TECHNICAL FOCUS PAPER

The role of decision support systems and models in integrated river basin management

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SIWI

Global Water
Partnership

Global Water Partnership (GWP), established in 1996, is an international network open to all organisations involved in water resources management: developed and developing country government institutions, agencies of the United Nations, bi- and multilateral development banks, professional associations, research institutions, non-governmental organisations, and the private sector. GWP was created to foster Integrated Water Resources Management (IWRM), which aims to ensure the co-ordinated development and management of water, land, and related resources by maximising economic and social welfare without compromising the sustainability of vital environmental systems.

GWP promotes IWRM by creating fora at global, regional and national levels, designed to support stakeholders in the practical implementation of IWRM. The Partnership's governance includes the Technical Committee (TEC), a group of internationally recognised professionals and scientists skilled in the different aspects of water management. This committee, whose members come from different regions of the world, provides technical support and advice to the other governance arms and to the Partnership as a whole. The Technical Committee has been charged with developing an analytical framework of the water sector and proposing actions that will promote sustainable water resources management. The Technical Committee maintains an open channel with the GWP Regional Water Partnerships (RWPs) around the world to facilitate application of IWRM regionally and nationally.

Worldwide adoption and application of IWRM requires changing the way business is conducted by the international water resources community, particularly the way investments are made. To effect changes of this nature and scope, new ways to address the global, regional and conceptual aspects and agendas of implementing actions are required.

A **Technical Focus Paper** is a publication of the GWP Technical Committee aimed at harnessing and sharing knowledge and experiences generated by Knowledge Partners and Regional/Country Water Partnerships through the GWP Knowledge Chain.

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Foreword

The use of analytical modelling tools in integrated water resources management (IWRM) provides important instruments both for finding the best water use solutions and achieving water security for multiple purposes in a sustainable and equitable manner. It also facilitates the management and mitigation of extreme climate events. Water security requires resolving trade-offs to maintain a proper balance between meeting various sectors' needs and taking into account present and future overall social, economic and environmental goals.

During the past four decades, model codes have been developed for hydrological, water resources and environmental analyses. Such codes have been developed at universities, public agencies and commercial companies and vary in complexity from relatively simple conceptual (or empirical) codes to complex process-oriented codes depending on their purpose and use. Embedded in so-called Decision Support Systems (DSSs), technical tools are now available which provide a framework for data and information management, socioeconomic evaluation and communication for sharing and disseminating information to the public. Despite the general acceptance and frequent use of model/DSS codes on specific problems, the adoption of models on a global scale for daily use in water resources planning and management, or as part of the IWRM processes, has been limited.

In this context, the Global Water Partnership and DHI co-convened a session at the 6th World Water Forum, held in Marseille, France, on how models could be used as tools for helping decision-makers implement IWRM to balance multiple water uses to best achieve desired goals. We have assembled a global community of experts and stakeholders devoted to frank dialogue, rigorous analysis and effective action to address the requirements to ensure that an enabling institutional environment for the sustainable use of the modelling framework is created and that the technological transfer is carried out as a collaborative effort between software supplier and water authority. These requirements form the basis for elaborating models/DSSs which can be tools for helping decision-makers implement IWRM.

This Technical Focus Paper honours a commitment, made at the end of the session, to prepare guidelines for elaborating and validating modelling/DSS tools to assist decision-makers in implementing IWRM. We are grateful to Jan Hassing from UNEP-DHI Centre, Børge Storm and Henrik Refstrup Sørensen from DHI, and John Joyce and Phillia Restiani from SIWI for their commendable efforts in drafting this document. We also thank Torkil Jønch Clausen and John Metzger for their valuable support throughout the process.

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Summary

The world's water issues are increasing in number, coverage and intensity and leading to a lack of water security. The availability of water in acceptable quality and quantity for human needs and for natural systems is paramount for sustaining life. Availability is under a constantly increasing threat from demands created by, amongst other factors, increasing populations, economic sector activities and requirements for environmental sustainability. Allocation issues at local, national and transboundary levels will become more and more contentious and flood and drought risks will be exacerbated by climate change. The IWRM approach has been developed to meet such challenges and to resolve such issues. IWRM assumes a governance system that is based on policy and legislation, institutional roles and a set of management instruments. Model codes and DSSs are among the management instruments which can assist at the management level of water agencies and other water-related institutional units to reach sound, evidence-based decisions.

While model codes describe isolated hydrological, hydro-economic, or water resources processes, a DSS is a framework that links together a database and processing environment, a knowledge and information system, a modelling and analysis framework, a socioeconomic analysis framework and a communication framework. Such sets of tools are seamlessly linked and tailored to a context. A DSS has an open interface and can access models from different suppliers, with the help of adapters, which enable the DSS to access prepared input data and model parameters and store relevant model results. A fully developed DSS can greatly assist many parts of the IWRM cycle, which describes the IWRM process right from the identification of water resources issues, over action planning, to the monitoring of the impact of interventions. The river basin level is the most common level at which a DSS assists the decision-makers in their quest for sustainable water resources management.

Data availability and quality is a concern no matter how ingeniously model codes are developed. Several hydrological and meteorological monitoring systems and networks are becoming increasingly weaker (with regard to operation and maintenance, choice of monitoring equipment, skills, etc.) and their density and coverage is decreasing in many parts of the world. At the same time, technological advances in sensor technology and high levels of integration of electronics and data communication have made the automation of hydrological and meteorological networks increasingly affordable and the amount of raw data huge. In a fast-changing world where climate change also poses huge challenges, efforts need to be made to collect, handle and use data more strategically, assisted by modelling and, in particular, assisted by DSSs.

As with other software, sustainability is an issue. To achieve sustainability, the DSS must be based on a real 'need' for the services that the DSS can provide and it must be flexible to adjust to new requirements. The software supplier must be able to provide continuous back-up services. The DSS must be anchored in an appropriate water agency with adequate funding and where qualified staff can be continuously available.

There are many good examples of DSS applications. Common to all, is that they have greatly assisted in understanding the river regimes – the analysis of development scenarios and the associated impacts – enhanced cooperation on water resources development and made stakeholder involvement more meaningful. The notable examples presented in this document include a Decision Support Framework (DSF) for the Lower Mekong Basin, the Nile Basin DSS, a DSS including hydro-economic modelling for the Euphrates-Tigris region, Zambezi River Basin

Multi-Sector Investment Opportunities Analysis (MSIOA), a DSS including hydro-economic modelling in the Rio Grande basin, the Okavango River Basin Decision Support System and 'DSS Planning' for integrated water resources development and management in India.

1 Rationale and background

Water resources systems are complex ones that encompass different interlinked components, including technical, economic, social, cultural, environmental and legal aspects. A river basin system, for example, can include several ecosystems with different hydrological sub-systems, various kinds of water uses supporting different social and economic activities, different types of actors with different interests related to water and numerous types of 'institutions' – sets of rules, regulations and policies – regarding water allocations.

Increasing pressure on water resources has, in many instances, resulted in, amongst other things, a lack of safe and affordable drinking water and basic sanitation, inadequate water resources for economic sectors such as agriculture and energy and transboundary conflicts over allocation. Such aspects have created public pressure, followed by government responses in terms of an increased focus on rational water resources management, planning and development. The search for efficient and effective approaches has led to the development of IWRM, which has been applied globally for the last 20 years.

The Global Water Partnership (GWP) defines IWRM as *"... a process which promotes the coordinated development and management of water, land, and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems ...."*

The basic concept of IWRM was developed in an expert meeting in Dublin, in early 1992 and later recognised in Agenda 21 of the UN Conference on Environment and Development in Rio de Janeiro in 1992. IWRM is a politically-driven process that strives to resolve conflicts of interest over water resources and their allocation, use and protection.

Today, IWRM is often associated with the need to achieve water security and as a precondition and a process to attain this goal. Grey and Sadoff (2007)[1] define water security as, *"The availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water risks to people, environments and economies."*

The role of IWRM will vary depending on the development stage of the country. Developing countries, countries in transition and developed countries will all have different ways of implementing the IWRM process and derive different benefits from it. Implementation modes will also depend on the geographic, social and economic context and, in particular, on the hydrology.

The three most critically important concepts for an IWRM process are (1) 'the economic efficiency, equity and environmental sustainability', (2) 'the enabling environment, institutional framework and the management instruments', and (3) 'the cross-sector/horizontal integration

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[1] Grey, D. and Sadoff, C. (2007) *Sink or Swim? Water security for growth and development. Water Policy* 9: 545-557.

across the natural systems and the human systems, combined with the vertical integration across local-basin-city-national and transboundary levels'.[2]

The first concept requires that management strikes a balance between the three goals, of which the first two deal with socioeconomics and the last with nature and its continued protection.

Box 1: The 'musts' of concept (1)

- Economic efficiency in water use: *Because of the increasing scarcity of water and financial resources, water must be used with maximum possible efficiency*
- Social equity: *The basic right of all people to have access to an adequate quantity and quality of water for the sustenance of human wellbeing must be universally recognised*
- Environmental and ecological sustainability: *The present use of the resource must be managed in a way that does not undermine the life-support system, thereby compromising use by future generations.*

The second concept requires that a rational framework for management is developed. The enabling environment is the set of required policies and legislation needed to support the management, the institutional framework is the set of government and private organisations and agencies which implements the IWRM. The management instruments are those tools, skills and capabilities needed by the water agencies in order to fill their mandated roles. The third concept requires the integration of the views and interests of various sectors in the development and implementation of the IWRM framework, as well as horizontal and vertical integration. Box 2 describes the status of the acceptance and use of the IWRM concepts worldwide.

The IWRM framework includes a general continuous process – the IWRM Planning Cycle – which outlines how an integrated approach can be applied (GWP, 2005). Since water resources systems and their management issues are very context specific, technical tools and instruments are required for water actors and managers to decide how those issues can be addressed pragmatically within the IWRM framework. One such issue is the strain on water resources from climate change and the adaptations needed at national and basin levels to adjust to the dynamic situation. Strengthening IWRM capacity in national and basin organisations will enhance the ability of such institutions to plan and implement adaptation measures.

The complexity of water resources systems can often be addressed by applying DSSs and computerised models, which can transparently present the elements of the system and their interrelationships. A DSS in the IWRM context can be defined by its components. *"A DSS for IWRM will typically include a database and processing environment, a knowledge and information system, a modelling and analysis framework, a socioeconomic modelling and analysis framework, and a communication framework."* Refer to Chapter 2 for more details. Using the DSS in an appropriate manner, the implications and trade-offs among management options and strategies can be assessed and evaluated in a clear and unambiguous way.

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[2] Detailed explanations of these key concepts are, for instance, found in GWP TEC Background Papers No. 4 and No. 10.

Box 2: Status Report on the Application of Integrated Approaches to Water Resources Management – UNEP-DHI Centre and GWP, 2012

In 2012, a report on the status of IWRM was prepared following a request by the UN Commission on Sustainable Development (UNEP, 2012). The report should take stock of the situation 20 years after the UNCED Conference in Rio where recommendations for integrated approaches were made. The report was based on responses from 134 UN member countries. Some of the key messages and recommendations from the report are:

- Since 1992, 80% of the countries have embarked on reforms to improve the enabling environment for water resources management based on integrated approaches
- Water-related risks and competition for water resources are perceived by a majority of countries to have increased over the past 20 years
- Countries that have adapted integrated approaches report more advanced infrastructure development, but further efforts are needed to ensure appropriate levels of coordination
- Countries report a gradual, but positive, trend in financing for water resources development and management with more diverse sources of finance, but little progress on payment for water resources services
- Countries report improvements to the institutional framework together with improved policies, laws and systems over the past 20 years. This has led to better water resources management practices bringing important socioeconomic benefits
- Integrated approaches to water resources management and development are critical for progress towards a green economy.

