

10. THE USE OF RIVER BASIN MODELING AS A TOOL TO ASSESS CONFLICT AND POTENTIAL COOPERATION¹

Objectives of the chapter. What will you know and understand after reading this chapter?

After reading this chapter you should have a general understanding of how river basin models are developed and how they are used within the field of international water resources. You should also have gained a basic understanding of some of the ways in which countries have attempted to use river basin models.

Main terminology used in the chapter. You will run into the following terms:

River basin model, Scenario, Constraint, Tradeoff, Simulation modeling, Optimization modeling, Emergency Water Management, Integrated River Basin Management, Systems approach, Node-link network, Priority-based Allocation, Economic-based Allocation, Multiobjective Analysis, Model Building Process, Calibration, Verification, Sensitivity Analysis, Geographic Information System.

Practice questions:

1. What is “systems analysis” and how can it aid in the planning and design of water resources projects?
2. What is the difference between “simulation” and “optimization modeling”? Give an example when it might be more appropriate to use one rather than the other.
3. In the model building process, why is it important to have independent data sets for the

¹ From: Dinar, A., S. McCaffery, S. Dinar, and D. McKinney, Bridges Over Water: Understanding Transboundary Water Conflict, Cooperation and Negotiation, World Scientific Publishing Company, 2007.

calibration and verification of a model?

4. What is sensitivity analysis and how would you use the results of such an analysis to guide data collection efforts?

5. Discuss the circumstances when countries might find themselves with conflicting river basin management objectives.

The allocation of water resources in river basins is a critical issue, especially when multiple riparian countries are involved. River basins are inherently complex systems with many interdependent components (streams, aquifers, reservoirs, canals, cities, irrigation districts, farms, etc.). The sustainability of future economic growth and environmental health in a basin depends on the rational allocation of water among the basin riparians (users sharing the basins water resources) and sectors (municipal, industrial, agricultural, and environmental, among others). Efficient and comprehensive models are available to make water allocation and water quality decisions that can lead to sustainable water use strategies in many river basins.

This chapter presents an overview of river basin modeling and its use in understanding conflicts and cooperation options. Also discussed are data needs and data manipulations, possible scenarios to be used in modeling and how they can affect conflicts and the prospects for cooperation.² In a later Chapter, a demonstration of modeling a generic river basin is presented, including quantitative results on non-cooperation-unilateral extraction, climate change impact, population growth pressure, and optimization-cooperation. More detailed information on river basin modeling can be found in the textbooks: Maass et al. (1962), Hall and Dracup (1968), Loucks et al. (1981), Viessman and Welty (1985), Mays and Tung (1992), Grigg (1996), Lee and Dinar (1996), and Loucks and van Beek (2005).

² River basin model, Scenario is an alternate future development or course of action depending on various system inputs or decisions taken to control the system.

HOW MODELS HELP US UNDERSTAND CONFLICTS AND COOPERATION OPTIONS

The principal sources of many transboundary rivers lie in mountainous states where water may be regulated by a cascade reservoirs for various purposes (e.g., energy production) and compete with water use for other uses (e.g., agricultural production) in downstream countries (e.g., the Sry Darya basin in Central Asia). In these cases, the issues of river basin management are international, and policy solutions often entail regional cooperation among the concerned riparian countries.

If a basin is wholly contained within one country, some sort of locally optimal allocation of water to uses that are most economically efficient can be a good solution. However, in transboundary basins, where countries exert their (limited) sovereignty over water resources on their territory, this is often impossible. In this case, the water allocated to a country by agreement between the basin riparians becomes an upper limit on water available for that country. The allocation of that water share within the country is, by and large, a domestic policy issue for that country. However, the allocation of shares between countries is an international issue faced by all the basin riparians.

In many cases, downstream countries do not have local water sources, but they have developed significant irrigated lands and they must rely on upstream countries for water supply (e.g., Nile, Indus, and Aral Sea basins). An upstream country's goal in river basin management may be to maximize hydroelectric power production, and this could be in conflict with the downstream country, whose goal may be to maximize the utilization of water for irrigated agricultural production. Sometimes the temporal characteristics of the goals of upstream and downstream countries in a basin may lead to international water management problems. For instance, upstream peak power demand may occur in the winter, while in downstream countries, peak demand for irrigation water typically occurs in the summer. Without cooperation, these situations can lead to international conflict over the shared waters of a basin.

River basin models have been used to aid in the determination of fair and equitable long-term water sharing agreements or short-term operational plans in transboundary basins. A river basin model is mathematical model that represents the

relevant processes in a river basin and can predict the behavior of the basin under different conditions or management scenarios.

These models help decision makers from the basin states understand the ramifications of different water allocation scenarios and operational regimes and the corresponding benefits to themselves and their neighbors. They can be used to understand the tradeoffs³ between water releases made for one use (say, agricultural production) versus those made for another (say, hydroelectric power generation).

As an example, consider a transboundary basin where an upstream country's water management goal is power generation and a downstream country's goal is irrigation water supply. Making releases for power generation in the winter will not allow saving that water for summer release for irrigation. The following scenarios could be considered by the different countries for this situation:

Upstream country:

- Maximize power generation in the upstream country over the planning period; or
- Minimize power deficits in the upstream country in winter months over the planning period.

Downstream country:

- Maximize water supply for irrigation in the downstream country over the planning period.

Clearly, the upstream and downstream scenarios could be in direct conflict with one another. An analysis of modeling results of trying to satisfy these different management objectives can be helpful in determining possible cooperative solutions to water management in the basin (Objectives are goals intended to be attained by a stakeholder in managing a river basin). Such results would include deficits of water for

³ Tradeoff in the context of a basin model is the amount of one objective value that must be given up in order to increase the value of a conflicting objective

irrigation as well as deficits of power delivered under the different management scenarios. Economic valuation of the water uses (agricultural production, electricity generated, municipal users served, etc.) can also be evaluated by the model. The application of such a model in the Syr Darya basin of Central Asia is discussed later in this Chapter. The results of such a model can be used in the creation of a game theory setting for water management in the basin.

As with any model certain assumptions are made and constraints exist. (A constraint in a river basin model is a limitation on the values which a variable may take on in a river basin model.) Models are always constrained by the available data (e.g., streamflow records, reservoir operations, water demands, etc.) and by the constraints of the countries in question. Assumptions must be made about various data input to the model and the scenarios, such as, the length of the modeling period and the time step, the environmental flows required at various locations in the basin, initial storage volumes of the basin reservoirs. To model the uncertain nature of regional climate, various flow sequences should be used, such as sequences of normal, dry and wet years.

WHY WE MODEL

River basin models are interactive programs that utilize analytical methods, such as simulation and optimization algorithms, to help decision makers formulate water resources alternatives, analyze their impacts, and interpret and select appropriate options for implementation. Models are used to simulate water resource system behavior based on a set of rules governing water allocations and infrastructure operation. Models are also used to optimize water resource system behavior based on an objective function and accompanying constraints. Models tend to reduce the time for decision making in these uses, and improve the consistency and quality of those decisions.

In the context of transboundary river basins, models are needed by negotiators, planners, and managers of water resource systems, as well as other stakeholders who may be concerned about the economic or environmental uses of shared water resources. The objective of these decision makers is, among other things, to provide a reliable supply of water with a quality appropriate for its use, production of hydropower, protection from floods, and protection of ecosystems. In transboundary basins, the allocation of water to

various users and sectors is carried out in accordance with the prevailing institutional structure of water rights according to national laws, basin-wide negotiated agreements, and international laws.

River basin modeling requires, to varying degrees depending on the problem under consideration, the following activities (see Figure 10.1):

- *Data Measurement and Collection* – receipt of various data (e.g., water level and temperature, precipitation, air temperature, concentrations, etc.) from stations throughout a river basin. In addition, various economic and social data are measured and collected.
- *Data Processing* – storage and processing of data related to the processes of interest in the basin, both spatial features as well as time series data. In this context a relational database is used to store the measured data, a data model is used to organize the data in the database according to the “basin” principle, and a geographic information system⁴ is used to display the data graphically;
- *Analytical Tools* – models designed to predict basin response to various climate and development scenarios;
- *Decision Formulation and Selection* – use of results from the models and interaction with users to make decisions on water management in the basin; and
- *Decision Implementation* – dissemination of decisions regarding water use under various conditions.

⁴ Geographically referenced data in a relational data base with a graphical mapping system.

