which the transferability of system biotic responses will be questionable. But the work on such classifications is ongoing in the world and it is envisaged that a suitable classification system(s) may be identified.

Development, Evaluation and Application of Techniques

These activities could possibly include building a mathematical wetland model, which would then be applied to study the effects of changing water balance components (e.g., increased evaporation, reduced inflow, etc.) on other wetland (ecological) functions like nutrient cycling, habitat maintenance, etc. But the ability of existing wetland models to simulate these processes and to be used in the context of impact assessment should, of course, be examined first, as some sources report on as many as 87 wetland models (Costanza and Sklar 1985), and this number has definitely increased since then.

This would also include methods for separating different components of the hydrological regime (e.g., floods of certain magnitude, base flow) using digital filtering (Smakhtin 2001) or other methods, assemblage of filtered components in different ways and establishing the ecological effects of modified hydrological time series. This could become a very relevant approach to scenario analysis in benchmark basins (C. Scott, personal communication).

Other possible developments include the theory of stress in aquatic ecosystems (box 6), the economic assessment of environmental impacts caused by changing water regimes of rivers and wetlands and the development of an environmental flow assessment methodology for wetlands in the form of a software database. A range of new tools may be associated with the use of remote sensing techniques (box 7).

Box 6. Ecological Stress and Aquatic Ecosystems.

All aquatic organisms experience ecological stress, which is related to natural flow quantity and variability. The levels of such stress increase with decreasing flow and changing variability of flow caused by catchment, wetland or river development. Different species develop their specific stress profiles—relationships of stress versus flow. These profiles could be defined from the specialist qualitative ideas about how aquatic organisms operate under different flow conditions. For example, both fish and invertebrates will experience higher stress during the low-flow season than during wet or intermediate months, but the levels of increased stress will differ. As flow is diverted from a river, these organisms undergo even higher stress than under natural conditions. Certain threshold stress limits may be established with the help of freshwater biologists.

Once stress profiles are established, they can be converted into time series of stress and then into duration curves of stress. It can then be established, for example, how often a certain ecosystem component goes under certain stress thresholds and what its consequences are. The stress approach allows more explicit quantitative and standardized relationships between an ecosystem component and its response to flow (or via habitat change) to be developed. It is also a convenient way of comparing ecological outcomes of different flow scenarios.

There is much scope to exploit this basic concept in river environmental flow methodologies, and relevant research is underway in South Africa, for example. Another attraction is to explore this concept in a context of wetlands (e.g., floodplains, coastal lagoons), where it has been only marginally used before, and where the sea effects or flooding pattern will have to be considered. The databases on eco-hydrological links described earlier would be an important source of information for developing generic stress-flow relationships. A single generic approach is unlikely to be feasible. The method will need to be developed for different ecosystem components (invertebrates, fish, riparian vegetation, water quality) and for different flow components (e.g., low flows, high flows).

Importantly, research will be required to determine what the real ecological implications are of changes in stress profiles from natural to various impact scenarios. Such research will help to assess the relative degree of damage to aquatic ecosystems of different, proposed, and modified flow regimes (R.Tharme, personal communication).

Box 7. Remote Sensing for Habitat Assessment in Relation to the Flow Regime.

Remote sensing and aerial photography may provide possibilities for spatial delineation of aquatic habitat types, which are relevant for individual, population or community levels of organisms (in wetlands, estuaries, floodplains, etc.). Such delineated habitat types may then be used to construct empirical relationships between habitat availability and streamflow. Habitat availability may be traced back in time as far as the mid-1970s, using remote sensing photos although the resolution of such photos may not be sufficient for small- and medium-sized catchments (Y. Chemin, personal communication). Prior to that use can be made of aerial photos. Therefore, it would be possible to examine how habitat conditions have degraded over time.

The study of such kind should also have a second link to the relationships between the various habitat types that are identifiable using remote-sensing techniques and the biota that depend on them. This habitat-biota link is still poorly known for many aquatic organisms, but especially for those that are not in-stream inhabitants (R. Tharme, personal communication).

Matching the ecological nature of the habitats identified using remote sensing with those on the ground will be a key step in the validation of a new set of techniques, which may emerge from this approach. The habitat units may be too coarse for some levels of assessment or biota, but ideal at other levels. The approach is envisaged to be particularly useful for large, ecologically complex river basins, such as the Mekong, for example.

An important aspect of technique development is the adjustment of existing environmental flow methods to the information environment and social context of developing countries, as already mentioned in the section on Focus Areas above. The "hydrologically based" methods, like the Range of Variability Approach (RVA - Richter et al. 1997) may need to be simplified on the one hand, as they contain a number of highly correlated and, therefore, unnecessary indices and, on the other, they need to be filled as much as the current state of knowledge permits, with ecological meaning.

Methods for assessing ecological requirements of different types of aquatic ecosystems are often developed by different groups of scientists and may not match well with each other. But in most instances the aquatic systems are interlinked (e.g. river with floodplain wetland and estuary). Therefore further research on linking methodologies on the environmental water requirements is necessary (box 8).