There are many IWRM areas where models and DSSs can inform the process by allowing water managers to better characterise multiple factors and future uncertainties, which shape appropriate actions and strategies to meet management objectives. However, the most obvious area is the 'management instruments'. This area includes themes such as, water resources assessments, plans for IWRM, demand management, social change instruments, conflict resolution, regulatory instruments, economic instruments and information management and exchange. The specific findings from the UN Water Status Report, regarding application of management instruments as a whole, can be found in Box 3.

The UN-Water Status Report shows that except for the enabling environment (policy and law) there is a strong need to improve progress in the IWRM processes. It is, therefore, highly relevant to evaluate the potential use of DSSs and models to assist in taking the IWRM process forward and helping decision-makers to make more rational decisions based on the best available information, detailed model calculations and simulations, as well as communication with stakeholders. Here, we distinguish between a model code and a model. *"A model code refers to a computer program, which describes one or more generic processes. The processes can, amongst others, be hydrologic or hydro-economic. A model appears when the model code has been populated with input data and parameter values describing a specific situation, for instance in a designated river basin."*

Box 3: Specific findings on the application of management instruments from the UN Water Status Report on the Application of Integrated Approaches to Water Resources Management (UNEP, 2012)

- Progress on integrated approaches to water resources management is demonstrated by a strong correlation between progress on the enabling environment of policy, laws and plans and a positive impact on management practices
- Water resources assessment and monitoring systems are being implemented in over 60% of countries
- Water resources management programs (including allocation systems, groundwater management, environmental impact assessment and demand management, among others) are being implemented in more than 84% of the highest HDI[3] group countries, but in only around 40% of other countries
- Level of development does not seem to be a barrier to improved management of water resources. The survey shows that progress is not constrained or guaranteed by HDI status. While very high HDI countries tend to cluster at the top, this is not an exclusive space.

Real-time modelling of flood and reservoir operation processes can greatly improve the usefulness of water resources infrastructure. The DSSs and models are expected to play an increasingly important role in IWRM. The potential roles are analysed in the following chapters and cases are given showing the applications of DSSs, including hydro-economics, in management decisions.

The most obvious level of application of a DSS is that of the river basin where the assessments relate to the management of water resources within a single basin. The scale of such a basin could be national or transboundary, where several nations cooperate in their quest for an equitable sharing of benefits. Examples of transboundary DSSs are found in the Mekong River Commission's DSF, the Nile Basin DSS and the Zambezi River Basin MSIOA. The 'DSS Planning' for Integrated Water Resources Development and Management project in India has been piloted in a sub-basin within Maharashtra State with the intention of expanding the application to other parts of the state and to other states. These cases, along with other notable cases, are found in the Annex. A DSS can also be applied at the national level, for instance in a study of the impacts of a particular water policy component, such as allocation priorities or pricing principles. However, this document has its primary focus on the river basin level.

2 State of the art in model codes

During the last four decades a wealth of model codes has been developed for hydrological, hydro-economic and water resources oriented model applications. Such model codes give a deeper understanding of the cause-effect relationships in the water cycle arising from human interventions or changes in the natural conditions. Hydro-economic models can broaden this

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[3] The Human Development Index (HDI) is a composite index that measures health, knowledge and income. Countries are categorised in four HDI bands: 'Low', 'Medium', 'High' and 'Very High'.

understanding by adding economic model codes to the ensemble of analytical tools which together take into account engineering, hydrological, environmental, social, economic and institutional elements. These model codes assist decision-makers in reaching evidence-based decisions relating to the governance of water resources. Models are, by necessity, gross simplifications of the conditions they try to emulate. Only by going through rigorous testing procedures can their value be established and confidence in their results consolidated.

"...essentially all models are wrong, but some are useful..."

George E.P. Box, 1987

2.1 The value of model codes for water resources management

For more than four decades it has been an important scientific activity to develop mathematical simulation software (model codes) to describe the whole or parts of the hydrological system; describing specific water resources and environmentally oriented processes, or describing management oriented processes, e.g. how water could be best used and allocated. Such model codes can vary in complexity, ranging from simple empirical relationships, e.g. those based on the observed relationship between rainfall and stream flow, to process-oriented descriptions, which attempt to mirror the natural system in a physically-based manner taking into account spatial and temporal variations in catchment characteristics. In between, a plethora of model codes have been developed, which can be broadly characterised as lumped conceptual codes describing the hydrological system based on our perception of how the water flows within the catchment area.

Code developments have been driven not only by a desire to gain increasing understanding about the hydrological cycle, but also from the need to quantify the water resources and predict the impact of human activities or the occurrence of short-term or long-term natural events. They have also been developed to investigate how the available land and water resources can be best used for food and energy production, thus realising the importance of the water-food-energy nexus. They are also assisting in the protection of vulnerable water resources and ecosystems. The important aspect of adding economic perspectives to the decision process can be addressed through hydro-economic modelling.

Hydrological and meteorological monitoring systems and networks are becoming increasingly weaker (with regard to operation and maintenance, choice of monitoring equipment, skills, etc.) and their density and coverage are decreasing in many parts of the world. Data quality becomes a major issue. At the same time, technological advances in sensor technology and high levels of integration of electronics and data communication have made the automation of hydrological and meteorological networks increasingly affordable and the amount of raw data huge. In this situation, it becomes crucial to develop and use appropriate model codes and software to check, validate and handle the data in order to obtain the most benefit and to prepare it for assessments, analysis, simulations and forecasts. Real-time operations place additional requirements on the data stream and the model codes. In a fast-changing world, where climate change also poses huge challenges, efforts need to be made to collect, handle and use data more strategically, assisted by modelling.

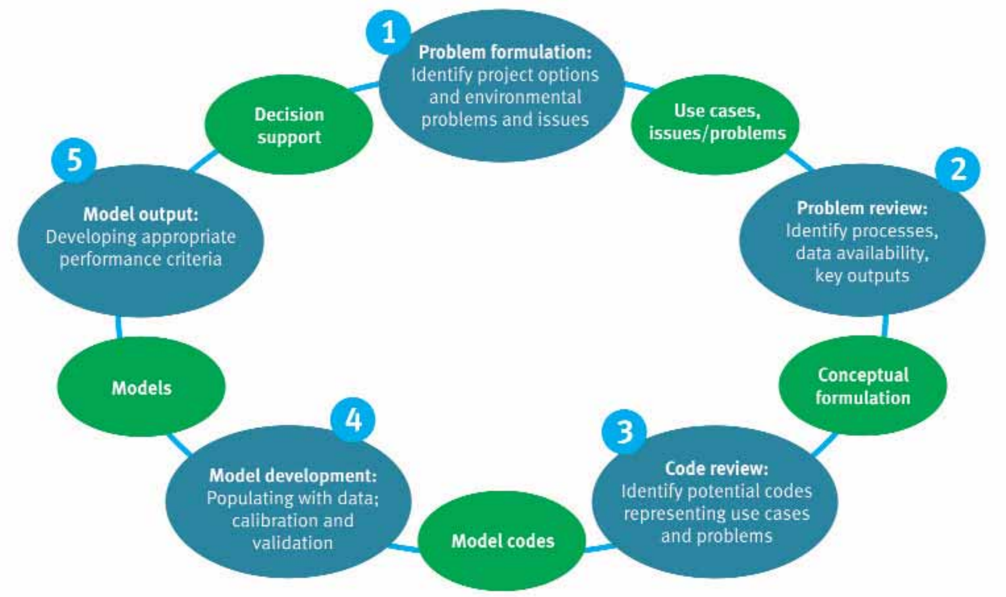
Model codes are indispensable analytical tools because they allow water resources professionals to conduct structured analyses of complex phenomena, which often require massive amounts of spatially and temporally varying data. With these tools, it is possible to make more reliable interpolations and extrapolations from existing data measured in the field and, thereby, enhance the information obtained from monitoring programs.

2.2 Model code development and application

A model code is a generic mathematical algorithm, so it can, without program changes, be used to establish models for different study areas, using the same basic type of equations. Generic model codes are effective and efficient tools, because they are not limited to use for one specific geographic area, one specific time period, or one specific problem. They are developed on the basis of a conceptual understanding of the natural system in terms of narratives, equations, governing relationships, or natural laws. When applied to a specific area and for a specific purpose, the *model code* becomes a site-specific *model* established for a particular study area, when it includes input data and parameter values (which can be temporally and spatially varying) which describe the area.

Models become powerful and reliable tools for water managers, when they are applied correctly. The credibility of a model's output for decision-making depends both on its ability to represent the natural system and the user's ability to ensure that it represents the system correctly by going through specific procedures of model *confirmation, verification, calibration and validation.* These steps ensure that 1) a correct understanding of the natural processes, 2) a correct description of these in terms of mathematical equations, 3) a correct set of parameters developed by comparing the model output with observed data, and 4) a correct prediction capability through model validation are achieved. Fig. 1 illustrates the above procedure.

Fig. 1. Illustration of the procedures for the application of models



Successful development and use of a model in IWRM depends on several factors, including:

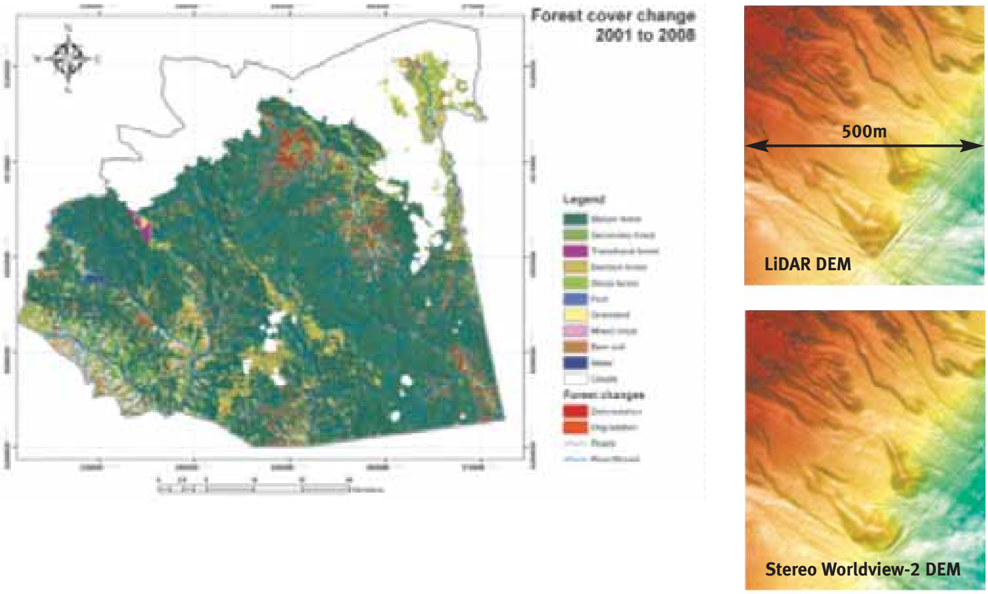
- Awareness of, and access to, appropriate model software
- Availability of qualified staff to undertake the modelling studies
- Availability of reliable data to create a model which can provide good decision support
- Appropriate guidelines/agreements for accepting the model results.

It is important to emphasise that the results and findings to be used in an IWRM process must be accepted by all parties involved, i.e. the decision-makers and the stakeholders. This requires openness and transparency in all phases of the model development and application in which the modelling principles, procedures and criteria are established. Furthermore, it is important to assess the model responses in relation to the data quality and availability and the associated uncertainties.