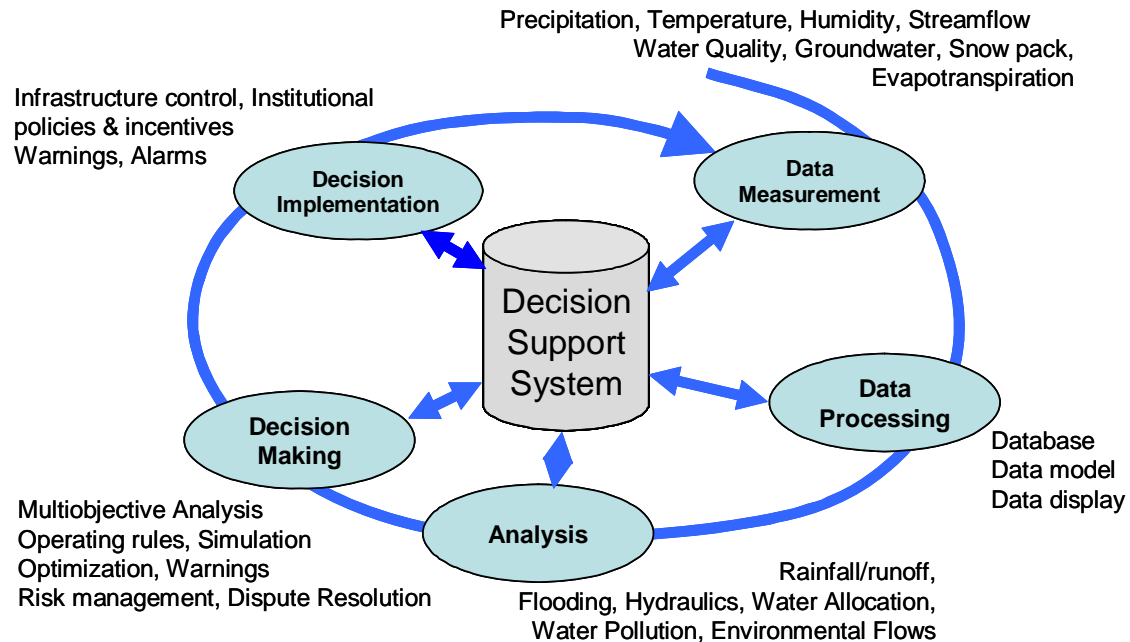


Figure 10.1: General framework for the application of a river basin model.

WHAT WE MODEL

River basin modeling requires the consideration of a wide scope of social, economic and environmental aspects of resource use and protection. Principal areas of decision making in water resources management include: emergency water management, water regulation, allocation, and quality. Decision making regimes tend to be different for these areas due to differences in time available for making decisions (hours in the first case, days to months in the second, and years to decades in the third).

Emergency Water Management

We distinguish between river basin management problems dealing with early warning of extreme events, flood management, and accidental chemical spill management.

Early Warning

Early warning systems for floods or accidental chemical spills are information systems designed to send automated hydrologic and water quality data regarding water-related disasters to river basin planners, who combine them with meteorological data and river

basin models to disseminate hazard forecasts and formulate strategies to mitigate economic damage and loss of human life.

Flood Protection

Protection from flooding events requires higher dimension models and smaller time steps than for many other water resource management models, such as municipal or agricultural water supply, recreation, water quality, etc. Flood flows usually occur over short time intervals (hours to days or weeks) making it impractical to model such events in multipurpose water resource planning models using simple mass balances. Calculating flood inundation as a result of flood wave propagation in a watershed requires two-dimensional modeling, rather than one-dimensional modeling.

Structural measures (e.g., reservoirs, levees, flood proofing) and non-structural measures (e.g., land use controls and zoning, flood warning and evacuation plans) are used to protect against floods. Upstream reservoir operators must provide storage capacity for flood protection and emergency warning to populations living in downstream floodplains. These operators need to know how much water to release and when in order to minimize expected flood damage downstream. The flood flow and peak in a basin depend on flood storage capacity and flood flow release policies. These can be determined by simulating flood events entering basin reservoirs. Expected flood damage can be predicted if the distribution of peak flows and the relationships between flood stage and damage, and flood stage and peak flow are known.

Chemical Spills

Accidental chemical spills are a major concern for areas that have vulnerable riverine ecosystems and cities with vulnerable drinking-water supplies and weak spill response capabilities. In order to protect against accidental spills, studies are performed to determine travel times in river reaches and to plan emergency responses to chemical spills into rivers, including guiding decisions regarding closing and reopening of intakes to drinking-water systems.

Emergency planning for spills in rivers and lakes entails having advective, nonreactive, nonmixing transport models capable of providing quick, worst-case

scenarios of chemical concentrations at critical points downstream of spill sites. These allow for planning and deciding on alerts to be issued. More detailed, advective-dispersive, reactive modeling of the chemical fate and transport in the river system typically follow after the immediate response actions are taken.

Water Regulation, Allocation, and Quality

River Basin Management

In the area of general river basin management, decision makers are faced with a myriad of problems, including:

- Operation of reservoirs to supply water for various purposes including recreation, municipal and industrial water use, environmental flows, irrigation, and hydropower production;
- Examination of the effects of land-use and land-management policies on water quality;
- Assessment of eutrophication in surface water bodies;
- Development of pollution control plans for river basins and estuaries, including hydrodynamic and water quality impacts of alternative control strategies;
- Design and operation of wastewater treatment plants, i.e., what level of treatment is necessary to meet water quality goals under specific flow conditions; and
- Management of river basins, including the evaluation of the interrelationships between economic productivity and environmental degradation in a basin.

Lake and Reservoir Operation

In this area decisions must be made regarding pollution control, water supply, and hydropower operation, mitigation of climate change effects, reservoir eutrophication, phosphorus control strategies, and operation of multiple reservoir systems. Different types of models are required in this area, such as, water allocation models to determine the distribution of water for economic production and environmental protection in a basin; or two- and three- dimensional models to analyze water quality in lakes.

Non-Point Source Pollution

Here plans are made for agricultural chemical use or protection of vulnerable water bodies, stream and aquifers. Modeling and managing agricultural non-point source pollution typically requires the use of a distributed parameter watershed model. The data management and visualization capabilities are needed to allowed decision makers to identify and analyze problem areas easily.

Conjunctive Use of Surface and Ground Water

Because decision makers are typically required to consider a multitude of social, legal, economic, and ecological factors, models have great potential for improving the planning and management of conjunctive use (ground and surface water) systems. This can require the integration of a number of simulation and optimization models with graphic user interface capabilities to provide an adequate framework for the discussion of water allocation conflicts in a river basin. Conjunctive use models and multiobjective decision methods can be combined to provide effective inter-basin water transfer planning allowing decision makers to analyze the social, economic, and environmental impacts of water transfers. Models are valuable in facilitating the consideration of a wide range of impacts, allowing decision makers to incorporate technical information into the decision making process, and providing output which can be interpreted easily.

For further discussion: To what extent do the different areas of water resources decision making discussed above: emergency water management, water regulation, allocation, and quality, have different data requirements? For example, the time periods are different for each area (hours, to days, to months).

Some Issues in River Basin Modeling

There are a number of issues related to water management that must be considered for effective river basin modeling. First, water management takes place in a multidisciplinary and multi-jurisdictional environment and the problems must be approached from an integrated perspective (McKinney, 2003). Second, water management must be considered at the scale of the river basin in order to internalize the

major, potential externalities between activities of users in different parts of a basin. Finally, the importance of scale effects in trying to model the integrated effects of water uses across an entire basin must be addressed.

Integrated River Basin Management

Integrated River Basin Management are River basin management concepts based on the premise that water as an integral part of the ecosystem, a natural resource and a social and economic good, whose quantity and quality determine the nature of its utilization. River basin management includes both structural interventions and nonstructural rules and policies. *Structural interventions* include the design and construction of physical works under criteria of safety, workability, durability, and economy, including short-term, operation and maintenance activities with existing structures and long-term investments in new structures (McKinney et al., 1999). *Nonstructural interventions* combine optimal operating rules of hydrologic systems, economic optimization of water allocation, and understanding community behavior and institutional processes related to the formation and support of agencies making decisions about water management. These institutional directives, economic/financial incentives, and hydrologic system operating rules have greatly modified the traditional, structural approach to water management. The interdisciplinary nature of water problems requires the integration of technical, economic, environmental, social, and legal aspects into a coherent framework for decision making purposes. The requirements of users as well as those relating to the prevention and mitigation of water-related hazards should constitute an integral part of the integrated water management process.

Water allocation between competing uses is best addressed at the river basin scale through the use of combined economic and hydrological models. To be effective, river basin models must adopt an interdisciplinary approach and a number of barriers must be overcome:

- Hydrological models often use simulation techniques, whereas most economic analyses are performed with optimization procedures;
- Political and administrative boundaries of economic systems are rarely the same as those of hydrological systems; and

- Different spatial development scales, and time horizons are frequently encountered in economic versus hydrologic models.

River basin models are often used to assist planners in answering water policy questions, including socio-economic issues, such as:

- What is the appropriate level of transaction cost for various market based incentives to improved water use efficiency (e.g., the acceptable level of cost for information, monitoring, contracting and enforcement of market transactions)?
- How should water be allocated to achieve optimal productivity and net benefits of different water uses (e.g., agricultural, domestic and industrial use)?
- What will be the demand for and economic value of water (e.g., production costs and willingness to pay) under various management scenarios?

