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Review of Integrated Approaches to River Basin Planning, Development, and Management

A review of models for river basin development operations, management, water quantity and quality, recreational demand, countrywide planning, and multiple objective planning.

Donna J. Lee
Ariel Dinar

The World Bank
Agriculture and Natural Resources Department
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REVIEW OF INTEGRATED APPROACHES TO RIVER BASIN PLANNING, DEVELOPMENT AND MANAGEMENT

Donna J. Lee

Department of Economics
University of Hawaii

Ariel Dinar

Agriculture and Natural Resources Department
Agricultural Policies Division
World Bank

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INTRODUCTION

Over 70% of the world's land area can potentially be influenced by river basin development (Scudder 1994). Many countries have access to the resources of at least one river basin, and some countries can access the resources of several river basins. How the river basin is developed and managed will have, therefore, a major impact on present and future living standards of its inhabitant and on the basin ecosystem.

Water resources have several characteristics that make the role of the public sector in their development and management more essential than in other goods that can be handled efficiently in a market framework. For example, some water services have a public good nature that may lead to under-investment; other services are characterized by economies of scale, leading to monopolistic power and socially inefficient allocation. Water projects are associated with large volumes of investments relative to the capacity of the capital market. Because of the range of market failures and the large volume of capital needed for water projects, a significant share of water related infrastructure investments are conducted by the public sector (World Bank, 1993).

However, fragmented public investment programs for development and management of water resources, that have failed to take into account the interdependencies among using sectors, and the impact on other (non-water) economic and non-economic activities, are frequent problems associated with mismanagement of the scarce resources in many developed and developing countries (World Bank, 1993).

What is true in the general case of water resource development and management, is true in the particular case of river basins. Water development projects in river basins are being implemented in many cases without considering the interactions within the hydrological and economic system.

Because a river basin system is comprised of many components with interdependencies, piecemeal approaches to river basin development and management have often failed to lead to an optimal outcome, resulting in inefficient resource use, economic losses and environmental degradation.

To remedy these problems, comprehensive approaches to river basin development have been proposed. The advantages associated with a comprehensive approach are listed by Le Moigne (1994):

- Ability to meet short- and long-term demands in an economically efficient manner
- Ability to include activities and objectives that are not always economically and technically feasible in separable approaches
- Ability to benefit from cost reduction through economies of scale
- Ability to identify efficient solutions to water quality and pollution problems
- Facilitates action of reaching a consensus among the riparians, thereby reducing tension and conflicts

However, the complexity of the natural and economic system within a river basin makes it difficult to plan and design an optimal investment program. A model may be helpful in accounting for all relevant components comprising a river basin, in addressing various planning and management objectives, and in utilizing the advantages provided above. Several (modeling) approaches have been used in river basin planning, development and management.

The purpose of this paper is to selectively review the literature on economic models developed for river basin planning and management. The review includes models addressing water quantity and quality issues, environmental considerations, and conflicts over the above issues at the sectoral, regional and international levels. The review may serve as a source of references for those who need to consider whether they can make use of a model. The review is organized according to various classifications of modeling approaches and river basin planning, development and management objectives and scope. The review allows the reader to evaluate the suitability of a particular model to a certain project, and the associated advantages and disadvantages. The review does not attempt to survey all existing river basin models, but rather to select the ones that would best demonstrate the potential application to projects at river basin level. A brief list of specific computer models used for various aspects of river basin planning and management is summarized in an Appendix. The interested reader is referred to a report by the U.S. Army Corps of Engineers (1994), that provides technical details of computer models for water resources planning and management.

RIVER BASINS DEVELOPMENT AND MANAGEMENT

Water within a basin serves human needs such as drinking, cooking, and washing and sanitation; allows arid land to become productive through irrigation; provides a habitat for plants, fish, and wildlife; supplies urban and industrial uses; generates electricity through hydropower; and supports many recreational uses. River resources around the world have been developed and managed for centuries to control volatile supplies of water in order to meet demands for water quantity, quality, and reliability in time and space (Loucks et al, 1981).

A river basin is defined by its watershed area. At the highest elevation are the upper reaches where snow melt or precipitation feed into narrow streams that rapidly descend a steep gradient. These upper reaches feed into a middle reach creating a "mainstem" of the river. Floodplains, lakes and swamps characteristically are found around the slow flowing river mainstem. Below the mainstem is the lower reach where the river meets the ocean. In the lower reach, saline and fresh water mix, silt settles, and a delta forms. Highly productive estuaries, mangrove forests, wetlands, coral reefs, tidal marshes and mud flats predominate (Marchand and Tornstra, 1986). Subsurface water flows including underground aquifers are also part of the basin (World Bank, 1993).