2.3 Types of model codes

Over time, the scientific community has been the main driver in developing mathematical model codes and models. As the need for such tools has become more evident to water agencies and decision-makers, the development of model codes has been taken also up by other organisations, including technological institutes, consultants and public water agencies. This has promoted the technological developments and increased the acceptance of their practical use.

Fig. 2. Examples of modern data collection techniques to support modelling. Satellite information about forest cover change (left), and detailed land surface information obtained from Lidar (an optical remote sensing technology) and satellite (right) [courtesy of Geographic Resource Analysis and Science A/S, Denmark)

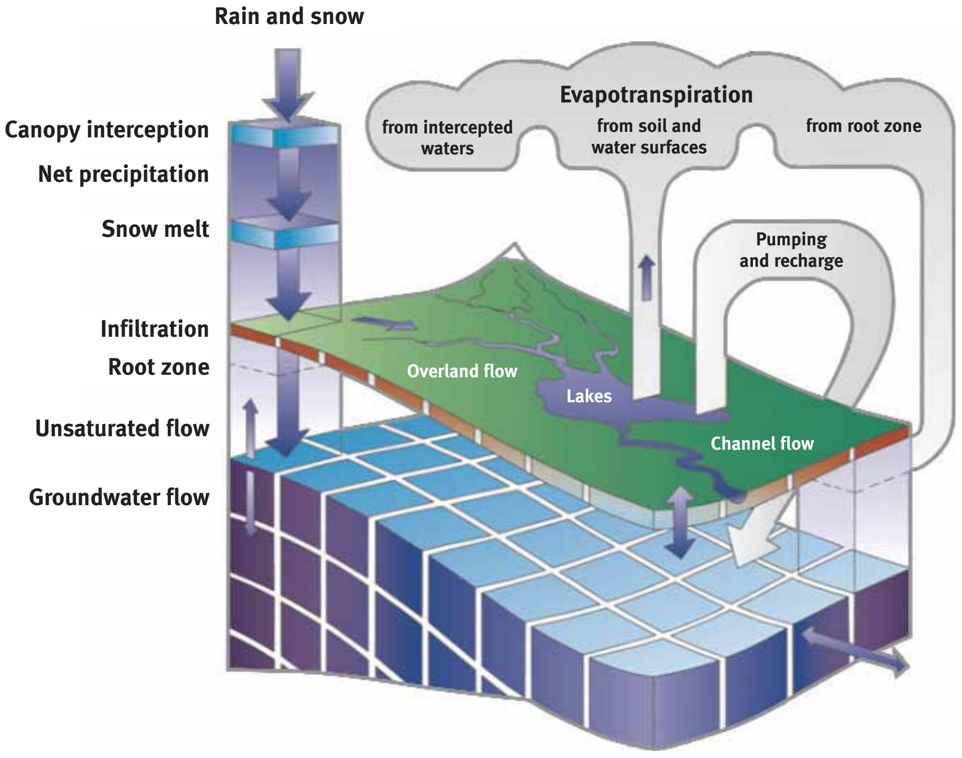


In practice, model code developments have been dictated by the requirements of water managers and, therefore, they do not automatically advance towards more detailed physical descriptions, but rather towards good conceptual descriptions reflecting the water management aspects. However, it is evident that many water management issues being encountered within IWRM are complex and require very detailed mathematical formulations. Therefore, today there exist a whole range of mathematical model codes, in the public and commercial domains, which can address almost any kind of water management problem. A brief introduction to some of the types of model codes which have been used in IWRM is given in the following section.

2.4 Watershed/catchment system model codes

As early as in 1969, Freeze and Harlan proposed a blueprint for modelling the hydrologic cycle. This blueprint described how various hydrological flow processes could be described mathematically and be solved numerically. The equations introduced were generally accepted to represent the physical processes at the appropriate scales in the different parts of the hydrological cycle. This blueprint presented an approach, which, at that time, was impossible to implement, because of computer technology limitations. Only recently, codes based on this concept are becoming fully operational.

Fig. 3. Illustration of the hydrological cycle as represented in a fully distributed and physically-based model code such as MIKE SHE



Approximately seven years later in 1976 Abbott initiated development of an ambitious mathematical model code, the Système Hydrologique Européen (SHE), following the concepts formulated by Freeze and Harlan. The motivation for developing SHE was that existing hydrological modelling systems of the lumped conceptual type, such as the Stanford model, the HBV model, and many others, were considered inappropriate for a range of analyses. These were not able to adequately address issues within the impacts of land-use change and the simulation of sedimentation and water quality processes at field and catchment scales, or account for both surface water and groundwater processes.

Since the mid-1980s two separate model codes, SHETRAN and MIKE SHE, emerged from this work to become advanced frameworks for hydrologic modelling.

Today, after continuous development and use in practice, MIKE SHE has become a modelling system (framework) for simulating the major processes in the hydrologic cycle and their interactions. Processes can be represented at different levels of spatial distribution and complexity, according to the needs, the availability of field data and the modeller's choices. Also, MIKE SHE can be nested within a river basin model and deliver detailed inputs to certain components of the basin model.

Mathematical model codes of the MIKE SHE type have a broad range of applicability and have been adopted and used operationally by water authorities and organisations ranging from universities and research centres to engineering consulting companies. This type of model code finds application in many areas requiring an integrated view of surface water and groundwater resources, as exemplified in Table 1.

Table 1. Areas of application where an integrated view of surface water and groundwater resources is needed

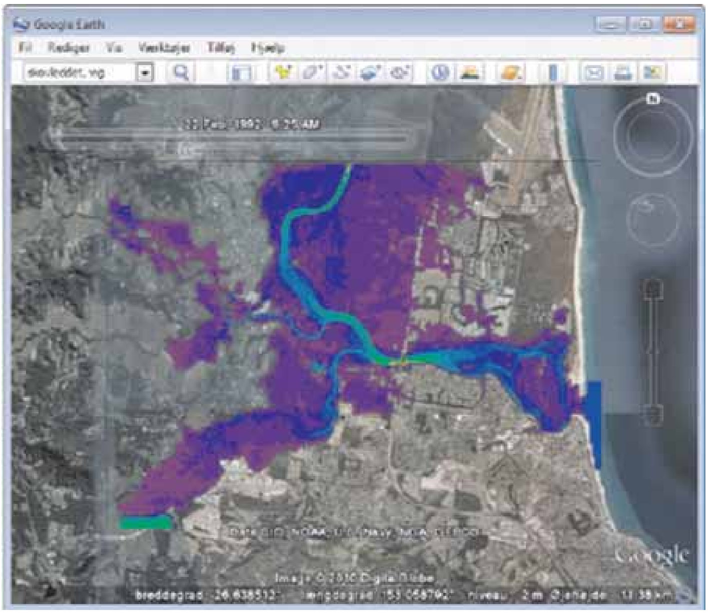
- River basin management and planning
- Water supply design, management and optimisation
- Irrigation and drainage
- Soil and water management
- Surface water impact of groundwater withdrawals
- Conjunctive use of groundwater and surface water
- Wetland management and restoration
- Ecological evaluations
- Groundwater management
- Environmental impact assessments
- Aquifer vulnerability mapping
- Contamination from waste disposal
- Surface water and groundwater quality remediation
- Floodplain studies
- Impact of land use and climate change
- Impact of agriculture (irrigation, drainage, nutrients and pesticides, etc.)

Although, the MIKE SHE concept has been increasingly recognised by hydrologists over the last 30 years, advanced codes have been developed and widely applied for single, specific parts of the hydrological cycle, e.g. for rivers/canal systems or for groundwater aquifer systems.

2.5 Model codes for rivers, canals and sewer systems

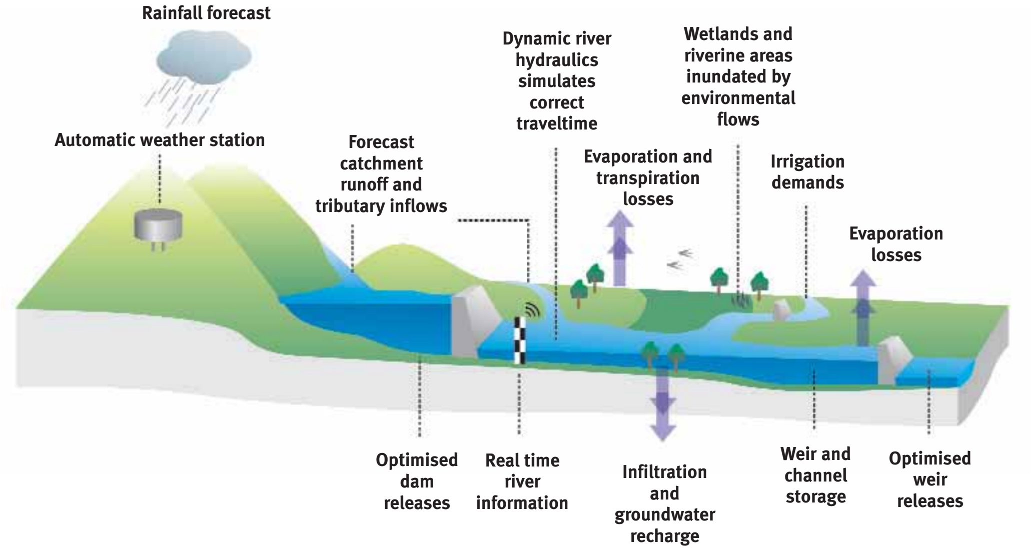
Mathematical (hydraulic) models for river, channel and sewerage systems are perhaps the most widely used types of modelling codes available to water authorities and their consultants. These codes emerged in the 1980s. They have proven to be important tools for investigating and predicting the in-stream flows, travel times, and water level variations in rivers, channels and canal systems. As floodplains have become preferred areas for habitation, floods have increasingly adverse impacts on economic activities and result in loss of life and property. Accurate and reliable flood analysis and management and flood forecasting provide, therefore, important bases for mitigating flood hazards and issuing early warnings. In recent years, in-stream hydraulic model codes and real-time simulations have been important instruments for the above issues.

Fig. 4. Example of dynamic flood prediction illustrated as an application in Google



Since water is a limited resource, efficient use of water can mean high economic gains in irrigated agriculture. Through the real-time operation of dams and structures, water can be delivered in the right amount, at the right place, and at the right time. In many river basins around the world, water is a limited resource and river operations, which minimise losses and improve delivery efficiencies, are vital to ensure equitable, reliable and sustainable use of a limited and valuable resource.

Fig. 5. Illustration of important issues and factors involved in real-time river operation



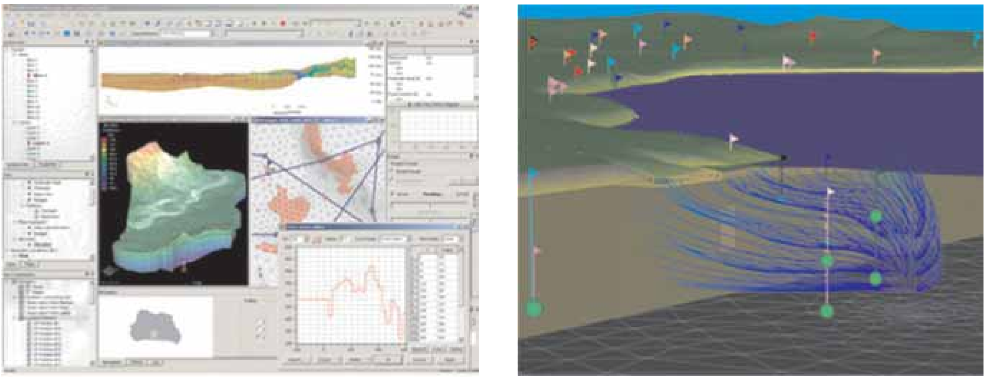
2.6 Groundwater aquifer systems

A water supply based on groundwater is often both economically and environmentally desirable, and many countries rely in part or solely on such a supply. The sustainable development and protection of groundwater resources include integrated groundwater and surface water assessments to ensure that sustainable exploitation of groundwater resources takes place. Model codes support authorities in their evaluations regarding:

- Identification of suitable well field locations, aquifer yields and their roles in the basin water balance
- Estimation of net rainfall and groundwater recharge, delineation of well head protection zones, and expected changes in groundwater recharge and capture zones with changes in water extraction patterns, land use, or climatic conditions
- Environmental impacts of groundwater developments on surface water depletion and degradation
- Evaluation of leaching risks for diffusive pollution (nutrients and pesticides) and leaching risks from point sources
- Seawater intrusion
- Impacts of industrial activities, e.g. mining.