River Basin Systems

Figure 10.2 shows the components of a river basin system, including possible sources of water supply (groundwater and surface water), a delivery system (river, canal and piping network), water users (agricultural, municipal, and industrial), and a drainage collection system (surface and subsurface). The atmosphere forms the river basin's upper boundary, and mass and energy exchange through this boundary determines the hydrologic characteristics of the basin. However, the state of the basin (e.g., reservoir and aquifer storage, and water quality) and the physical processes within the basin (e.g., stream flow, evapotranspiration, infiltration and percolation) are affected by human actions, including impoundment, diversion, irrigation, drainage, and discharges from urban areas. Therefore, a river basin model should include representations of not only the natural and physical processes, but also the artificial "hardware" (physical projects) and "software" (management policies) systems as well. The model should represent human behavior in response to policy initiatives. This may be as simple as a price elasticity of demand coefficient or as complex as a model of farmers' simultaneous choice of optimal water use, crops, and water application technology. The essential relations within each component and the interrelations between these components in the basin must be considered in river basin models.

It has been noted by some water resources professionals that there is a tendency for modeler to include too much detail into a model or to neglect important and relevant components of a model. This can lead to inaccurate model results and to inappropriate interpretation of those results. The complexity of a model should be dependent on the problem being analyzed and no more (Ford, 2006).

River basin models need to include interactions between water allocation, agricultural productivity, non-agricultural water demand, and resource degradation to estimate the social and economic net benefits from water allocation and use.

In order for decision makers to understand critical water management aspects in the basin the model should represent:

- The underlying physical processes,
- The institutions and rules that govern the flows of water and pollutants in the basin,
- The water diversion, use and return sites in the basin, including consumptive use locations for agricultural, municipal, industrial, and in-stream water uses (incorporating also reservoirs and aquifers); and
- The economic benefits of water use by applying production and benefit functions for water for use in the agricultural, environmental, urban, and industrial sectors.

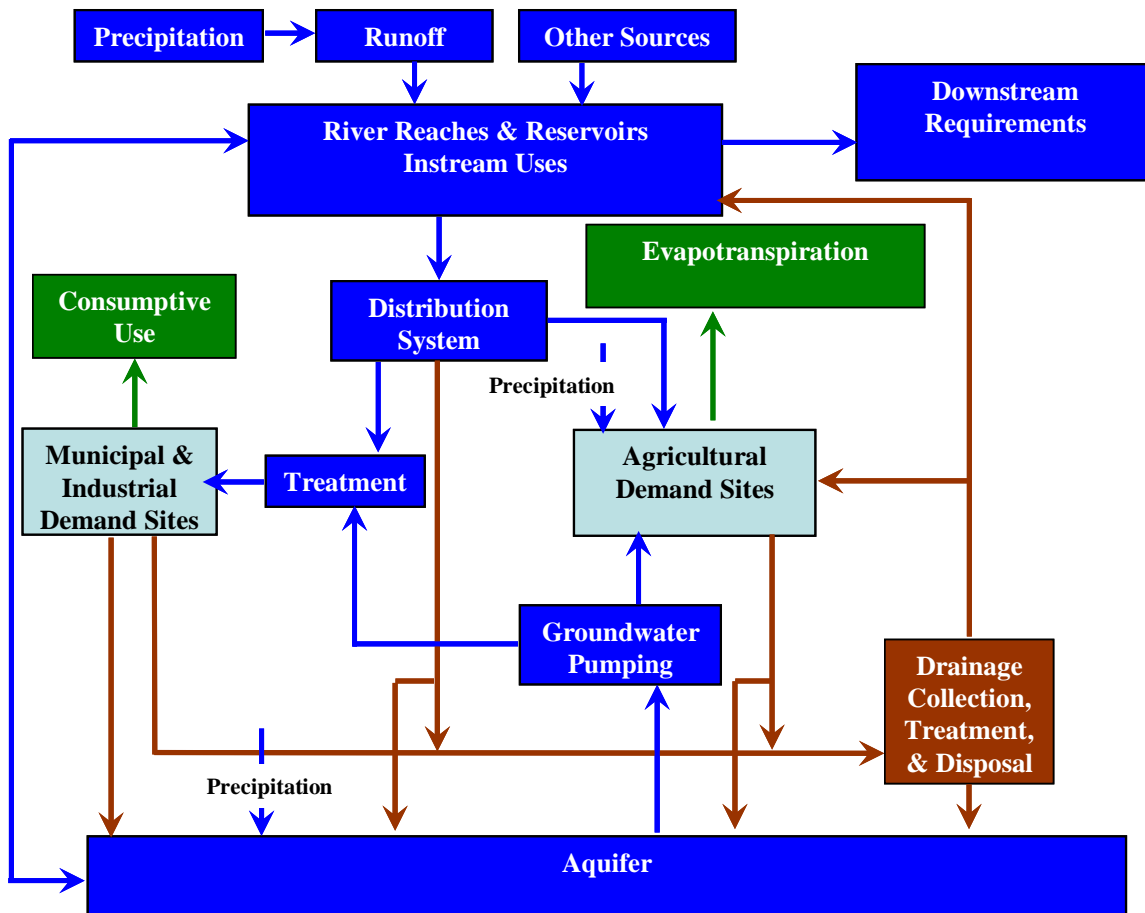


Figure 10.2: Schematic diagram of the components of a river basin system.

Scaling of Processes

Figure 10.3 illustrates the scales (basin, district, and user) of relationships and decisions in river basin management. Water is used for in-stream purposes (hydropower generation, navigation, recreation, environmental flows, etc.) as well as off-stream purposes (agricultural, municipal and industrial (M&I) water uses). Basin planners often attempt to maximize the socio-economic net benefits to the basin stakeholders, such as the economic value of M&I water use, profit from irrigation, and benefits from in-stream water uses, but also minimize environmental damages due to waste discharges, irrigation drainage, and negative impacts on in-stream uses.

At one level, institutional policies such as water rights and economic incentives (e.g., water price, crop prices, and penalties on waste discharge and irrigation drainage) constrain or induce system operations and water use decisions. The management of water quantity and quality in a basin is based on the operation of reservoirs, aquifers, and conjunctive surface and ground water systems. The connections between water supply and demand and between upstream and downstream users are important considerations when considering return flows in the basin. The regulation of spatially distributed flows, pollutants, and demands has to be considered in a river basin model integrated over the proper scale within the river basin network.

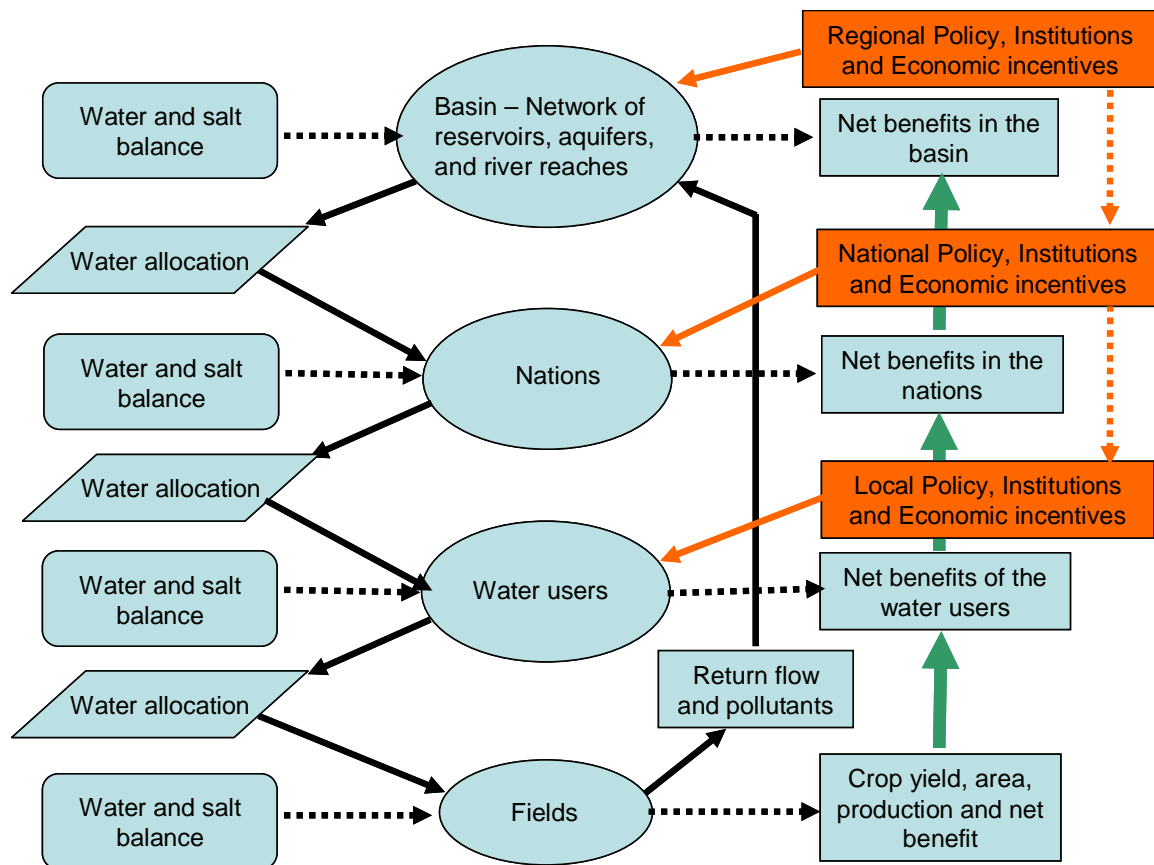


Figure 10.3: Framework for river basin modeling at various scales.