River basins are typically large, crossing not only private property lines, but regional and international boundaries as well. Localized development of water resources to meet community and regional needs for clean water and food has often come without regard to other users or uses. Thus, comprehensive plans to develop and manage basin resources have been the exception rather than the rule. Private agendas, contradictory objectives, and histories of noncooperation increase the difficulty of achieving efficient resource management. High information costs due to the many users of river basin has impeded the process of negotiation and exchange that could lead to a socially optimal allocation. Consequently, conflicts over the development and allocation of water persist.

The dominant use conflicts over river basin resource allocation are for water quantity and water quality in space and time. Uses may be classified as either consumptive or nonconsumptive. Consumptive use is defined to be the amount of water withdrawn from the system in such a way that it is no longer available for other uses. In this respect, river basin water has common pool characteristics in that one use precludes other uses. Examples are agricultural irrigation and urban water use. Consumptive uses may compete by sector (e.g. municipal, agricultural, and industrial/commercial), within sectors (allocation to one farm versus another farm); or regionally (upstream regions versus downstream regions). Nonconsumptive uses do not result in a significant reduction in net stream flow, and depending on the type, may allow for multiple nonconflicting uses at the same time and location. Examples of nonconflicting nonconsumptive uses include reservoir storage, fish habitat, passive recreation (e.g. sightseeing, swimming). More problematic situations occur when nonconsumptive uses interfere with or lower the value of water precluding or impairing its use by others. For example, nonconsumptive uses such as leaching salts from agricultural fields, diverting river water to cool power plants, and using the river to dispose of partially treated or untreated waste, degrades water quality at the expense of other uses. Although the upstream users may be best suited to improve the quality of downstream water by altering water use practices, often the upstream user has no means of capturing the benefits or even of recouping the costs, thereby having no incentive to reduce pollution loads. Consequently the externalities persist. Nonconsumptive uses of water also conflict in time. For example, residential users may prefer that a quantity of water be stored for future use, environmentalists may prefer that water be released to support the fish habitat, and the industrial sector may prefer a release for electricity generation. For each user, although the water extracted and its quality remains the same, one use at a particular time precludes another use.

Because the use and the value of river basin resources depend on the quantity and quality of water available in space and in time, and because many of the uses are physically linked through the basin hydrology, managing water resources can be more efficient using a comprehensive, basin-wide approach. For example, the objectives of a basin-wide plan may be to: foster economic growth, maintain environmental quality, achieve agricultural self sufficiency, enhance foreign export trade, promote regional development/autonomy, increase employment, provide resources for a growing population, improve quality of life, retain national security, meet energy demands, and improve public health (Loucks, 1981). Some of these objectives are compatible, others are conflicting. Information about the tradeoffs made when choosing between objectives is needed to make rational, informed management decisions. River basin models can prove an indispensable tool for aiding in the decision-making process.

Models offer a simplified representation of problems that enable information to be processed quickly and efficiently. Models are often used to predict and evaluate the outcomes of alternative policies, and reveal social and economic trade-offs (Haith and Loucks, 1976). For example, models can be used to determine the optimal size, location, and type of water development projects (Technical Co-operation, 1990), to meet a community's needs. Models can also be used to evaluate projects both jointly and individually based on their cost effectiveness and marginal contribution to society, and can reveal the economic and social trade-offs between alternative competing projects. Models can be applied to reveal strategies for managing and allocating scarce resources to their highest and best use. It is important to note that while models excel at handling large amounts of quantitative and quantifiable information, actual decisions are often made with regard to both quantitative and qualitative information. Thus, the primary function of models is as an informational tool in the overall decision-making process.

Although models can be useful for river basin development and management, in the real world they might be more effective

- in small rather that in large river basins
- in situations where the model will continue to be used by managing agencies that played an active role in the development of the model.
- in situations where Quantity and/or quality problems are clearly defined, and
- where the institutional framework allows implementation of the model results and recommendations.