Detailed groundwater models, which can simulate flow in two or three dimensions, provide the means to build large regional-scale models without losing local precision where necessary.

Fig. 6. Illustration of advanced groundwater modelling of path lines for assessing e.g. recharge zones



2.7 Water management systems

A set of important mathematical model codes, which have been developed over the years, are sometimes categorised as river basin model codes. These may be used for determining long-term water sharing and allocation arrangements or operational river basin planning. River basin model codes are relatively simple network-oriented codes, representing relevant water transfers and storage operations based on the spatial and temporal variation in water availability and water demand. These models enable authorities to better understand the impacts of different water allocation scenarios and operational regimes and their corresponding benefits, and to evaluate the trade-offs between water releases made for competing sectors. An example of such a model code is DHI's MIKEBASIN which has shown a wide range of applicability.

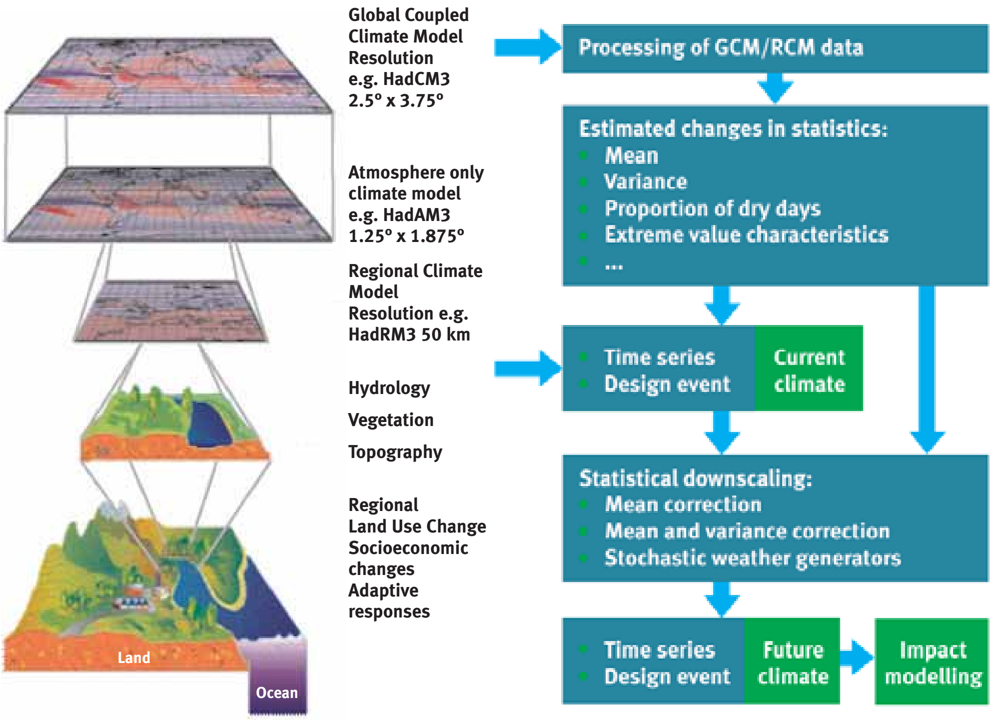
Fig. 7. Example of schematisation of a river network for river basin planning in Greece

2.8 Climate change impact assessment and adaptation

Many water authorities are concerned with the impacts of, and adaptation to, climate change. The basis for climate change impact analysis at the river basin scale is formed of climate change projections at the global scale using General Circulation Models (GCM). These models simulate the future climate (up to the year 2100) according to different development scenarios quantified in terms of emission scenarios for CO_2 and other greenhouse gases. In reports from the Intergovernmental Panel on Climate Change, results from GCMs are reported, each considering several emission scenarios. The GCMs model the atmosphere on a rather coarse horizontal scale (typically of the order of 200-300 km). For climate change studies, therefore, it is necessary to downscale the climate change projections.

Dynamic downscaling is based on Regional Climate Models (RCM), which use GCMs as boundary conditions to simulate the state of the atmosphere in a region with a smaller grid resolution than that used in the GCM. RCM models are usually defined on a grid size of 10-50 km and are able to better represent topography and land use heterogeneities than GCM models. Statistical downscaling procedures may be required for different types of applications, ranging from simple mean correction (delta change) procedures to more complex stochastic weather generator procedures which provide more reliable downscaling of extreme events. In order to facilitate the analysis of climate change impact and adaptation, a DSS should be able to use (or simply include) the climate change projection data produced by the GCM simulations.

Fig. 8. Model used for downscaling climate change projections



2.9 Hydro-economic models

Hydro-economic modelling has been used since the 1960s. The basic characteristics of hydro-economic models are detailed in Box 4.

Box 4: Characteristic elements of hydro-economic modelling

- Integration of hydrologic, agronomic and economic relationship in an endogenous system that allows for adaptation to changes in environmental, ecological and socioeconomic states
- Hydrological model codes that represent mass balance of surface water and/or groundwater stocks and flows across time and spatial scale, including water management infrastructures that affect those stocks and flows
- Economic model codes that represent measures of water demand or benefits (producer and consumer surpluses), arising from off-stream use (agriculture, industry, domestic) as well as in-stream use (hydropower, recreation, waste dilution, environmental purposes) from all sectors
- Specification of a river basin network that includes a water supply system (surface and groundwater), delivery system (canal network), water-user system (agricultural and non-agricultural), drainage collection system, waste water disposal and treatment system, and connections between these sub-systems
- Costs, which include: 1) operating costs related to pumping, water abstraction, treatment, artificial recharge, water delivery; and 2) externality costs
- Institutional rules and constraints related to water allocation, such as legal regulations, social or informal rules, market-based instruments and property rights
- Incorporation of economic incentives to address inefficiency and externality problems
- Spatial models that serve as platforms to integrate hydrological and economic models.

Applications of hydro-economic modelling span a wide range of water issues and geographical locations, as well as innovations. One of the advantages of hydro-economic modelling is its ability to explicitly address the issue of externality, environmental flow and equity in the model. The value of externalities and the environmental value can be estimated using both market-based and survey techniques. Alternatively, an environmental flow can be set as a constraint. Likewise, institutional and political criteria can be included as constraints in the model. Further, equity issues can be assessed in different ways, such as the distribution of benefits and costs across groups of water users, comparison between inter-temporal and spatial equity, the effects of differential pricing to water-user groups and inter-generational equity.

There are a number of challenges in building hydro-economic models that can adequately integrate the hydrological and economic components. For example, the boundaries of the economic sub-systems (political and administrative) might be different from those of the hydrological sub-systems. This will have implications for data collection and management as well as in aligning socioeconomic impacts with hydrological or biophysical spatial units. There may also be differences in time steps and the planning horizon between hydrological processes and economic ones. Economic models most often involve larger time steps and longer planning horizons, while hydrological models require small time steps to reflect real-world processes with the horizon for analysis determined by data availability and computational capacity.

3 Decision Support Systems (DSSs) for IWRM

In parallel with model code developments, DSSs have been developed over the years. A DSS can be characterised as interactive software which assists in using data and information and providing answers for decision maker on complex issues.

Traditionally, DSSs have been used within many disciplines. In some cases within water resources management, the DSS concept has evolved independently of mathematical model codes, and in other cases as simple enhancements of existing mathematical model codes with a graphical user interface and a set of post-processing tools.

The DSSs have emerged in an attempt to make model codes more usable for water authorities, by building an information technology (IT) framework, which is tailored to the requirements of the decision-making process and supports the workflow of authorities. A DSS typically encompasses additional capabilities beyond the modelling framework, including tools for data and information management, socioeconomic evaluation tools and an (interactive) communication framework for sharing and disseminating information to the public, as illustrated in Table 2.

Table 2. Potential generic functionalities required in a modelling/DSS framework for IWRM

Potential functionality	Potential use
Data base and processing environment	- Coordinated use of available data bases - Efficient use of all existing information - Data review and data quality checking - Data analysis and processing - Identification of cost-effective monitoring programs
Knowledge and information system	- Keeping track of basin studies and initiatives - Knowledge sharing among relevant stakeholders - Annotated bibliographies of available relevant literature - Creating reports, e.g. Basin Plans and "The State of Basin Reports" and other material promoting public accountability
Modelling analysis frameworks	- Hydrologic/hydrodynamic analytical tools covering multiple river basin aspects - Sector analysis of water consumption and impacts (e.g. irrigation, hydropower) - Environmental analysis (wetlands, flows, land-use change, water quality, sediment loads) - Adaption to e.g. climate change
Socioeconomic analysis	- Identification of sustainable options acceptable to stakeholders

Continued on next page

Table 2. Potential generic functionalities required in a modelling/DSS framework for IWRM *Continued...*

Potential functionality	Potential use
	■ Multi-criteria analysis for the objective comparison of alternative plans ■ Cost-benefit analysis ■ Benefit sharing/trading
Communication framework (e.g. public web portal)	■ Stakeholder involvement ■ Proactive information sharing and networking ■ Supporting involvement of stakeholders ■ Consensus building and conflict resolution ■ Training activities

IWRM at the river basin level deals with many facets of water management, from striving for water security for all purposes in a sustainable and equitable manner to being able to manage and mitigate disaster risks. This can be supported by a DSS by developing and adding generic tools, many of which water resources planners may already be acquainted with from their daily work. Fig. 9 presents examples of such tools.