For further discussion: Why is scale an important issue in river basin modeling? How does it enter into the formulation of models? What processes are predominant in

considering the integrated management of river basins and why are they so important?
How has neglecting the integrative nature of river basins resulted in environmental, economic or social problems in the past?

HOW WE MODEL

Simulation and Optimization Models

Multi-objective, multi-purpose, multi-facility solutions to problems encountered in river basin management must be not only technically feasible but socially, environmentally, economically, and politically feasible as well. In most river basin management situations it is hard to see how all the disparate components can be combined into a management plan or design which meets prescribed and sometimes conflicting objectives and constraints. The “systems approach,” that is, disassembling complex phenomena into smaller, isolated, more readily understood, subsystems and analyzing the interactions between the subsystems and between the subsystems and the larger environment (Churchman, 1968), can aid in identifying situations where a minimum investment of funds and energies will produce maximum gains in terms of resource allocations, economic development and environmental welfare. Using this approach we can focus on the functioning of the components and the relationships and interactions between them under conditions to which the system may be subjected. This provides a means of sorting through the myriad of possible solutions to a problem and narrowing the search to a few potentially optimal ones in addition to determining and illustrating the consequences of these alternatives and the tradeoffs between conflicting objectives.

Basin-scale analyses are often undertaken using one of two types of models (McKinney et al., 1999): ones that *simulate* water resources behavior in accordance with a predefined set of rules governing water allocations and infrastructure operations, or ones that *optimize* and select allocations, infrastructure, and operations based on an objective function and accompanying constraints. Often system performance can best be assessed with simulation models, whereas, system improvement can often be achieved through the use of optimization models.

River basin models that simulate the behavior of various hydrologic, water quality, economic, or other variables under fixed water allocation and infrastructure

management policies are often used to assess the performance of water resources systems. A distinguishing feature of these simulation models, as opposed to optimization models, is their ability to assess performance over the long term, i.e., decades. Consequently, simulation is the preferred technique to assess water resources system responses to extreme, nonequilibrium conditions, and thereby to identify the system components most prone to failure, or to evaluate system performance relative to a set of sustainability criteria that may span decades. However, sustainability analysis has been accomplished through optimization recently (Cai et al., 2002).

Models that optimize water resources based on an objective function and constraints must include a simulation component, however rudimentary, with which to calculate flows and mass balances. A distinct advantage of optimization models over simulation models is their ability to incorporate values (both economic and social) in the allocation of water resources. However, to be adopted by policy makers and system managers, optimal water allocations must agree with an infrastructure operator's perspective. This often requires that models be calibrated not only with respect to physical parameters of the system being modeled, but also with the respect to the system management, i.e., the operation and decision making processes for the system. This later aspect is often overlooked in model development and application and can lead to poor acceptance of models in practice.

Many river basin models tend to have unwieldy input files and cryptic output files, making them useful only to technical specialists. Wide use of these models and the vastly expanded access to data have brought about the need for other technologies (e.g., databases and GUIs) to be integrated with models in order to make data accessible to models and to make inputs and results understandable to analysts and decision makers. Unfortunately, except in a very few cases, most models have yet to utilize the capabilities of modern relational databases.

River basin models have been reviewed by several authors (e.g., Yeh, 1985; Wurbs, 1993; Wurbs, 1994; Wurbs, 1998; Yeh, 1992; Wagner, 1995; Watkins and McKinney, 1995, and Labadie, 2004; McKinney, 2004). Yeh (1985) provided a comprehensive state-of-the-art review of reservoir operation models with a strong

emphasis on optimization methods. Wurbs (1993) provided a review of a wide array of reservoir simulation and optimization models and evaluated the usefulness of each approach for different decision-support situations. He hoped that his paper would help practitioners choose the appropriate model from the overwhelming number of models and modeling strategies which currently exist. Labadie (2004) points out the need to improve the operational effectiveness and efficiency of water resource systems through the use of computer modeling tools. He notes that the demand for this is increasing as performance-based accountability in water management agencies increases and as operators and managers come to rely more on modeling tools to respond to new environmental and ecological constraints for which they have little experience to draw on.

River basin models range from fully data oriented models to fully process oriented models. Data oriented models are represented by regression models or neural networks (i.e., black box models). Process oriented models are represented by models which have detailed representations of processes, but require few site specific data (i.e., white box models). The choice depends on the quantity and quality of data available and the knowledge of important physical, chemical, biological, and economic processes affecting the system.

For further discussion: What are some situations when simulation modeling of a basin may be preferred to optimization modeling and *vice versa*? How might one go about formulating an appropriate objective for optimization modeling of a river basin?

Components of River Basin Models

A typical river basin model is developed as a node-link network, in which nodes represent physical entities and links represent the connection between these entities (Figure 10.4). The nodes included in the network are: (1) source nodes, such as rivers, reservoirs, and groundwater aquifers; and (2) demand nodes, such as irrigation fields, industrial plants, and households. Each distribution node is a location where water is diverted to different sites for beneficial use. The inflows to these nodes include water flows from the headwaters of the river basin and rainfall drainage entering the entities. Agricultural water users are assumed to allocate water to a series of crops, according to

their water requirements and economic profitability. Both crop area and yield may be determined endogenously depending on the model.

In order to solve the river basin model and obtain values for flow and storage in all arc and nodes of the basin network, some solution criterion must be established to provide regulation of the water resources of the basin river under various imposed conditions (scenarios). In other words, the model tries to:

- Balance water at the model nodes during each period of a specified planning horizon;
- Satisfy, to the extent possible, the demands of water users in the basin during the planning horizon;
- Follow the operation regimes of the basin reservoirs according to their technical requirements and rules of their operation; and
- Satisfy, to the extent possible, requirements for environmental flows.

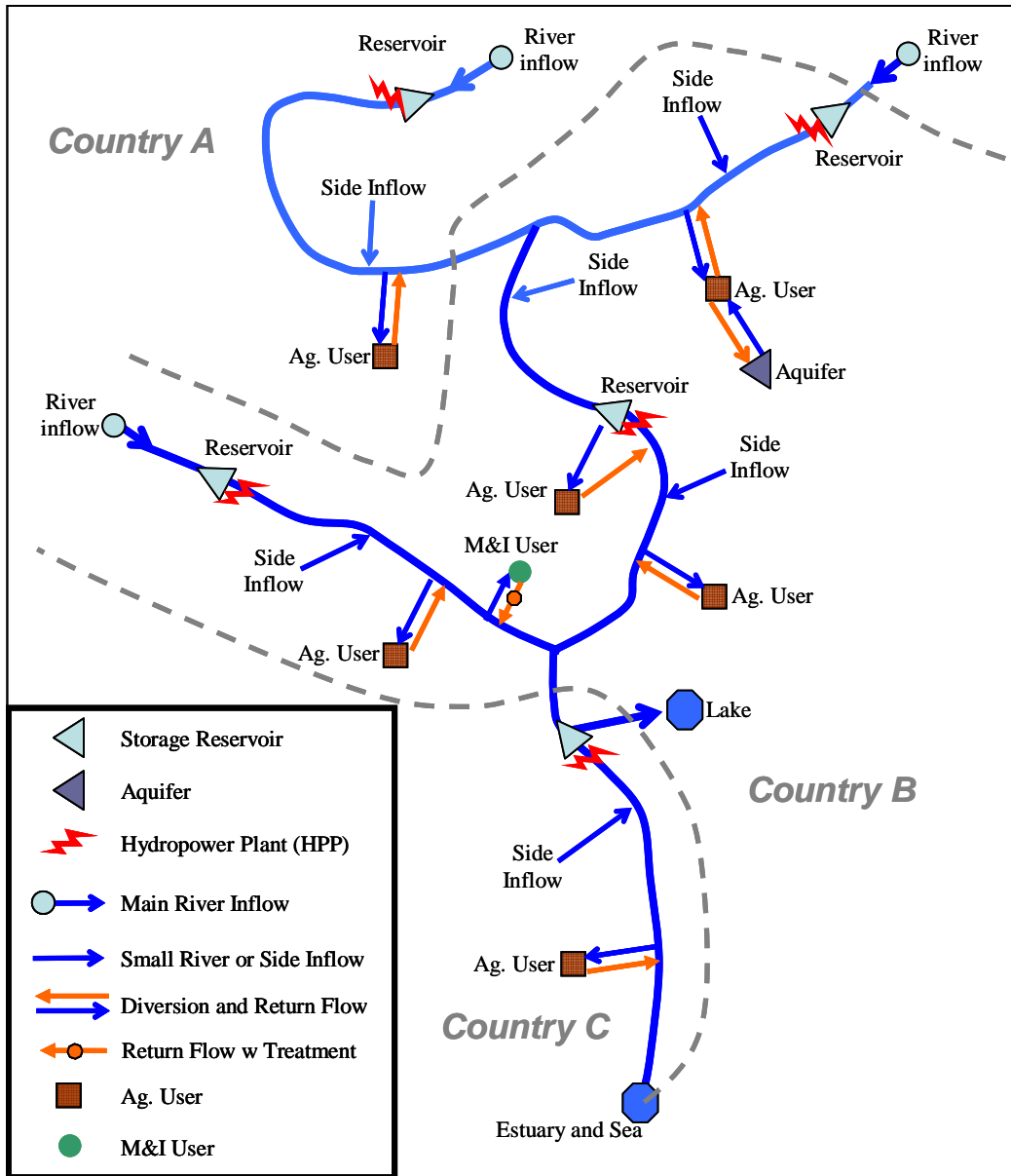


Figure 10.4: Schematic representation of a transboundary river basin.