MODELING APPROACHES FOR RIVER BASIN MANAGEMENT

Use of models

River basin models are used to assess the economic, social, and environmental effects of alternative development and management policies. Positive (descriptive) models are used to explain and understand the underlying processes in the system and to predict the outcome under changing conditions that may result, for example, from construction of a new project or implementation of a new set of operational policies. Alternatively, models can be used to choose from a range of alternatives those best suited for achieving stated objectives. Normative (prescriptive) models are used in nearly all facets of water development, policy making, and management. For example, normative models can be used to indicate optimal project location and size, to formulate suitable operational and maintenance policies, and to determine efficient allocation of water and levels of water quality. Results from normative models can be interpreted to reveal opportunities for improvement over the status quo.

The insight into problems that models provide answers to, make them an indispensable tool for informed decision making. Depending on the nature of the problems and the issues to be addressed, models may be static or dynamic, deterministic or stochastic, single or multiple objective, economic or engineering-oriented.

Static vs. dynamic. Static models can be used to examine the effect of a change in conditions in the system. The effect can be, for example, the nature of construction of a wastewater treatment plant on river water quality. Dynamic models, that describe intertemporal behavior of some of the model components, can capture the transition or evolution of the system over time due to a change in the conditions. The transition between construction of a dam and the time until the system reaches its new equilibrium may be many years. A dynamic model can be used to capture the transitory effects such as the changing landscape, alteration in water flows and water quality, and shift in fish and wildlife species.

Deterministic vs. stochastic. Deterministic models are used when it can be assumed that the information affecting the outcome is known and predictable, and the influence of unknown or unpredictable factors are small. Stochastic models are used to incorporate information about the reliability (or unreliability) of information in the model (estimated parameters, data), or uncertainty due to unknown or unpredictable events that influence outcomes. Results from stochastic models can indicate the outcomes of alternative projects in probabilistic terms.

Single vs. multiple objective. Single objective economic models, which are the most common, rely on the assumption that all use values affected by decisions can appropriately be denominated in common units and compared in those units. Multiple objective models allow for the evaluation of tradeoffs between competing objectives, where the objectives may be expressed in completely different units.

Economic vs. engineering. Economic models are distinctly different from engineering models in their focus on the quantifiable effects of activities on human welfare, where human welfare is denominated in monetary units in terms of income, costs, and returns to investment. In contrast to engineering models, the hydrological system will often be characterized only to the extent necessary to capture its influence on human welfare (Howe, 1973). Engineering and economic modeling, however, need not be mutually exclusive. Many contemporary integrated river basin models contain both engineering and economic components.

Model limitations, strengths and weaknesses

Models can provide information solutions that maximize welfare, or minimize damage, and on tradeoffs between alternative outcomes, and risk and uncertainty. The results from any model, positive or normative, will depend on the model assumptions embedded in the objective function, the constraints, and all the factor relationships. By nature, models are based on assumptions that are inherently uncertain and are therefore *limited* by the accuracy of the specification, the data used to parameterize the model, and the solution techniques used to solve the model (Haimes, 1977). Additionally, qualitative factors and subjective inference, also part of the decision making process, may necessarily be omitted from the model (Loucks, 1981).

Model design

Models are by definition intended to abstract from reality. Ideally, a model should only be as complex as necessary to obtain the information desired. By contrast, "all purpose" models, are typically not very useful (Biswas, 1976). The most useful model will be designed to make best use of the available data. It will be designed with the skills and abilities of the intended user in mind, and be compatible with the computational technology available to the intended user. The useful life of a model can be extended with a design that accommodates new information easily as it becomes available.

Model specification

To help focus and streamline the model development process, whenever possible, it is recommended (Dept. of Technical Co-operation, 1990) that modelers consult with those who will be using the model or the model results When specifying a model the primary considerations are as follows. What are the objectives of the study? Why is the study being done? Is a model necessary? What is the purpose of the model? What data is required for the analysis? What data is available? How will the model be used? Will the model be used to address a single issue? Or, is it being designed as a tool to support ongoing operations and policy decisions? Can the model simulate all or most likely future scenarios? What computer technology is available to the study? How much time and budget will be made available to develop the model? The "best" model will be the "leanest" and most transparent. It will utilize the available information in a more sophisticated manner than alternative candidate models to provide useful, nonintuitive information, and can be completed, on time and within budget. Trade-off exists in the model specification. A more complex model than needed will not necessarily yield better information and may in fact confound interpretation of the results. While an overly simple specification may yield insufficient information to address the problem at hand.

SELECTED REVIEW OF EXISTING MODELS

A search of the literature reveals a wide range and number of published reports on river basin models. For purposes of discussion, this paper has selected a few studies representing basin-wide integrated modeling. The models are presented under the following broad categories: development, operations, water quality, water quantity and quality, recreation demand, country-wide planning, and multiple objective planning.