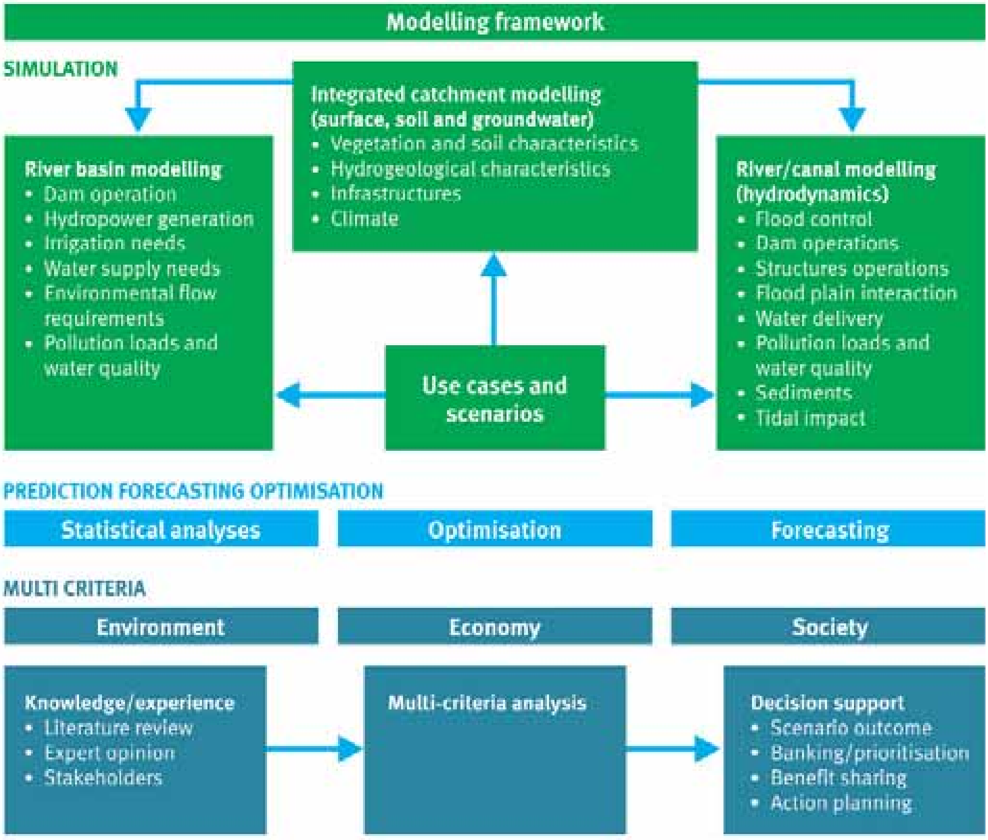
Fig. 9. Examples of generic tools which may be included in a DSS platform

3.1 DSS modelling frameworks

An open modelling interface will allow a generic DSS framework to access and apply mathematical models from different suppliers within the DSS for the management purposes required, e.g. general water resources management, flood management, climate change analysis, etc. An open interface to model codes requires so-called adapters, which enable the DSS to access prepared input data and model parameters, and store relevant model results. The benefits of an open architecture and adapters are that the DSS is not tied to a particular vendor and, moreover, that new tools developed in the future can be plugged into the DSS. Often model codes have already been developed, accepted and applied by a water authority, and instead of replacing them with new model codes, the creation of adapters to existing codes ensures that the work already invested in existing model codes is not wasted.

Fig. 10 illustrates an example of a configuration of a DSS framework as an umbrella for a series of model codes and other tools.

Fig. 10. Example configuration of a DSS framework



3.2 Optimisation

Optimisation algorithms capable of optimising one or more model parameters, given a number of user-defined competing objectives, can be valuable in different aspects of IWRM. Optimisation can be used to carry out automatic model calibrations as well as identifying optimal strategies for e.g. the operation of reservoirs and other structures taking into account competing objectives, such as flood protection, minimum flow requirements and the demands of water users.

In establishing an accurate and objective decision basis for the decision maker, the DSS must include a provision for undertaking *multi-criteria analyses*, which process selected information, typically time series of forecast results or measured time series, to compute a set of indicators for a range of possible strategies. If indicators can be derived from the modelling scenarios and compared, they can provide a transparent and objective decision basis.

3.3 Web publishing

As described above, dissemination of information and knowledge and communication (preferably interactive) with the public is an important facet in IWRM-related DSSs. Public web pages can be established for disseminating data, relevant information and model simulation results, which are considered appropriate for the public. Web publishing offers an easy way to provide access control, allowing various organisations different access rights.

Fig. 11. Illustration of DSS web portals incorporating GIS functionality and time series visualisation

4 DSS and its role in informing IWRM and development processes

There are many issues and challenges in the IWRM process at the river basin level. To comprehensively address these, analytical tools are required, preferably included in a DSS.

To obtain a comprehensive and reliable overview of the water resources status and the possible problems and conflicts, it is necessary to carry out water resources assessments in which water availability is compared with the water demands in time and space. Water demand can arise from sector needs as well as environmental ones for sustaining ecosystems.

Reliable water resources assessments may be hampered by the lack of information on what data is available as well as the lack of data to get an overview of water availability and water demands. DSSs may play an important role in the provision of the framework for an information management system (IMS) in which all relevant data can be collected, stored, displayed, analysed and processed. Once this is established, analytical tools, e.g. hydrological models and water resources management models, can use this information to establish an overview of water availability and relate this to the existing and future water demands. In developing countries this can be used to define the needs for and establish appropriate monitoring of networks, which are tailored to the country's capabilities. In this respect monitoring and modelling may provide an efficient and cost-effective combination for establishing an adequate information basis for water resources assessment.

A transparent and cooperative water management is one of the success criteria for the IWRM process. A DSS provides a good and efficient platform for interactive communication with stakeholders and the public by sharing data, information, studies and decisions. Using a DSS to publish such information on the internet, with appropriate links to the data and information repositories, provides an efficient means of communication.

A DSS also provides an effective platform for management and strategic planning and an understanding of the future impacts of multiple factors, e.g. population growth, climate change, land-use change, economic development, energy supply and needs, etc. The use of appropriate models in the DSS, combined with the development of indicators and multi-criteria ranking and cost-benefit analysis, provides an effective tool for identifying the most desirable solutions. The DSS can be used also in a more operational manner to handle basin issues, e.g. water allocation, or alleviate potential disasters, e.g. flood or drought management.

Comprehensive DSSs have been adopted traditionally in countries where accurate decisions have a significant economic impact. An example is the efficient use of water in major irrigation schemes, where the timely delivery of water has an important impact on the economic benefits. Another example is the prevention of disasters, e.g. floods, where appropriate operations and warnings can have huge impacts on the economy and the livelihoods of the population concerned.

The DSSs can also be effective tools for infrastructure development (e.g. reservoir construction), or enhancement (e.g. sewer systems) to adapt to climate change and extreme events. For this last purpose, urban DSSs have been developed. These systems are often based on a real-time registration of flows and levels in the sewers and drains and will give alerts and instructions for the opening and closing of gates, operation of pumps and use of retention basins, for instance. In many cases the instructions are automatically implemented without manual interference.

4.1 The IWRM cycle and the DSS's role in each component

Fig. 12 illustrates the IWRM cycle and its key components. The starting point for IWRM often lies in water resources issues at the transboundary, national or basin level. Political will and stakeholder support are essential to move the process forward. Gaps, potentials and constraints in management need to be analysed, leading to a strategy and action plan for continued progress. Political will, stakeholder acceptance and funds are prerequisites for the next step, which involves the implementation of the IWRM frameworks. A monitoring and evaluation exercise will serve to establish the new status of IWRM and, if necessary, the steps in the cycle can be repeated, fully or in part.

Table 3 illustrates where in the IWRM cycle a DSS can play an important role by addressing the key issues and challenges often found in water resources management.

Fig. 12. The IWRM cycle and its key components

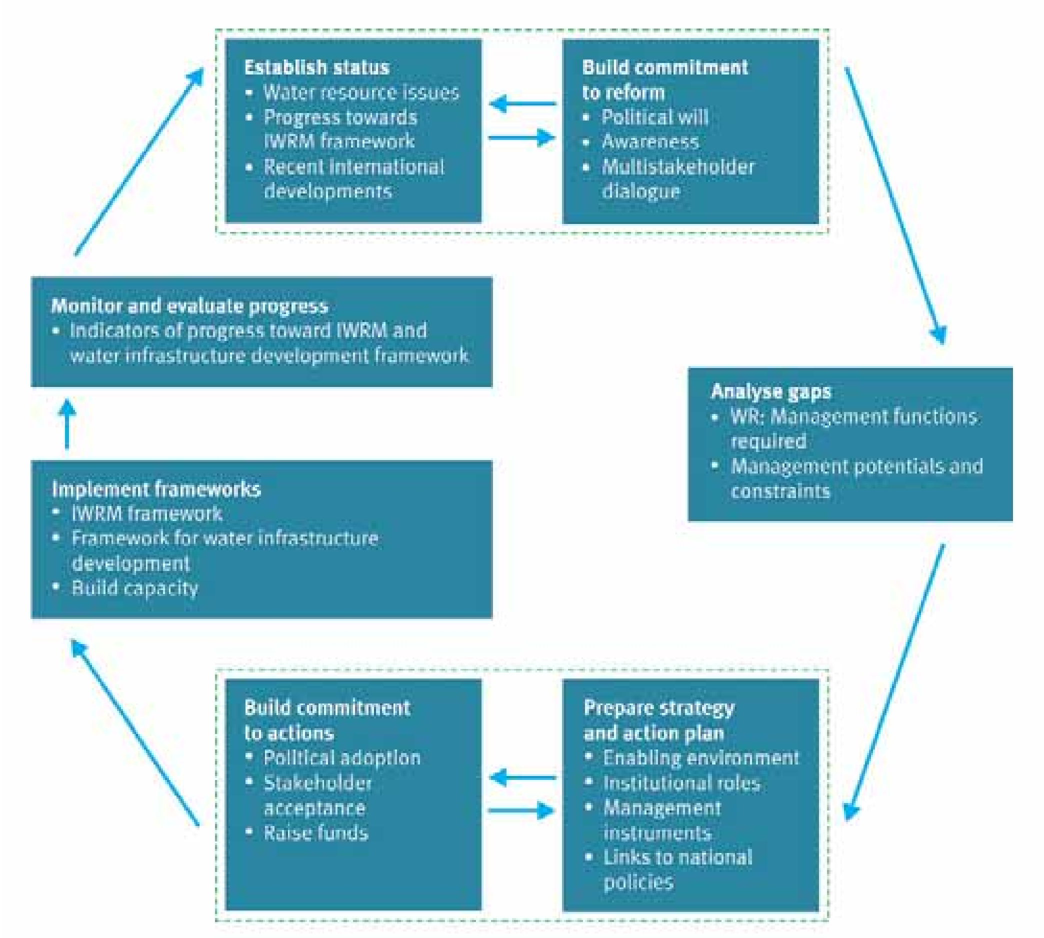


Table 3. Issues and challenges in IWRM where a DSS can contribute to management processes

Components of IWRM cycle	Issues and challenges	DSS role and contribution to water resources management
Water resource status and Issues	■ Poor knowledge of water resources availability and scarcity	■ A comprehensive structure to review the water resources of a basin
	■ Water resources data scattered and difficult to access	■ A repository for water resources and water use data
	■ Data processing uneven and made in an ad hoc manner	■ A tool for data processing
	■ Poor knowledge of geographically distributed water surpluses/deficits	■ A tool to compare water availability and demand
	■ Impact estimates predominantly qualitative	■ A tool to assess environmental and socioeconomic impacts
Commitment to reform and actions at the political and stakeholder levels	■ Low awareness of water resources management at the stakeholder level	■ A platform for communication and stakeholder interaction
	■ Reform objectives are unsupported statements	■ Structured evidence to underpin reform objectives
	■ Reform measures and objectives are not coherent	■ A tool to evaluate reform measures against objectives
	■ Political dialogue has little or no evidence base	■ A tool to underpin political dialogue
	■ Information is not sufficiently available nor understood	■ Increases transparency of information
Management framework and functions	■ Scenarios, climate change risks and environmental risks are not systematically analysed	■ A tool for scenario and risk management planning
	■ Strategic planning is done using a poor evidence base	■ A tool for strategic planning
	■ Investment planning is done on a precarious basis	■ A tool for investment planning
	■ Operational planning and management is done in a static fashion	■ A tool for operational planning and management
Strategy and action plans	■ Multi-criteria analysis is lacking in the set of management instruments	■ A tool for options, scenarios, trends, forecasts and multi-criteria analysis
	■ Allocation is done in a haphazard manner and without environmental flow considerations	■ A tool for allocation management and environmental sustainability planning

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Table 3. Issues and challenges in IWRM where a DSS can contribute to management processes *Continued...*