The network representation of a river basin in a model is an arrangement of the river reaches, reservoirs and power plants, water users and lateral inflows (see Figure 10.4). For every reservoir, water balances are calculated as (see Figure 10.5):

$$[10.1] \quad S_j^t - S_j^{t-1} = Q_{in,j}^t - Q_{out,j}^t - L_j^t$$

where

S_j^t volume of water in reservoir j at time t (million m3);

$Q_{out,j}^t$ release from reservoir j in period t (million m3);

$Q_{in,j}^t$ inflow to reservoir j in period t (million m3); and

L_j^t loss from reservoir j over time t (million m3) from seepage or evaporation.

The energy generated at a hydropower plant associated with a dam and reservoir is calculated as (See Figure 10.5):

$$[10.2] \quad E_j^t = 2730 * \varepsilon_j * Q_{out,j}^t * H_j^t$$

where

E_j^t energy generated by plant j in time period t (kWh);

H_j^t effective hydraulic head on plant j in time period t (m). For “run-of-the-river” power plants, this value is a fixed constant; and

ε_j efficiency of plant j.

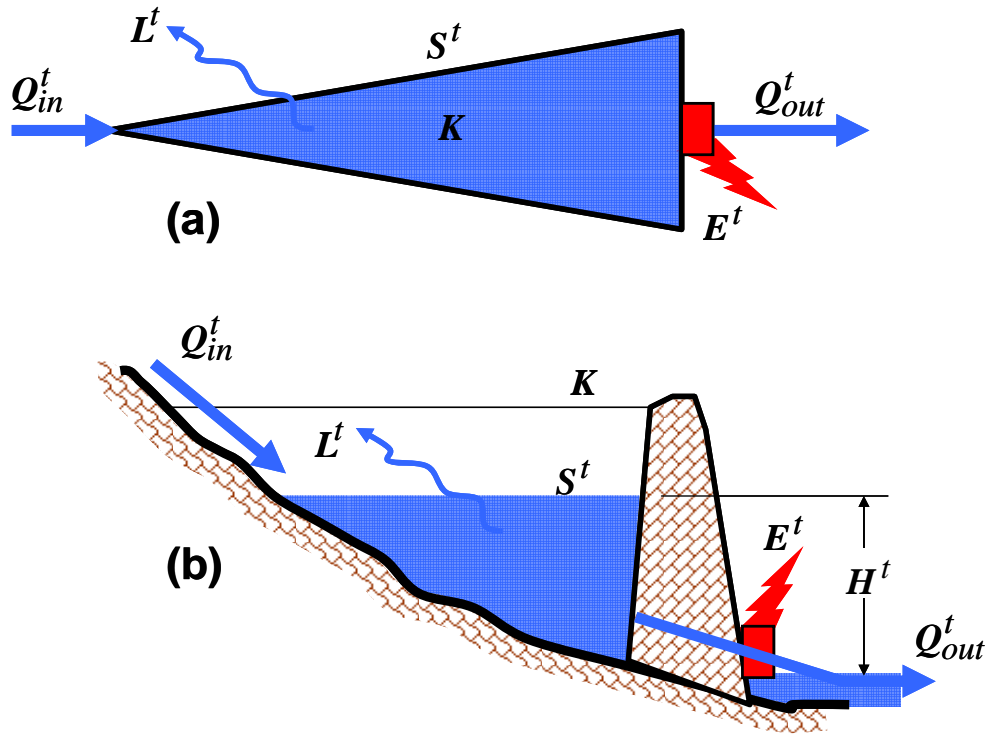


Figure 10.5: Schematic diagram of a reservoir with power plant; (a) plan view; and (b) side elevation view.

For nodes representing confluences of rivers, we have for each node j of this type and for each time period t , we have (see Figure 10.6)

$$[10.3] \quad \sum_{out} Q_{out,j}^t = \sum_{in} Q_{in,j}^t + Q_{source,j}^t$$

where

$Q_{in,j}^t$ inflow to the node j in period t (million m³);

$Q_{out,j}^t$ outflow from the node j in period t (million m³); and

$Q_{source,j}^t$ source of water for node j in period t (million m³).

For water users, return flow from their diversion can be calculated as

$$[10.4] \quad Q_{out,j}^t = r_j * \sum_{in} Q_{del,j}^t$$

where $0 \leq r_j \leq 1$ is the return flow coefficient for node j (dimensionless).

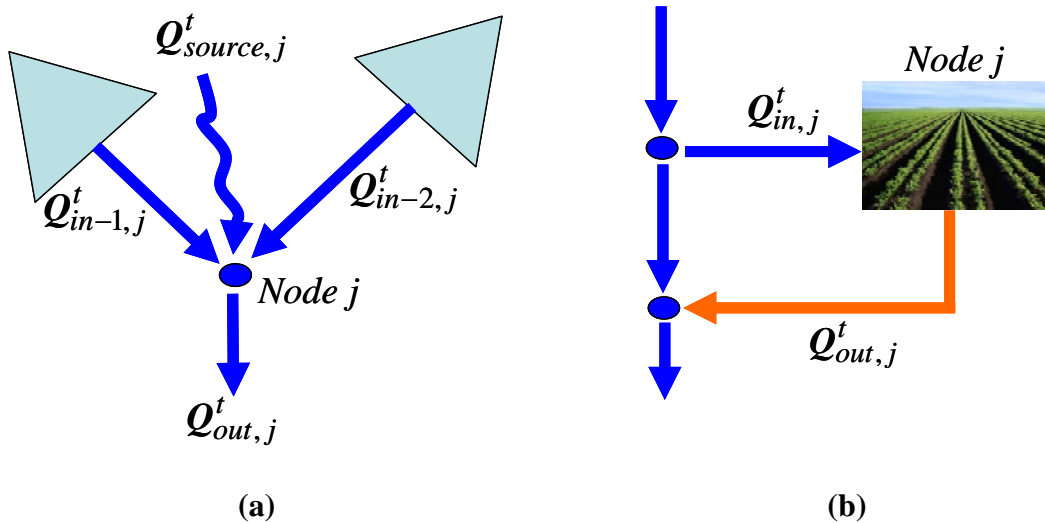


Figure 10.6: Nodes representing: (a) Flow at a river confluence with a local source; and (b) Return flow from an agricultural water user.

Allocation of Water to Users

Priority-based Allocation

Such allocation of water to users in a river basin is based on a set of imposed or agreed upon priorities assigned to water users. Often, the criterion used to calculate the allocation of water to users in a river basin model is to minimize deficits of water delivery to all users in each time period

$$[10.5] \text{ Minimize } \sum_i w_i \frac{Q_{dem,i}^t - Q_{del,i}^t}{Q_{dem,i}^t}$$

where

$Q_{dem,i}^t$ water demanded by user i in period t (million m³);

$Q_{del,i}^t$ water delivered to user i in period t (million m³); and

w_i priority of user i in the allocation process (dimensionless).

This method is used in the Water Evaluation and Analysis Program (WEAP) software discussed in a later Chapter. There are different methods that can be used to endogenously or exogenously estimate the demands for water in the basin (primarily agricultural and municipal); however, an exogenous determination is the most common.

In the priority allocation method, for each time step a network flow solver attempts to satisfy the demands of the water users with the highest priority first. Then the lower priority users are satisfied in decreasing order of priority. This is a typical method of solution for several well known river basin models including WEAP (SEI, 2004), WRAP (Wurbs, 2001), ModSim (Labadie, 2000), and Oasis (Hydrologic, 2004).

River basin simulation models use of network flow optimization algorithms to solve large sets of simultaneous equations in order to balance the flows in the network representing the basin. To mimic operating policies, such sets of procedures can be difficult to generate for complex systems, and very different and new rule sets may be needed if structural or significant policy changes are to be investigated. In order to avoid this, river basin models can be formulated as minimum cost capacitated network flow problems solved using network flow solvers, such as the out-of-kilter algorithm (used in HEC-ResSIM) or the more efficient Lagrangian approach (used in ModSim) of Bertsekas (1994). The network flow solver computes the values of the flows in each arc so as to minimize the weighted sum of flows, subject to constraints on mass balance at each node and upper and lower flow bounds. The weights are penalties expressing relative priorities

in user defined operating rules (WEAP, 2004). The user must provide lower and upper bounds on diversions, instream flows, and reservoir storage levels and assign relative priorities for meeting each flow requirement and for maintaining target reservoir storage levels. The network solver computes the flows and storage changes in a particular time interval (say, a day or a month), and then uses the solution as the starting point for calculations in the next time interval.