Most of the recent work in the field of environmental water requirements has been focused on relatively fine scales. There is however a scope of developing methods for large scale, global assessments. Currently, such methods do not exist, but may be very suitable for evaluating areas of overutilization of water resources (present and future). Such global assessments may very clearly highlight areas of "environmental water scarcity" (box 9).

Box 8. Linking Groundwater and Surface Water Ecosystems.

If a river has a permanent hydraulic connection with groundwater, and water is abstracted primarily or only from groundwater, ideally there should be a limit to which this aquifer is exploited. This limit is determined by the ecological flow requirements of the river.

If the flow record at some point in a river is available (observed or simulated), the base-flow component of the flow can be filtered out using available digital filtering techniques. This base flow may be considered as an outflow from an underground reservoir. If the ecological requirements of the river are established, using available relevant techniques, and presented as a time series, it is possible to filter an "ecologically relevant" base flow. Having a time series of ecological base flows, it is possible to establish a time series of "ecologically sustainable" groundwater storage. This could be done using the principle of a linear reservoir, for example (groundwater storage is proportional to base flow).

This draft scheme should effectively allow joint environmental water requirements to be established for both an aquifer and a river. It will also allow the sustainable levels of groundwater exploitation to be evaluated. The prerequisite for such a study is a catchment with detailed geohydrological and hydrological data.

This scheme is a small example of a possible study on the links between groundwater and surface water in an environmental context. Exploring the interdependencies of rivers/lakes/wetlands with groundwater aquifers, and ecosystem dependency on such links form an emerging area of environmental flow research.

A logical continuation of the development of techniques is, of course, their application and validation, as no method is proved practical until applied in the real world. However, attention should also be paid to assessment of the suitability of methods and software developed elsewhere for projects focusing on environmental water assessment and management issues.

In general, it would be flexible and pragmatic to have a toolbox for environmental water projects, which would operate at different scales of resolution and information requirements. Some of the tools in this box will be developed and validated, others will be acquired and validated.

Wetland Inventory and Assessment

It is important to collect and scientifically document the environmental impacts of agriculture on aquatic ecosystems at different scales, from a single wetland or river basin to a country, regional or global scale. These activities may be associated with a wetland inventory, assessment and monitoring studies, which are numerous in the world (e.g., Pisey and Ang 1997; Wetland Characterization…, 1998; Wetland inventory…, 2001). The difference between inventory, assessment and monitoring primarily relates to the depth of study and, consequently, to the types of collected information. Most such current studies are definitely at the "inventory" level, and focus primarily on the wetland extent and location. It is important to bring wetland inventory one step forward and start addressing the question "How to use wetland inventories?" One possible solution is the

Box 9. Global Assessment of Environmental Requirements of Aquatic Ecosystems

The issue of environmental water requirements can be considered at different scales: from a large-scale planning perspective to a detailed environmental flow management plan in a particular river. The prospects of water resources development at the global scale have been previously assessed without proper attention to the needs of natural aquatic ecosystems. The introduction of at least a rough assessment method of water needed for the environment should fill an important knowledge gap for policy making and change future modeling efforts of water use. Developing such a rule would provide a better sense of the areas where nature and agriculture are "competing for the same resource," identify possible impacts of environmental water allocation on irrigation development (current and future), and also point to possible management measures or options. It may also bring a new content to the issue of water scarcity, pointing on areas of "environmental water scarcity," current and projected.

The method to be developed is likely to be similar to that of Tennant (1976), who identified eight categories of habitat quality in rivers and related these categories to Mean Annual Runoff (MAR). 10 percent of MAR for environment was considered as the lowest limit, which helps biota just to survive. 60 to 100 percent was considered optimal habitat conditions. Several other environmental thresholds were identified in between.

Assuming that environmental water requirements have to be satisfied first and comparing natural MAR with different ecological thresholds, current total water use and future water use (projections), present and future problem areas can be identified. The issue may be explored further by looking at water requirements for environment and agriculture over different periods of the year, for example, dry and wet seasons.

The developed method may be tested in several river catchments with different water use patterns and physiographic characteristics. It should be tested among multiple stakeholders, e.g., aquatic ecologists, policy makers, etc. Eventually, a set of world maps illustrating the consequences of maintaining the environmental requirements at the global scale may be produced.

identification of representative wetlands and in-depth quantitative studies of their physical processes, of which hydrological processes are of primary importance. Such studies would lead to the identification of the status of, and threats to, wetlands (wetland assessment). Long-term collection of specific information for purposes of wetland management would constitute monitoring, which activity may be more relevant as part of a benchmark catchment methodology (section on "Research in Benchmark Catchments").