Components of IWRM cycle	Issues and challenges	DSS role and contribution to water resources management
Implement management frameworks	■ Regulations, rules and instruments applied without solid evidence of the consequences	■ A tool to design and test reform of management rules and instruments (regulations, social or informal rules, market-based instruments, property rights)
	■ Economic instruments are applied without thorough impact estimates	■ A tool to incorporate economic incentives to address inefficiency and externality issues
Implement Infrastructure development under the management framework	■ Impact of infrastructure not known in sufficient detail	■ A tool to determine the location, scale and the cost effectiveness of infrastructure
	■ Irrigation systems impact not known in sufficient detail	■ A tool to assist conceptual design of irrigation systems
	■ Hydropower systems impact not known in sufficient detail	■ A tool to assist conceptual design of hydropower infrastructure
	■ Environmental flow requirements not taken sufficiently into account	■ A tool to determine environmental flow requirements
	■ Flood protection and drought emergency plans not sufficiently evidence-based	■ A tool for the conceptual design of flood protection and drought emergency plans
	■ Optimal design of urban water systems not achieved	■ A tool for the conceptual design of urban water systems
Monitor and evaluate progress within the management framework and infrastructure development	■ Monitoring of development objectives indicators is deficient	■ A tool to benchmark and assess progress against development objectives
	■ Management is not sufficiently informed about issues and lack of progress	■ A tool to provide feedback to management on progress and to facilitate management responses
Operate water resources management infrastructure	■ Operation of infrastructure is done in a static and haphazard manner	■ A tool for optimisation analysis
	■ Real-time operations lacking	■ A tool to manage real-time operations
	■ Disaster risks and emergency responses are insufficiently assessed	■ A tool to manage disaster risks and emergency response

4.2 DSS and hydro-economic modelling applications on the ground

Over time, the applications of DSSs and of hydro-economic modelling have demonstrated their strength in assisting decision-level staff to address issues relating to IWRM. Seven notable examples/cases are described briefly in the Annex and they are summarised below.

4.2.1 Mekong River Decision Support Framework (DSF)

The DSF for the Lower Mekong Basin is an example of a transboundary decision support system where four countries – Lao People's Democratic Republic, Vietnam, Cambodia and Thailand – together have developed a system which allows them to assess development scenarios and their impacts. The Mekong River has immense socioeconomic and environmental value for the four countries and is a determining factor in the livelihoods in the basin. Water supplies, irrigation, hydropower, fisheries and river transport are among the sectors depending on the river system. The applications of the DSF have greatly assisted in understanding the river regime, its robustness, and the impacts of infrastructure developments. Thus, cooperation on, and coordination of, water resources developments have been considerably enhanced.

CASE TITLE

Mekong River Commission (MRC) – Decision Support Framework (DSF) – Basin Modelling and Knowledge Base developed under the Water Utilisation Programme (2002-2007)

MRC Decision Support Framework

Development of a comprehensive knowledge base and a suite of numerical basin models and modelling tools, collectively known as the Mekong River Commission's Decision Support Framework (Mekong DSF), were undertaken under the Water Utilisation Programme of the MRC during the period 2002 to 2007. The objective was to enable description of the changes in river flow and assessment of related biophysical, social and economic impacts that may occur as a result of infrastructure development – mainly irrigation and hydropower – and climatic variations within the basin. In this way IWRM processes in the basin would be supported. The DSF was developed in a fully participatory manner with the MRC member states and resulted in a new understanding of the management and development of the water and related resources within the basin.

4.2.2 Nile Basin Decision Support System

When fully developed, the Nile Basin DSS will assist the nine riparian countries in the basin on their road towards IWRM. The riparian countries on the Nile River are hugely dependent on the river. Egypt, for example, has no other source of water than the Nile and upstream water resources developments will decrease water availability. Historically, competition for the water of the Nile has been a key issue between the riparian countries, especially for those countries downstream of Lake Victoria. The Nile Basin Initiative has recognised the need for tools and knowledge bases to assist the riparian countries in their assessment of water resources development scenarios and projects. The present DSS development work has resulted in two interim releases and a deployment of the Nile Basin DSS takes place in September 2012.

CASE TITLE

Development and Deployment of the Nile Basin Decision Support System (2010-2012)

A DSS was developed for the Nile Basin Initiative under the Water Resources Management Project based in Addis Ababa, Ethiopia (World Bank funded)

Nile Basin DSS

The riparian countries of the Nile – Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda – have embarked on the Nile Basin Initiative (NBI). The NBI is governed by the Council of Ministers of Water Affairs of the Nile Basin States and seeks to develop the River Nile in a cooperative manner, sharing socioeconomic benefits and promoting regional peace and security. Their shared vision is to "achieve sustainable socioeconomic development through the equitable utilisation of, and benefit from, the common Nile Basin water resources." A Strategic Action Program (SAP) should translate this vision into concrete activities and projects. An important part of the shared vision is the establishment of shared and accepted water management tools and technologies. For this purpose the Nile Basin DSS was developed.

4.2.3 DSS including hydro-economic modelling in the Euphrates-Tigris region

This case illustrates the value of a decision support tool with substantial economic content in initiating cooperative activities and starting discussions on joint decision-making regarding transboundary water resources development. Pressures on water resources and the upstream-downstream competition for these scarce resources have encouraged the four riparian countries – Iran, Iraq, Syria and Turkey – to cooperate in tool development and use. The model shows the trade-offs in water use across sub-basins and the benefits to be reaped from increased water use efficiency in the region.

CASE TITLE

Hydro-economic Modelling in the Euphrates-Tigris Region

Euphrates-Tigris hydro-economic modelling

The four riparian countries in the Euphrates and Tigris (ET) Region – Iran, Iraq, Syria, and Turkey – recognise that rapid population growth and economic development will increase the demands for water for energy production, food production, industry, and domestic use at the regional level, while ecosystem goods and services need to be maintained and/or restored. Hence the already high pressure on the freshwater resources in the region will

Continued on next page

CASE TITLE

Hydro-economic Modelling in the Euphrates-Tigris Region *Continued...*

increase unless radical measures to generate more value from the existing water resources for all the riparian countries are implemented. For these reasons, a hydro-economic model, populated with publicly available data, was created to analyse the potential benefits of cooperative actions in water management.

4.2.4 Zambezi River Basin Multi-sector Investment Opportunities Analysis (MSIOA)

The work on MSIOA combined hydrologic and economic modelling tools to provide a comparative assessment of the economic implications of various development scenarios. The analysis sought to determine and maximise mutually beneficial economic gains while meeting essential water supply and environmental sustainability requirements. The analysis focused primarily on hydropower and irrigation as the key investment areas in the Zambezi Basin. The analysis demonstrated that the riparian countries could achieve short- and long-term benefits through coordinated operation of existing and planned hydropower facilities, cooperative flood management and cooperative irrigation development.

CASE TITLE

The Zambezi River Basin Multi-sector Investment Opportunities Analysis (MSIOA)

Hydro-economic modelling in Zambezi Basin
The objective of the Zambezi River MSIOA was to demonstrate the mutual benefits of cooperation among the eight riparian countries in the Zambezi River Basin (ZRB) through a multi-sector economic evaluation of water resources development and management options and scenarios from both national and basin-wide perspectives. The study, funded by the World Bank, was carried out between 2008 and 2010 in consultation with the riparian states, the South African Development Community (SADC) Water Division and Development Partners. It built on the earlier Zambezi Action Plan Project 6, Phase II (2008) with the intention of informing decision-making on optimal development, environmental sustainability and poverty alleviation in the region.

4.2.5 DSS including hydro-economic modelling in the Rio Grande Basin

This modelling case illustrates the value of including substantial economic content in the decision support tool to sustain assessments of various management options. The pressures on water resources and the upstream-downstream competition for the scarce resources are found to be the key drivers for cooperation in tool development, use and assessments.

CASE TITLE

The Application of Hydro-economic Modelling in the Rio Grande Basin

Hydro-economic modelling in the Rio Grande basin
The Rio Grande is a transboundary river basin shared by the USA and Mexico. It is governed by a complex set of institutions, with long-standing competition for water resources and an increasing water demand. Most of the water is used for agriculture (85%), while the river also supplies three major cities (Albuquerque and El Paso in the USA and Ciudad Juárez in Mexico). Despite a number of well-established institutions governing the Rio Grande, further developments in management will be needed to address current and future challenges. Three key issues facing the Rio Grande are an unsustainable abstraction rate, the reallocation of water from agriculture to other uses, and provision of safe and affordable water to all. These issues are subjected, therefore, to hydro-economic modelling.

4.2.6 The Okavango River Basin Decision Support System

This DSS was developed in the context of a Transboundary Diagnostic Analysis (TDA) and a Strategic Action Program (SAP) supported by the Global Environment Fund. The custom-built DSS was produced to interpret the ecological and livelihood impacts of flow changes and estimate their impact on the overall river basin health and socioeconomic status. The DSS tool can be used to explore any further water resources development scenarios of interest in the Okavango River Basin and can be updated with new knowledge and responses over time.

CASE TITLE

The Okavango River Basin Decision Support System

Decision Support System capturing ecological and social outcomes in scenario studies
The Permanent Okavango River Basin Water Commission (OKACOM), with the participation of Angola, Namibia and Botswana, initiated a project, with Global Environment Facility funding, to develop a Transboundary Diagnostic Analysis (TDA) and a Strategic Action Program (SAP) for the Okavango Transboundary River Basin. Whereas the objective of the TDA was to identify current and anticipate emerging pressures on the river basin, and attempt to estimate their transboundary impacts, the objective of the SAP was to develop a program of actionable interventions for the sustainable management of the river and related resources. A DSS was developed, where the future scenarios, flow regimes and response curves for biophysical and socioeconomic parameters were combined in order to assess the outcome of selected scenarios.

4.2.7 'DSS Planning' for integrated water resources development and management in India

A DSS Planning system was developed for the Upper Bhima River Basin in Maharashtra State, India with the intention of rolling out similar systems for other participating states. The ‘DSS Planning’ system sought to address issues within the planning of reservoir management, conjunctive use of surface and groundwater, the planning of seasonal groundwater use, artificial groundwater recharge, drought monitoring, flood analysis and water quality modelling.

CASE TITLE

National Institute of Hydrology, India, 'DSS Planning' for Integrated Water Resources Development and Management; developed under the Hydrology Project II (2008-2012)

Development of a 'DSS Planning' tool for several states in India
Requirements for integrated water resources and water security planning and management are increasing as a result of increasing population pressures and the associated competing water demands from, among other sectors, agriculture, industry, domestic supplies and the environment. The project was defined with the objective of developing a customised DSS – 'DSS Planning' – applicable to several states in India. It would address issues identified specifically in each state within: (i) surface water planning; (ii) integrated operation of reservoirs; (iii) conjunctive surface water and ground water planning; (iv) drought monitoring, assessment and management; and (v) management of both surface and ground water quality. 'DSS Planning' is based on DHI's generic DSS framework.

5 Sustainability issues in DSS

There are many examples of models and expensive software which have been used only a few times by the client organisation and then have been considered obsolete. As early as in the planning phase, when the need for a DSS is realised, the constant use and maintenance of the system has to be considered and the conditions for a continued benefit from the DSS have to be listed, itemised and assessed. The overall condition is the 'need' for a DSS. The organisation embarking on a DSS project must have a strongly felt need at the management level. Scarce water resources, competition for water, serious water pollution and frequent risks (floods and droughts) will make decisive management responses necessary and emphasise the need for a DSS to support IWRM approaches. Key considerations on the sustainability of a DSS are given below.