A distinguishing feature of these hybrid simulation/optimization models is the use of optimization on a period by period basis to “simulate” the allocation of water under various prioritization schemes, such as water rights, without perfect foreknowledge of future hydrology and other uncertain information.

Economic-based Allocation

As an alternative to priority-based allocation, economic optimization can be used to allocate water based on economic criteria, such as priority to those uses that return the highest net benefits in the basin. Agricultural water demand can be determined endogenously within such a model using crop production functions (yield vs. water, irrigation technology, salinity, etc.) and an M&I water demand function based on a market inverse demand function. Water supply can be determined through a hydrologic water balance in the river basin with extension to the irrigated areas. Water demand and water supply are integrated into an endogenous system and balanced based on the economic objective of maximizing net benefits from water use, including irrigation, hydropower, and M&I benefits (Rosegrant et al., 2000).

The net benefit (profit) from agricultural water use at a particular site can be expressed as crop revenue minus fixed crop cost, irrigation technology improvement cost, and water supply cost:

$$[10.6] \quad NB_{Ag} = \sum_{cp} A * Y * p - A * fc - w * p_w$$

where

NB_{Ag} net benefit from agricultural water use (US\$);

A	harvested area (ha);
p	crop price (US\$/mt);
fc	fixed crop cost (US\$/ha);
p_w	water price (US\$/m ³); and
w	water delivered to demand sites (m ³)

A crop yield function, yield as a function of applied water, can be specified as follows:

$$[10.7] \quad Y = Y_{\max} [a_0 + a_1 (w / E_{\max}) + a_2 \ln(w / E_{\max})]$$

where

Y	crop yield (metric tons [mt]/ha);
Y_{\max}	maximum attainable yield (mt/ha);
a_0, a_1, a_2	regression coefficients;
w	applied water (mm); and
E_{\max}	maximum evapotranspiration (mm)

The net benefit from M&I water use can be derived from an inverse demand function for water (Rosegrant et al., 2000):

$$[10.8] \quad NB_{M\&I} = w_0 p_0 / (1 + \alpha) [(w / w_0)^\alpha + 2\alpha + 1] - w \cdot wp$$

where

$NB_{M\&I}$	net benefit from M&I water use (US\$);
w_0	maximum water withdrawal (m ³);
p_0	willingness to pay for additional water at full use (US\$);

e price elasticity of demand; and
 α $1/e$

Net benefits from power generation can be calculated as:

$$[10.9] \quad NB_{Power} = E * (p_{price} - p_{cost})$$

where E is the produced hydropower (KWh), p_{price} is the price of power production (US\$/KWh); and p_{cost} is the cost of power production (US\$/KWh).

A river basin model based on this development will also include institutional rules, including minimum required water supply for users, minimum and maximum crop production, and environmental flow requirements. In such a case, the objective is to maximize net benefits in the basin from the supply of water to agriculture and M&I water uses, and hydroelectric power generation, subject to institutional, physical, and other constraints. The objective is:

$$[10.10] \quad \text{Maximize } Z = \sum_{j-Ag} NB_{Ag,j} + \sum_{j-M\&I} NB_{M\&I,j} + \sum_{j-power} NB_{power,j}$$

For further discussion: What are the reasons for not using economic allocation of water in a transboundary basin? What are the issues of national sovereignty that must be considered in this case? How can we build these into a river basin model?

Multiobjective Analysis Techniques

Water resources problems are inherently multifaceted with conflicting uses of water where tradeoffs must be made between stakeholders with differing goals. In the previous section, we developed an objective function with three components representing the net benefits from allocating water to agricultural use, municipal and industrial use, and hydropower generation. Using net benefits in common monetary units, these individual

objectives are commensurate. When the components are equally weighted, then each component is being given equal priority in the solution process according to its contribution to net benefits. That is, a dollar of agricultural benefit is equivalent to a dollar of hydropower benefit. However, these components or objectives can often be in conflict with one another, such as when agricultural water demand peaks in the summer growing season and hydropower demand peaks in the winter heating season.

Modeling methods that are used to determine the tradeoffs between various conflicting objectives in water resources problems are used in multiobjective analyses. Multiobjective modeling methods have been used for several decades to determine the tradeoffs between various objectives in water resources problems. Several books devoted to the subject of multiobjective planning, many with applications to water resources problems, have been published over the past three decades, including Haimes, et al. (1975), Keeney and Raiffa (1976), Cohon (1978), Zeleny (1982), and Steuer (1986).

Examples of multiobjective modeling in water resources planning include Bogardi and Duckstein (1992), who presented an interactive multiobjective analysis method to embed the decision maker's implicit preference function; Ridgley and Rijsberman (1992), who employed multicriteria decision aid for policy analysis of the Rhine estuary; and Theissen and Loucks (1992), who presented an interactive water resources negotiation support system. In these last two examples, multicriteria evaluation to support group decision making was emphasized. Other work has focused on integrating technologies to support multiobjective analysis. Simonovic et al. (1992) presented a rule-based expert system to facilitate and improve multiobjective programming in reservoir operation modeling.

Model Building Process

The river basin model building process consists of several steps (see Figure 10.7):

- Problem identification - identify the important elements of the basin to be modeled and the relations and interactions between them. That is, a general outline and purpose of the model must be established. The modeler must identify the appropriate type of model for the system and the degree of accuracy needed given the time and resources available for modeling. Generally the simplest model with the least number

of parameters which will produce reliable results in the time available is preferred (Ford, 2006).

- Conceptualization and development – establish the mathematical description of the relationships identified previously. In this step appropriate computational techniques are also determined and implemented for the problem.
- Calibration - determine reliable estimates of the model parameters. In this step model outputs are compared with actual historical or measured outputs of the system and the model parameters are adjusted until the values predicted by the model agree, to a reasonable degree of accuracy, with the measured.
- Verification - an independent set of input data, i.e., different from that used in the calibration step, is used in the model and the model results are compared with measured outputs. If they are found to agree the model is considered to be verified and ready for use.

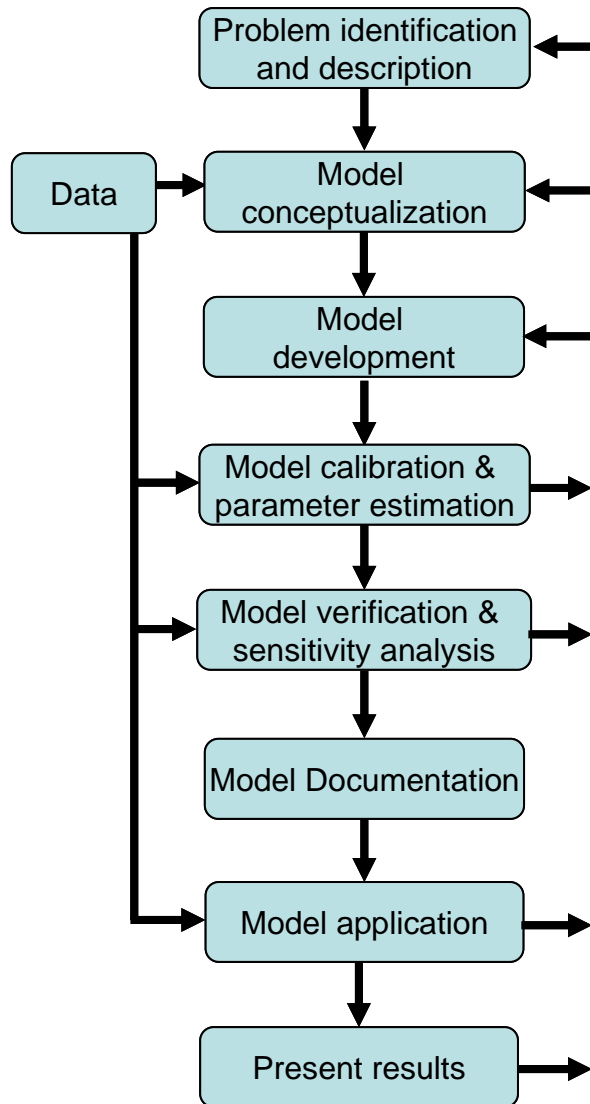


Figure 10.7: General diagram of the steps in the model building process.

- Sensitivity Analysis – Many of the input data and assumptions that are used to construct a model are inaccurately measured, estimated from sparse data, or poor approximations. Modelers need to know what impact these potential sources of error or uncertainty may have on their model results. Sensitivity analysis explores and quantifies the impacts of possible errors in input data on predicted model outputs and system performance indices (Loucks and van Beek, 2005). Sometimes small changes in model parameters can produce large, abrupt changes in model solutions. Often,

sensitivity analysis is a trial and error process of incrementally adjusting model parameters, coefficients, and inputs and subsequently solving the model. In this way, the modeler can see the change in model output values resulting from modest changes in input values and determine the importance of imprecision or uncertainty in model inputs in the modeling process (Loucks and van Beek, 2005).

Geographic Information Systems

Database systems provide comprehensive facilities for storing, retrieving, displaying and manipulating data essential to the decision-making process. Two common data manipulation and storage tools are the relational database, which relates information in a tabular way so that the rules of relational algebra can be applied, and the geographic database (or geographic information system-GIS), which relates information pertaining to fundamental spatial features such as points, lines, and polygons. GIS brings spatial dimensions into the water resources database, and it has the ability to better integrate social, economic, and environmental factors related to water resources planning and management for use in decision-making. GIS offers a spatial representation of water resources systems, but only limited analytical capabilities for solving water resources problems.