To bring wetland research to the stage of assessment, current inventories will need to be "filled" with such information as a) state of the current knowledge and routinely available hydrometeorological information (streamflow, rainfall, evaporation, etc.) in the vicinity of each wetland system, b) reference status of wetlands (in natural, predevelopment conditions) in terms of hydrology, water quality, habitat, species richness and diversity, etc., c) major water balance components, d) indicators of current wetland utilization, and e) wetland "health" indices and reports on the current wetland health status (through assessing the deviation from reference conditions).

This list is, of course, not complete and needs to be expanded. Such snapshot inventory studies may reflect, amongst other things, the current ecological status of wetland ecosystems in a study area and provide an initial basis for establishing policy and conservation priorities. Detailed wetland case studies should then focus on using this detailed information to quantify wetland processes and functions (box 10).

Box 10. Simulating Wetland Processes: Case Studies of Selected Wetland Systems.

Such studies may be carried out in benchmark catchnments and/or in parallel with regional wetland studies. Relevant modeling techniques should be applied to simulate a) wetland behavior itself and its changes under the upstream catchment and "in-wetland" developments, and b) downstream catchment responses in conditions of upstream wetland modification by agricultural development.

A selected or developed wetland model would most likely be of a lumped parameter type rather than of a complex hydraulic form, because the intention of such studies should be to make simulation exercises commensurate with the existing information, which is likely to be limited in Asia and Africa. By playing with the input of models (changing inflows, for example), it could be possible to establish which wetland functions are likely to be lost or modified by the development. An appropriate wetland module could be built in or linked with some existing, more general catchment model. One possible alternative is to analyze wetland processes from long-term observed flow records (e.g., upstream and downstream of a wetland).

Research in Benchmark Catchments

Benchmarking a river basin or a group of basins is a continuous process of data collection on multiple aspects pertaining to the research and management of water resources. Therefore, benchmark basins represent a methodology to develop long-term comprehensive data sets on selected basins in a variety of agro-ecological zones.

One of the examples is the Ruhuna group of catchments in Sri Lanka. Continuous hydrological observations are required, e.g., inflow to coastal lagoons, water levels, rainfall, spills and releases from tanks, groundwater levels, evaporation, etc. On the other hand, there is a need to sample fish and invertebrate populations, water-quality constituents, vegetation, other wildlife, etc. There are other groups such as wetland birds, semiaquatic mammals and amphibians, which may hold underutilized guiding information on flow-ecosystem links and which need to be drawn into environmental flow work more intensively (R.Tharme, personal communication). It would be useful to include such groups in at least one of the benchmark studies. It would be a new, complementary emphasis that may yield some helpful answers, as well as providing a more rounded approach that better addresses the current issue of biodiversity conservation.

The sampling points (or tracks) and gauging stations for monitoring locations need to be defined. Ideally, the set standards should be applied to other benchmark catchments. In some cases, it could be useful to arrange for snapshot measurements, which would produce a momentary picture of a variable(s) over the area. For other types of projects, experimental manipulation of the flow regime and monitoring of ecological responses would be of primary importance. Such an approach may provide new insights into ecosystem functioning and its resistance to alterations in hydrology.

Measuring environmental variables in benchmark catchments allows data sets to be built, which could then be used for impact assessment modeling, scenario analysis, validation of developing predictive techniques, etc. Thus it contributes directly to this research program and concludes the chain of focus areas and research activities, putting all of them in the context of information dependency. Eventually, at least one of the catchments should have reasonable data if the intention is to test and develop tools that can be readily adopted in the context of developing countries.

Conclusions

The paper suggests a framework for a research program on environmental water requirements of aquatic ecosystems and environmental aspects associated with irrigated agriculture in river basins. The program has its focus on developing countries. It is envisaged that it will serve as the basis for identification of specific research needs and niches as well as for developing partnerships in this field with other established and emerging research groups. The paper was also drafted with the intention to create awareness about a range of technical aspects and importance of problems, which pertain to environmental flow management in river basins and ecological aspects of agricultural development.

Research on agricultural water management and agricultural development in river basins has to be linked with research on environmental water requirements of various aquatic ecosystems, if the gap between water for food and water for environment is to be bridged. Several issues pertaining to environmental water research in river basins could be particularly important. They include

- Developing methods, which are parsimonious, in terms of required input information and which could, therefore, be appropriate in the context of developing countries.
- Developing methodologies for environmental flow requirements of wetlands (including riparian wetlands, floodplains, coastal lagoons, temporarily open/closed estuaries, etc.).
- Documenting and describing linkages between different aquatic ecosystems (rivers and wetlands, rivers and estuaries, rivers and aquifers) rather than treating these systems in isolation from one another.
- Building a consistent information base of quantitative information on various functions and services of aquatic ecosystems, quantifiable relationships between hydrological and ecological processes in aquatic ecosystems and methods used to assess them.
- Distinguishing between different scales of assessments of environmental water requirements, from ecosystem scale to basin scale and, further, to global scale.
- Building the information base for testing emerging assessment methods and models through consistent monitoring of environmental variables in a set of benchmark catchments.
- Building partnerships with relevant research groups in the sister CGIAR centers, other international agencies, leading universities and research centers.

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