5.1 Requirements of software, supplier, and client

- The client should have clear 'ownership' of the DSS, which requires that it is developed in a participatory manner and riparian countries need to acknowledge the validity of the model results to inform the decision-making processes
- The gap between the 'modellers' and the users should be bridged by defining how the system will be used and making sure that the model software can simulate the defined situations
- The DSS framework should be open-ended to support changes and new needs
- The DSS software must support efficient knowledge/information sharing and stakeholder participation through web solutions
- The DSS must support the use of new or emerging technologies for data and information capture and accommodate different levels of data availability
- The DSS must be flexible and able to provide solutions which match the technical capabilities of the receiving institution
- The software provider must be capable of responding to urgent needs for new codes or functionality
- The software supplier must be able to provide continuous and long-term technical support and maintenance.

5.2 Organisational requirements

- The DSS needs to be anchored in an appropriate department with staff with technical knowledge of IWRM
- The DSS team needs to have their responsibilities clearly defined
- The DSS department needs to have strong links to the management level regarding delivery of analyses, assessments and recommendations on IWRM
- The organisation needs to have an IT support function
- The organisation needs to have strong links to sector stakeholders in order to accommodate their development plans and water requirements
- The organisation needs to have a communication team to ensure that the public is sufficiently involved, e.g. through workshops and web sites – SharePoint discussion forums, etc.

5.3 Training requirements

- New technical staff need to be trained continuously to maintain a highly qualified, experienced DSS team
- Incentives and career planning should be established to keep existing staff and recruit new staff
- Training in new codes and new functionalities should be received from the software supplier.

5.4 Financial requirements

- Funds must be available to request services from the software supplier and/or the consultants, e.g. for technical support and upgrading of the DSS, or for applying the DSS to new projects
- Funds must be available to sustain a DSS team in the appropriate department
- Funds must be available to upgrade computer/IT equipment regularly and to pay for Internet services
- If appropriate, the DSS team can create revenue by delivering services to other agencies/organisations.

Thus, it is clear that the institutional and financial environment in which the DSS will function is just as important as the functioning of the model codes and other software.

Annex: Seven cases of the application of DSS and hydro-economic modelling

- Mekong River Commission (MRC) - Decision Support Framework (DSF)
- Development and Deployment of the Nile Basin Decision Support System
- Hydro-economic Modelling in the Euphrates-Tigris Region
- The Zambezi River Basin Multi-sector Investment Opportunities Analysis
- The Application of Hydro-economic Modelling in the Rio Grande Basin
- The Okavango River Basin Decision Support System
- National Institute of Hydrology, India, 'DSS Planning' for IWRM

CASE TITLE

Mekong River Commission (MRC) – Decision Support Framework (DSF) – Basin Modelling and Knowledge Base developed under the Water Utilisation Programme (2002-2007)

Rationale

A comprehensive knowledge base and a suite of numerical basin models and modelling tools – collectively known as the Mekong River Commission's Decision Support Framework (Mekong DSF) – were developed under the Water Utilisation Programme of the MRC during the period 2002 to 2007. The objective was to describe changes in river flow and assess the related biophysical, social and economic impacts that may occur as a result of infrastructure development – mainly irrigation and hydropower – and climatic variations within the basin. In this way IWRM processes in the basin would be supported.

Description

The Mekong DSF was developed between 2002 and 2004 in a fully consultative and participatory manner with the Mekong Basin member states by an international consultant supervised by the MRCS under the Water Utilisation Programme. The DSF was endorsed by the MRC Joint Committee in 2004, so the modelling results are understood to be mutually acceptable to all MRC member countries. The DSF consists of a set of core features and add-ons. The core includes the ability to store the required data and results in a consistent and auditable manner, the ability to transfer these results between the different tools and export quality-assured information in reports to other users, or to a MRC-Master Catalogue. The add-ons include different process models to analyse the behaviour of the water and related natural resource systems (whether physical, biophysical, social, or economic), together with the necessary tools to visualise, analyse and report on the results of the process models. Add-ons also include local area models, which may be developed to meet specific needs. Since completion of the DSF in 2004, there have been many applications of the modelling tools, notably including modelling support to the World Bank study in preparation for the Mekong Regional Water Resources Assistance Strategy and, in particular, the report *Modelled Observations on Development Scenarios in the Lower Mekong Basin, November 2004*. The first applications of the modelling tools through these

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assessments have revolutionised understanding of the potential impacts of water resources development in the Mekong Basin. They represented the first comprehensive assessments of a wide range of basin developments, including mainstream dams in China. An important outcome is that we now understand that the Mekong flow regime is highly robust and that, with good planning and management, there is likely much room for infrastructure developments benefiting all member states and including China.

Lessons learned

- The Mekong DSF is the first suite of such numerical models developed in a fully participatory manner with the MRC member states. It was accepted by all members of the MRC Joint Committee in 2004. Its development and application revolutionised understanding of the management and development of the water and related resources within the basin
- Capacity building has been, and continues to be, an important and challenging element to the introduction and application of the DSF's sophisticated numerical modelling tools throughout their development, application and maintenance.

Replicability

Development and maintenance of the suite of knowledge based and analytic modelling tools comprising the Mekong DSF have been complex, data-intensive, time consuming and costly. Nevertheless, the success of the development and application of the Mekong DSF demonstrates that it can achieve its objectives and be successfully maintained in the long-term given the commitment of the member's states and financial partners to do so.

Contact

Mekong River Commission Secretariat: www.mrcmekong.org.
Recent reports and applications of the DSF can be found at the MRC web-site: http://www.mrcmekong.org/publications/topic/basin-planning. The MRC's modelling toolbox can be found at: http://portal.mrcmekong.org/cms/models-and-scenarios.

CASE TITLE

Development and Deployment of the Nile Basin Decision Support System (2010-2012)

A DSS was developed for the Nile Basin Initiative under the Water Resources Management Project based in Addis Ababa, Ethiopia (World Bank funded)

Rationale

The riparian countries of the Nile – Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Rwanda, Sudan, Tanzania and Uganda – have embarked on the Nile Basin Initiative (NBI). The NBI is governed by the Council of Ministers of Water Affairs of the Nile Basin States and seeks to develop the River Nile in a cooperative manner, sharing socioeconomic benefits and promoting regional peace and security. Their shared vision is to "achieve sustainable socioeconomic development through the equitable utilisation of, and benefit from, the common Nile Basin water resources." A Strategic Action Program (SAP) should translate this vision into concrete activities and projects. An important part of the shared vision is the establishment of shared and accepted water management tools and technologies. For this purpose the Nile Basin DSS was developed.

Description

The development of the Nile Basin DSS contains two separate work packages. *Work package 1* is essentially an IT project focusing on the development of the Nile Basin DSS while *Work package 2* is designed for independent system testing and pilot application. Key activities were elaboration of the Nile Basin DSS software requirements, software architecture and design, software development and testing, training of local staff and system deployment in the nine countries. The Nile Basin DSS software requirements are rooted in 'use cases' developed by the NBI and further elaborated during the course of the project. The Nile Basin DSS is designed to support water resources planning and investment decisions in the Nile Basin, especially those with cross-border or basin level ramifications. The system consists of an IMS linked with river basin modelling systems and a suite of analytical tools to support a multi-objective analysis of investment alternatives. The Nile Basin DSS will aid in the development of core national capabilities, in the evaluation of alternative development paths and in the identification of joint investment projects at sub-regional and regional levels. The NBI has established a small, strong project management unit (PMU) staffed by DSS specialists and IT and modelling experts. In addition, IT and water resources modelling experts from all nine countries have participated in all project phases, ranging from elaboration of requirements to system testing. *Two interim Nile Basin DSS releases* have been successfully deployed, tested and accepted by the NBI. The final Nile Basin DSS will be deployed in all countries in September 2012. A service agreement is in place ensuring that the NBI will have access to support and software updates. The training and involvement of local staff have been key. At this stage, more than 50 Nile Basin water professionals have been trained by DHI. Moreover, the NBI PMU has invested substantial resources in involving additional engineers and managers through training sessions and workshops in the NBI countries. Through such training sessions a very large number of local staff have been trained or exposed to the Nile Basin DSS even before its final release.

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Lessons learned

- Substantial training and client involvement during the project has created a very strong feeling of ownership at the NBI
- Software requirements should be based on, or supported by, 'use cases' developed by the client. This process to ensure and demonstrate the ability of the system to address real-life problems and key issues in relation to client involvement and ownership is time consuming, but important
- To sustain and further enrich the Nile Basin DSS a post-project plan must be put in place, including staffing, institutional setup and funding.

Replicability

The NBI has chosen to base the Nile Basin DSS on DHI's MIKE Customised software platform. The NBI has contributed significantly to the development of the platform. The software platform will now be maintained and further developed by DHI and will be used to serve many other systems throughout the world.

Contact

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CASE TITLE

Hydro-economic Modelling in the Euphrates-Tigris Region

Rationale

The four riparian countries in the Euphrates and Tigris (ET) Region – Iran, Iraq, Syria and Turkey – recognise that rapid population growth and economic development will increase the demands for water for energy production, food production, industry and domestic use at the regional level, while ecosystem goods and services need to be maintained and/or restored. Hence the already high pressure on the freshwater resources in the region will increase unless radical measures to generate more value from the existing water resources for all the riparian countries are implemented. For these reasons, a hydro-economic model, populated with publicly available data, was created to analyse the potential benefits of cooperative actions in water management.

Description

This hydro-economic modelling exercise was carried out in four steps. *First,* regional baseline data on land use and hydrology were established and a conceptual hydrological model with 13 sub-basins was created. Remotely sensed data was used where possible, allowing for replicability and validation of data across a large and data scarce region. It was complemented with data from other publicly available sources, such as the United Nations.

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Second, the economic values of irrigated agriculture and hydropower were estimated for each of the 13 sub-basins, so that comparisons could be made regarding the marginal benefits of the use of the water saved. *Third,* a hydro-economic model was constructed to analyse the marginal benefits from water use efficiency (WUE) improvements. The model allows for the simulation of different management options based on WUE improvements and allocation of the water saved to additional productive water uses. When simulating increased WUE in irrigated agriculture, the model demonstrates a significant increase in marginal benefits by using the water saved for additional irrigated agricultural production or hydropower generation in all sub-basins. *Fourth,* the project team interacted throughout the study with a reference/observer group consisting of government representatives from Iran, Iraq, Syria and Turkey and representatives from universities and research centres in the region. The reference/observer group identified a set of cooperative options based on the modelling results that can be explored in subsequent collaborative work.

Lessons learned

- A hydro-economic model used with internationally recognised data can be used to initiate cooperative activities and start discussions on joint decision-making regarding transboundary water resources
- Shared benefits can be generated for all riparian countries through joint management of transboundary waters as a common resource
- Before benefits can be generated from cooperative action on water resources, a joint analysis of internal and external barriers must be carried out and strategies to overcome them must be developed. Barriers to cooperation, as identified by the reference/observer group, included low economic growth, social welfare issues and tensions from former civil strife.

Replicability

This study has demonstrated that it is possible to apply hydro-economic modelling even in regions where hydrological and economic data are scarce. However, a replication of this study in an area with better access to data will yield a more precise and accurate model.

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CASE TITLE

The Zambezi River Basin Multi-sector Investment Opportunities Analysis (MSIOA)

Rationale

The objective of the Zambezi River MSIOA was to demonstrate the benefits of cooperation among the riparian countries in the Zambezi River Basin (ZRB) through a multi-sector economic evaluation of water resources development and management options, and scenarios from both national and basin-wide perspectives. The study, funded by the World Bank, was carried out between 2008 and 2010 in consultation with the riparian states, the SADC Water Division and Development Partners and built on the earlier Zambezi Action Plan Project 6, Phase II (2008). The intended outcome was to inform decision-making on optimal development, environmental sustainability and poverty alleviation in the region.