There are several strategies for coupling environmental models to GIS (McKinney and Cai, 2002), ranging from loose couplings where data are transferred between models and GIS, and each has separate database management capabilities and systems; to tight couplings where data management in the GIS and model are integrated and they share the same database. Tighter coupling between GIS and river basin models has been enhanced by the ArcHydro data model (Maidment, 2002) that can easily represent river basins in GIS.

ArcHydro defines a data structure of classes, such as watersheds, cross sections, monitoring points and time series in a manner that reflects the underlying physical watershed. It also defines relationships between the data, so that a river basin (catchment) may know which point represents its outlet, or a monitoring point may be aware of time series records for that location. The ArcHydro data model is being used

for water resources planning in the Rio Grande basin shared between the U.S. and Mexico (Patiño-Gomez and McKinney, 2005) and the South Florida Water Management District for the basis of an enterprise GIS database to support flood control, natural system restoration, operations decision support, and regional modeling projects (PBS&J, 2004).

MODELS USED IN TRANSBOUNDARY SETTINGS

Syr Darya Basin

The Syr Darya Basin, with average annual flow of 37.2 billion m³ and area of about 484,000 km², stretches some 2,337 km from the Naryn River headwaters in Kyrgyzstan through the Fergana Valley shared by Kyrgyzstan, Uzbekistan and Tajikistan, the Hunger Steppe in Uzbekistan, the Kyzyl Kum desert in Kazakhstan, before finally reaching the Aral Sea. Kyrgyzstan's Toktogul reservoir is the largest in the Syr Darya Basin and the only one with multiyear storage capacity (14 billion m³ usable storage volume). The reservoir was designed and constructed in the Soviet period to operate in an irrigation mode with minimal winter season releases. Prior to independence in 1991, surplus power generated by summertime, irrigation releases from Toktogul was transmitted to neighboring regions of the Soviet Union. In return for this electricity and irrigation water, those regions sent electric power and fuels (natural gas, coal and fuel oil) back to Kyrgyzstan for winter heating needs. For a description the water resources situation in the basin and in Central Asia more generally, see McKinney (2004).

This situation changed drastically when independent states were established in Central Asia in 1991. Because of complications in intergovernmental relations and account settlements, the introduction of national currencies, and increasing prices of oil, coal, natural gas, the supply of wintertime fuels and electricity sent to Kyrgyzstan from the other Republics was reduced. This created a winter heating crisis to which the Kyrgyz responded by increasing wintertime releases from Toktogul for hydroelectric generation thus depleting reservoir storage during the middle 1990's.

To alleviate these problems, the Syr Darya basin countries authorized the formation of a group to negotiate an interstate agreement on the use of water and energy resources in the Syr Darya Basin. This resulted in an agreement that created a framework addressing trade-offs between the competing uses of water for energy and irrigation in the Basin. Under the agreement, compensation is paid for compliance with a Toktogul release schedule that takes into account both upstream (Kyrgyz) winter energy needs and downstream (Uzbek and Kazakh) summer irrigation water demand. To date, the system has remained stable without major conflict and the agreement has entered the second five-year implementation period without major revision.

A critical element in the negotiations of the Syr Darya agreement was helping the parties understand the trade-offs between the conflicting objectives of winter electricity releases and summer irrigation releases. A multiobjective optimization model was developed to promote understanding of, and aid in the development of, efficient and sustainable water allocation options for the republics (McKinney and Cai, 1997; Cai et al., 2003). The multiple objectives combined in the model included (1) minimizing upstream winter power deficits and maximizing downstream irrigation water supply. By integrating these objectives with the system's physical, political, and operational constraints in an optimization model, the tradeoffs between the conflicting objectives of satisfying agricultural water demand, and generating hydroelectric power were elaborated and used to develop a number of water allocation scenarios to aid decision making. Further analysis of the economic consequences of the proposed options was prepared using hydroelectric and agricultural input and output costs and prices (Keith and McKinney, 1997).

Rio Grande Basin

The Rio Grande originates in the San Juan Mountains of southern Colorado, flowing 3042 km from its headwaters to the Gulf of Mexico, passing through parts of three U.S. states (Colorado, New Mexico and Texas) and five Mexican states in (Chihuahua, Durango, Coahuila, Nuevo Leon, and Tamaulipas). The Rio Grande is the international border from the El Paso, Texas area to the Gulf of Mexico. The basin covers an area of about 869,000 sq. km. Of the part of this area that contributes runoff to the river, about

half is in Mexico and half is in the U.S. Principal tributaries to the river include the Conchos, San Rodrigo, Alamo, and San Juan Rivers in Mexico, and the Pecos and Devils Rivers in Texas. The Rio Grande water resources are almost entirely allocated and used by the time the river passes El Paso and the river has intermittent flow until it reaches the confluence with the Rio Conchos, flowing out of the Mexican state of Chihuahua.

Mexico and the United States have two treaties and various cooperative regulations that govern allocation of the water resources they share. The two nations signed the “Convention for the Equitable Division of the Waters of the Rio Grande for Irrigations Purposes” in 1906 (IBWC, 1906). This treaty allocated the water in the upper basin above Texas. In 1944, the United States and Mexico signed the Treaty for the “Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande” allocating the water of the lower part of the Rio Grande basin (IBWC, 1944). Under the treaty, each country receives half of the water in the main stem of the river, and full use of the waters in their tributaries (IBWC, 1944). However, the treaty provides that one-third of the flow reaching the river from several named tributaries is allocated to the United States, provided that this is not less than a specified annual amount (averaged over five-year accounting cycles). The vast majority of this water comes from the Rio Conchos basin, as flow in the other tributaries is minimal during much of the year.

Today the Rio Grande supports a thriving agriculture. It also provides water for drinking, hydroelectric power, sewage disposal, industry, and recreation for more than five million people that live in this basin. Current diversions from the river go primarily to agriculture (more than 87 percent) with Mexico irrigating about 445,154 ha, and the U.S. about 401,852 ha.

Drought has been a persistent problem in the Rio Grande basin. Indeed, a recent drought event lasted about 10 years, longer than was ever anticipated in the negotiations of the 1944 treaty, and, as a result, Mexico was unable to deliver the quantities of water required under the 1944 Treaty and accumulated a “water debt” at the end of two consecutive five-year treaty accounting cycles.

The traditional segment-specific approaches to water management planning have been deemed inadequate to meet the challenges of a large transboundary basin such as the

Rio Grande. In order to illuminate strategies to reduce future conflicts over water throughout the entire basin a comprehensive, model-based planning exercise was undertaken. These strategies include making agriculture more resilient to periodic conditions of drought, improving the reliability of supplies to cities and towns, and restoring lost environmental functions in the river system.

The effort consisted of two parallel, interacting and converging activities, one of which was building a water resources database (Patiño-Gomez and McKinney, 2006) and an associated hydrologic planning model that represents the entire basin (Danner et al., 2006). This model was used to evaluate the hydrologic feasibility of a suite of scenarios for improving the management of the limited water available in this system, particularly those opportunities that bridge across management units and jurisdictional boundaries. Hydrologic feasibility includes both physical viability and the ability to provide mutual benefits to stakeholders throughout the system. This enabled the elaboration and understanding of the hydrologic dynamics in the basin such that the tradeoffs associated with a range of management strategies could be clearly illuminated.

Simultaneously with the development of a basin-wide model, the project generated a set of future water management scenarios that respond to the needs and objectives of the basin stakeholders, including water users, planning agencies, environmental organizations, universities and research institutes, and local, state and national government officials. These scenarios were evaluated for hydrologic feasibility by the basin-wide model in a set of gaming exercises. Modeling is necessary to understand how these options will affect the entire system and how they can be crafted to maximize the benefits and avoid unintended or uncompensated effects.

The development of the scenarios informed the process of assembling the data to populate the planning model. In constructing the management scenarios, a 30-50 year planning horizon was used so that the issue of climate variability and climate change could be considered.

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ANNEX 10A – SOME AVAILABLE RIVER BASIN MODELING SYSTEMS

Some of the more common river basin modeling tools are listed in this Annex, particularly the ones related to water allocation.

Delft-Tools (Delft Hydraulics, 2004) – Delft-Tools is a framework for decision support developed by Delft Hydraulics for the integrating water resources simulation programs. Functions of the system include scenario management, data entry, and interactive network design from map data, object-oriented database set-up, presentation, analysis and animation of results on maps. DELFT-TOOLS integrates the Delft Hydraulics models: SOBEK, RIBASIM and HYMOS. SOBEK is a one-dimensional river simulation model that can be used for flood

forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, ground-water level control, river morphology, salt water intrusion and surface water quality. RIBASIM (River Basin Simulation Model) is a river basin simulation model for linking water inputs to water-uses in a basin. It can be used to model infrastructure design and operation and demand management in terms of water quantity and water quality. HYMOS is a time series information management system linked to the Delft Hydraulics models.

Mike-Basin (DHI, 2004) – MIKE-BASIN couples ArcView GIS with hydrologic modeling to address water availability, water demands, multi-purpose reservoir operation, transfer/diversion schemes, and possible environmental constraints in a river basin. MIKE-BASIN uses a quasi-steady-state mass balance model with a network representation for hydrologic simulations and routing river flows in which the network arcs represent stream sections and nodes represent confluences, diversions, reservoirs, or water users. ArcView is used to display and edit network elements. Water quality simulation assuming advective transport and decay can be modeled. Groundwater aquifers can be represented as linear reservoirs. Current developments are underway to utilize the functionality of ArcGIS-9 in MIKE-BASIN.

Basic input to MIKE-BASIN consists of time series data of catchment run-off for each tributary, reservoir characteristics and operation rules of each reservoir, meteorological time series, and data pertinent to water demands and rights (for irrigation, municipal and industrial water supply, and hydropower generation), and information describing return flows. The user can define priorities for diversions and extractions from multiple reservoirs as well as priorities for water allocation to multiple users. Reservoir operating policies can be specified by rule curves defining the desired storage volumes, water levels and releases at any time as a function of existing storage volumes, the time of the year, demand for water and possible expected inflows.

Water quality modeling in MIKE-BASIN is based on steady, uniform flow within each river reach and a mass balance accounting for inputs of constituents, advective transport and reaction within the reach. Complete mixing downstream of each source and at tributary confluences is assumed. Non-point pollution sources are handled in the model as well as direct loading from point sources. The model accounts for the following water quality parameters: biochemical oxygen demand, dissolved oxygen, ammonia, nitrate, total nitrogen, and total phosphorus. Non-point loads are represented using an area loading method accounting for the nitrogen and phosphorous loads originating from small settlements, livestock and arable lands assuming certain unit loads from each category.

ModSim (Labadie et al., 2000; Dai and Labadie, 2001) – ModSim is a generalized river basin DSS and network flow model developed at Colorado State University with capability of incorporating physical, hydrological, and institutional/administrative aspects of river basin management, including water rights. ModSim is structured as a DSS, with a graphical user interface (GUI) allowing users to create a river basin modeling networks by clicking on icons and placing system objects in a desired configuration on the display. Through the GUI, the user represents components of a water resources system as a capacitated flow network of nodes (diversions points, reservoirs, points of inflow/outflow, demand locations, stream gages, etc.) and arcs (canals, pipelines, and natural river reaches). ModSim can perform daily scheduling, weekly, operational forecasting and monthly, long-range planning. User-defined priorities are assigned for meeting diversion, instream flow, and storage targets. ModSim employs an optimization algorithm at each time step to solve for flow in the entire network to achieve minimum cost while satisfying mass balance at the nodes and maintaining flows through the arcs within required limits. Conjunctive use of surface and ground water can be modeled with a stream-aquifer component linked to response coefficients generated with the MODFLOW groundwater simulation model (Fredricks et al., 1998). ModSim can be run for daily, weekly, and monthly time steps. Muskingum-Cunge hydrologic routing is implemented in the model.

ModSim has been extended to treat water quality issues in stream-aquifer systems through an interactive connection to the EPA QUAL2E model for surface water quality routing, along with a groundwater quality model for predicting salinity loading in irrigation return flows (Dai and Labadie, 2001).

ModSim is well documented in both user manuals and source code comments. Model data requirements and input formatting are presented along with sample test applications useful in understanding model setup and operation. Currently, ModSim is being upgraded to use the “.NET Framework” with all interface functions handled in Visual Basic and C#. This will greatly enhance the ability of the model to interact with relational databases and all variables in the model will be available for reading or writing to a database.

ModSim is in the public domain, and executable versions of the model are available free of charge for use by private, governmental, and non-governmental users. Generally, the source code for the model is not available. However, some government agencies have negotiated agreements with the developer in which the source code is made available to the agency and the agency is allowed to change or modify the source code as necessary for agency-related projects.

OASIS (Hydrologics, 2001; Randall et al, 1997) - Operational Analysis and Simulation of Integrated Systems (OASIS) developed by Hydrologics, Inc. is a general purpose water simulation model. Simulation is accomplished by solving a linear optimization model subject to a set of goals and constraints for every time step within a planning period. OASIS uses an object-oriented graphical user interface to set up a model, similar to ModSim. A river basin is defined as a network of nodes and arcs using an object-oriented graphical user interface. Oasis uses Microsoft Access for static data storage, and HEC-DSS for time series data. The Operational Control Language (OCL) within the OASIS model allows the user to create rules that are used in the optimization and allows the exchange of data between OASIS and external modules while OASIS is running. OASIS does not handle groundwater or water quality, but external modules can be integrated into OASIS. Oasis does not have any link to GIS software or databases.

RiverWare (Carron et al., 2000; Zagona et al., 2001; Boroughs and Zagona, 2002; CADWES, 2004) – The Tennessee Valley Authority (TVA), the United States Bureau of Reclamation (USBR) and the University of Colorado’s Center for Advanced Decision Support for Water and Environmental Systems (CADWES) collaborated to create a general purpose river basin modeling tool - RiverWare. RiverWare is a reservoir and river system operation and planning model. The software system is comprised of an object-oriented set of modeling algorithms, numerical solvers and language components.

Site specific models can be created in RiverWare using a graphical user interface (GUI) by selecting reservoir, reach confluence and other objects. Data for each object is either imported from files or input by the user. RiverWare is capable of modeling short-term (hourly to daily) operations and scheduling, mid-term (weekly) operations and planning, and long-term (monthly) policy and planning. Three different solution methods are available in the model: simulation (the model solves a fully specified problem); rule-based simulation (the model is driven by rules entered by the user into a rule processor); and optimization (the model uses Linear Goal-Programming Optimization).

Operating policies are created using a constraint editor or a rule-based editor depending on the solution method used. The user constructs an operating policy for a river network and supplies it to the model as “data” (i.e., the policies are visible, capable of being explained to stakeholders; and able to be modified for policy analysis). Rules are prioritized and provide

additional information to the simulator based on the state of the system at any time. RiverWare has the capability of modeling multipurpose reservoir uses consumptive use for water users, and simple groundwater and surface water return flows.

Reservoir routing (level pool and wedge storage methods) and river reach routing (Muskingum-Cunge method) are options in RiverWare. Water quality parameters including temperature, total dissolved solids and dissolved oxygen can be modeled in reservoirs and reaches. Reservoirs can be modeled as simple, well-mixed or as a two layer model. Additionally, water quality routing methods are available with or without dispersion.

RiverWare runs on Sun Solaris (Unix) workstations or Windows based PCs. RiverWare does not have a connection to any GIS software; however, a hydrologic database (HDB) may be available (Frevert, et al., 2003; and Davidson et al, 2002). HDB is a relational database used by the USBR and developed by CADWES to be used in conjunction with RiverWare. HDB is an Oracle-based SQL database and includes streamflow, reservoir operations, snowpack, and weather data.

Dynamic Simulation Software () –Dynamic simulation software has been applied to river basin modeling. This includes the software STELLA (High Performance Systems, 1992), POWERSIM (Powersim, 1966), VENSIM (Ventana, 1996), and GOLDSIM (Goldsim, 2003). These are dynamic simulation packages that stem from the system dynamics modeling method “Dynamo” invented by J. Forrester at MIT in the 1960’s. The latest generation of these packages use an object-oriented programming environment. The models are constructed from stocks, flows, modifiers, and connectors, and the software automatically creates difference equations from these based on user input. These methods all include components for: (1) identification of stocks and flows in a system; (2) graphically representing dynamic systems in "stock-and flow-diagrams"; and (3) a computer language for simulating the constructed dynamic systems. Models can be created with by connecting icons together in different ways into a model framework so that the structure of the model is very transparent.

WEAP (Raskin, et al., 1992; SEI, 2004) – The Water Evaluation and Planning System (WEAP) developed by the Stockholm Environment Institute’s Boston Center (Tellus Institute) is a water balance software program that was designed to assist water management decision makers in evaluating water policies and developing sustainable water resource management plans. WEAP

operates on basic principles of water balance accounting and links water supplies from rivers, reservoirs and aquifers with water demands, in an integrated system. Designed to be menu-driven and user-friendly, WEAP is a policy-oriented software model that uses water balance accounting to simulate user-constructed scenarios. The program is designed to assist water management decision makers through a user-friendly menu-driven graphical user interface. WEAP can simulate issues including; sectoral demand analyses, water conservation, water rights, allocation priorities, groundwater withdrawal and recharge, streamflow simulation, reservoir operations, hydropower generation, pollution tracking (fully mixed, limited decay), and project cost/benefit analyses. Groundwater supplies can be included in the WEAP model by specifying a storage capacity, a maximum withdrawal rate and the rate of recharge. Minimum monthly instream flows can be specified.

WEAP is relatively straightforward and user-friendly for testing the effects of different water management scenarios. The results are easy to view for comparisons of different scenarios. Changing input data to model newly proposed scenarios can be readily accomplished, as long as it is not necessary to make any changes to the ASCII file of historical data.

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