Description

Hydrologic and economic modelling tools were applied to enable multi-sector and regional assessments of the costs and benefits of a range of management and development scenarios for the ZRB. The modelling package adopted for the analysis was an existing HEC-3 river and reservoir system model. The economic assessment tool incorporated the outputs from the hydrologic modelling to provide a comparative assessment of the economic implications of the various scenarios. The scenario analysis was carried out with the primary objective of determining and maximising mutually beneficial economic gains, while meeting essential water supply and environmental sustainability requirements. This approach provided an objective analytical knowledge base useful for informed decision-making about investment opportunities, financing and mutual-gains benefit sharing. Moreover, the analysis can assist the Zambezi Watercourse Commission, SADC and the individual riparian countries in formulating the basin level Strategic Plan by providing insights into the available options for joint and/or cooperative development. Within the context of an integrated approach to the development and management of the basin's water resources, all water-related sectors are important. However, this analysis focused primarily on hydropower and irrigation as the key investment areas in the ZRB. The water management needs of other closely related sectors and topics, including water supply and sanitation, flood management, environment, tourism and wetlands, were also taken into account. Water users in all these sectors were considered to be legitimate stakeholders with claims on water allocations.

Further information and the background, approach, outputs and recommendations of the study can be found at http://water.worldbank.org/node/83707.

Lessons learned

This report has analysed a set of development scenarios for growth-orientated investments in water and power in the ZRB. Key observations include:

- The ZRB and its rich water and related natural resources, present ample opportunities for mutually beneficial and sustainable, cooperative investments in hydropower and irrigated agriculture, as well as other investments
- The approach and analysis has demonstrated that the riparian countries could achieve short- and long-term benefits through coordinated operation of existing and planned

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hydropower facilities, cooperative flood management and cooperative irrigation development.

Additional observations and conclusions are presented in the main report.

Replicability

The multi-sector approach to the management and development scenario analysis of options for the management and development of water and related resources in the ZRB, although complex, is feasible and useful for identifying the optimal paths for management and development of the ZRB.

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CASE TITLE

The Application of Hydro-economic Modelling in the Rio Grande Basin

Rationale

The Rio Grande is a transboundary river basin, shared by the USA and Mexico and governed by a complex set of institutions, with long-standing competition over water resources and an increasing water demand. Most of the water is used for agriculture (85%), while the river also supplies three major cities (Albuquerque and El Paso in the USA and Ciudad Juárez in Mexico). Despite a number of well-established institutions governing the Rio Grande, further developments in management will be needed to address current and future challenges. Three key issues facing the Rio Grande are an unsustainable abstraction rate, the reallocation of water from agriculture to other uses, and provision of safe and affordable water to all. These issues are subjected, therefore, to hydro-economic modelling.

Description

Currently, the Rio Grande is subject to an *unsustainable abstraction rate*. Thus, water managers need to guide water users towards a sustainable water-use pattern. A basin-wide hydro-economic model was used by Ward and Pulido-Velázquez (2012) to determine the costs of three management options: (1) acceptable decreases in water stocks, (2) sustaining water stocks, and (3) renewing water stocks.

The model shows that maximising economic benefits under the first option reduces water stocks. However, it is hydrologically and institutionally feasible to manage the basin's water supplies sustainably at a cost of 6-11% of the basin's average annual total economic value of water over a period of 20 years. *Reallocation of water from agriculture to other uses* is often the intended outcome of agricultural water conservation subsidies. For instance, subsidies

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given to farmers who change from flood irrigation to drip irrigation could save water. Ward and Pulido-Velázquez (2008) examined this hypothesis by setting up a hydro-economic model for the Rio Grande Basin, analysing the effects on the water used in irrigation as well as that conserved (and available to other users). The model maximises the discounted net present economic value summed over water uses, water environments, irrigation technologies, locations and time periods. The results show that drip irrigation results in higher evapotranspiration than flood irrigation and, thereby, there is an increase in overall water use and a decrease in return flows and aquifer recharge. To continue *providing safe and affordable water to all* its users following a new water quality standard, the Albuquerque and El Paso water utilities had to devise a new tariff structure, to cover the increased treatment costs of arsenic pollution abatement. A comparison of economic benefits from marginal cost pricing and two-tiered pricing was done in a model integrating hydrologic, economic and institutional factors (Ward and Pulido-Velázquez, 2006). The results of this study are that the economic losses incurred at the basin scale when applying two-tiered pricing, which covers the increased treatment costs, were only 0,3 % of marginal cost pricing.

Main conclusions/lessons learned

- Hydro-economic models can be used to calculate the economic cost of implementing policies that ensure sustainable water resources
- Ensuring that improvements in WUE are achieved requires detailed analysis of the technical, economic and hydrologic aspects of water use. In the case of more efficient irrigation, a more detailed analysis of the effects of decreased return flows and increased evapotranspiration on other water users is needed at a basin-wide scale
- It is not under all circumstances that the rights of low income groups to water can be financed through two-tiered pricing. This pricing structure is unlikely to be sustainable, for example, if only a small percentage of the water users use larger quantities (and thereby pay the higher tariff) and if new water quality standards require a significant increase in the higher tariff.

Replicability

The models described above were initially developed for the Rio Grande, but they are easily adaptable to other basins, geographic conditions, legal systems and water allocation rules.

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CASE TITLE

The Okavango River Basin Decision Support System

Rationale

The Permanent Okavango River Basin Water Commission (OKACOM), with the participation of Angola, Namibia and Botswana, initiated a project, with Global Environment Facility funding, to develop a Transboundary Diagnostic Analysis (TDA) and a Strategic Action Program (SAP) for the Okavango Transboundary River Basin. Whereas the objective of the TDA was to identify current and anticipate emerging pressures on the river basin, and attempt to estimate their transboundary impacts, that of the SAP was to develop a program of actionable interventions for the sustainable management of the river and its related resources.

Description

Initially a baseline study of the basin was conducted to establish the ecological integrity, the natural flows, socioeconomic status and emerging trends – threats and pressures. This trend analysis included an assessment of anticipated and planned land-use change and water resource developments over time. Based on these anticipated pressures on the river's water resources, three development scenarios (low, medium and high) were formulated and their requisite simulated future stream flow sequences were superimposed onto the natural flows. In addition, two contrasting climate change scenarios were considered. To simulate the effects of future water resource developments at representative sites, the study used the Water Evaluation and Planning (WEAP) (www.weap21.org) modelling system, as it incorporates a simple, but powerful, scenario creation tool. Present day and future water resource developments (irrigation schemes and urban abstractions, in-channel impounding dams, inter-basin transfers, run-of-river and storage based hydropower schemes) were then configured in the WEAP model. For the Okavango Delta, a specialised hydrologic model was used to accommodate its unique characteristics. A team of experts in hydrology, river morphology, water quality, vegetation, macro-invertebrates, fish, birds, wildlife and socioeconomics, then developed a series of indicators that captured the relationship between the river flow and quantitative changes in the thematic areas. A series of *response curves* describing the relationships between indicators and flow were developed. A DSS tool was developed to capture the knowledge of the biophysical and socioeconomic specialists. The *response curves* formed the knowledge base of the system. Simulated flow regimes for each development scenario, for the whole basin, prepared by the hydrological team, were also entered into the DSS. The DSS used its knowledge base to predict the ecological and social outcomes for each scenario. The DSS was created using standard spreadsheet functions augmented with macros. The DSS houses *response curves* to flow change for all the biophysical and social indicators used in the assessment. The inputs to the DSS are the hydrological data representative of development scenarios, summarised as a time series of ecologically-relevant statistics, such as duration of the dry season, minimum dry season discharge and flood season peak discharge. The outputs of the DSS include, time series of abundance, area, or concentration for all indicators, also including statistical variations as well as changes in discipline-specific and ecological integrity. In addition, changes in social indicators, such as household income from local agriculture, from access to natural resources, and from

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tourism were included. The Okavango DSS is presently limited in scope in that it only considers the impacts of variation and reduction in hydrological flow. The system should be augmented to consider changes to the sediment regime, land use, water quality and biodiversity. An integral part of a wider DSS would be an IMS which would contain, among other things, water resources, land use, fisheries, socioeconomic and biophysical databases.

Lessons learned

The full implications of this tool, in terms of the Okavango River Basin management, are still to be realised as the TDA and SAP were only completed less than a year ago. However, it is evident that a DSS is a useful technical tool which can provide objective information to inform decision-making on the future management and development of water and related resources in a basin.

Replicability

Similar integrated flow assessments and DSSs have been developed elsewhere.

Contact

The WEAP model was developed by the Stockholm Environment Institute (ref. www.sei.org and http://www.weap21.org/) while the DSS is owned and maintained by the OKACOM (www.okacom.org). This home page also includes the TDA and the SAP. The Integrated Flow Assessment process and the DSS structure were developed by Southern Waters (http://www.southernwaters.co.za).

CASE TITLE

National Institute of Hydrology, India, 'DSS Planning' for Integrated Water Resources Development and Management, developed under the Hydrology Project II (2008-2012)

Rationale

Requirements for Integrated Water Resources and Water Security Planning and Management are increasing as a result of increasing population pressures and associated competing water demands from, among other sectors, agriculture, industry, domestic supplies and the environment. The project was tasked to develop a customised DSS – 'DSS Planning'– applicable to several states in India, to address issues identified specifically in each state within (i) surface water planning; (ii) integrated operation of reservoirs; (iii) conjunctive surface and ground water planning; (iv) drought monitoring, assessment and management; and (v) management of both surface- and ground water quality. 'DSS Planning' is based on DHI's generic DSS framework.

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Description

The Upper Bhima River Basin in Maharashtra was selected as a pilot area for the application of 'DSS Planning', with the other participating states to follow. The water resources management themes in Maharashtra, for which 'DSS Planning' was required included 1) short- and long-term planning of reservoir management, 2) conjunctive use of surface- and groundwater, 3) planning seasonal groundwater use, 4) artificial groundwater recharge, 5) drought monitoring, 6) flood analysis, and 7) water quality modelling. Decision-makers needed, among other things, to address issues on how to respond to increased water demands in the most efficient way; how to communicate drought indicators to the broader public; and how to reduce flooding and flood damages. The 'DSS Planning' assisted with detailed answers to questions on the risk of reaching critically low reservoir levels in the dry season and the likelihood of filling the reservoir in the forthcoming wet season. Based on the calculated risk, decision-makers could resolve that the live storage could be increased. The 'DSS Planning' was also applied to the analysis of droughts with low post-monsoon reservoir storage and falling groundwater levels. Mathematical models included in 'DSS Planning' were used to identify a sustainable situation with the addition of artificial recharge. Conjunctive use was shown to be an efficient way of supplying water and reducing the risk of water logging. On-line data presentations from the database showed the likely severity of future droughts and thus remedial measures could be taken accordingly. The 'DSS Planning' was further applied for flood analysis, and the potential for reducing flooding and flood damage through forecasting was assessed and used by the decision-makers. The continued use of the 'DSS Planning' system's methodologies require extensive training of the implementing agency's staff. The emphasis has been on modelling, data processing, model setup and calibration, and model use. This was supplemented by training in more generic areas, such as use of GIS and time series tools.

Lessons learned

- The 'DSS Planning' system can be installed as the central hub for water resources data and information in the state and access can take place through a PC, local area networks and secure internet connections
- The 'DSS Planning' system is very useful for long- and short-term planning and the management of water resources and for impact assessments
- Training is necessary to maintain knowledge and skills within the organisations involved.

Replicability

The model codes used in 'DSS Planning' are generic and can be populated in any given context assuming the necessary data series are available and accessible. In a new situation, however, it may be necessary to combine and add other model codes depending on the issues at hand.

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