Development

In the Russian River Basin in California, planners faced the problem of determining the optimal sequence and timing of a finite number of water development projects to meet the rising demands of a growing population. Regev and Lee (1975), in designing the Russian River Basin Model, defined all existing dams as state variables[1] and proposed new dams or dam expansion projects as control variables. Returns to water use were stated as a function of available water and water to be made available in the subsequent year. Total returns were defined to be direct returns, flood control benefits, and recreational benefits, less the cost of construction, operation, and maintenance. The model objective was to maximize the discounted stream of net returns to development plus the terminal value of the water projects. The solution was obtained with mathematical programming methods. Using stochastic programming methods, the model was solved to allow for random population growth.

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[1] A state variable in a decision making model is a variable that describes the condition of the analyzed system. A state variable is affected by the levels of decision variables and by external effects. For example, in a river basin model, the level of water flow in the river is a state variable that is affected by decision (control) variables such as water diversion at various locations, and by external variables such as rainfall in the catchment area.

The problem of sequencing projects over time was also considered for the Guadiana River Basin in Southern Portugal by Tavaras (1981). This largely undeveloped water resource was selected for a large water project that included a hydroelectric power station and multiple reservoirs that would supply water for agricultural irrigation, rising urban demands, and industrial uses. Tavares (1981) developed a model to determine the optimal configuration of the system (location, storage size, distribution), optimal scheduling of the projects within the system, and the indirect economic effects of the project on local communities (e.g. employment). Mathematical programming was applied to determine the discounted present value of investment required to complete the project, and to determine the sequence of development that would maximize net benefits to the districts serviced by the system. The indirect economic effects were obtained with input-output analysis that describes the economic relationships of all consuming and producing economic units in the river basin.

Economic productivity in the Maule River Basin in Chile, a low productivity agricultural region, could be enhanced by a dam project which would provide hydroelectric power, irrigation water, municipal and industrial water, navigation opportunities, pollution abatement, fishing, and recreational water uses. Bulkley and McLaughlin (1966) developed a political simulation model to predict the political response to various development proposals those, for example, that would be suggested from the results of an engineering-economic model. Results from engineering-economic model would provide the allocations of water and income to three competing uses, hydropower, irrigated agriculture, and flood control, to be used as the starting point for the political response model. The political response model simulated the distribution of power within the political system, projected conflicts, and anticipated coalitions formed. In lieu of engineering-economic results, the authors synthesized three scenarios in which both water and financial resources were allocated to exclusively one use, and a fourth scenario in which resources were allocated to all three uses. Results were reported in terms of the probability of acceptance of a proposed allocation.

Cooperation amongst parties involved can help to insure efficient development of basin resources. The transactions necessary to insure success, however, become increasingly difficult when the power structure at the decision-making level is divided and when the desired objectives are conflicting, as is often the case when projects cross jurisdictional boundaries. Dufornaud and Harrington (1990) examined the problem of water development across jurisdictional boundaries. They developed a model of three parties with no history of cooperation but an interest in developing water resources and securing international funds for joint efforts. The authors specify a cooperative game[2] in two time periods to examine the benefits and costs incurred by each party under various schemes. The model shows the scenarios that minimize total international subsidies, side payments, and contingency funds required to achieve joint water development among the parties.

Operations

In a multiple reservoir system in the Murray-Darling River Basin in Australia, poor water quality (salinity) is responsible for significant economic costs to municipal and industrial users serviced by the basin. Dandy and Crawley (1992) augmented an operational water quantity model of the basin with a

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[2] A cooperative game is a public choice model that attempts to maximize and allocate gains from joint actions among several decision making units that agree to participate in the "game".

water quality model to capture salt flows through the system and estimate economic salt damages. The primary objectives of the joint model were to: minimize total shortfalls below target storage levels, minimize combined pumping cost and salt damages, and minimize spills. The model included losses from evaporation and seepage, and constraints on storage, conveyance and pumping capacity. A solution to the problem was obtained with linear goal programming. Linear goal programming requires that the relative priority of the objectives be specified exogenously, then optimizes each objective in turn. Results showed that a change in operations could reduce salt damages, yielding a significant improvement in the objective values over current operational practices.

A series of dams was built in the Tana River Basin in Kenya, the fifth dam was completed in 1988. The dams supply water for public use and irrigation, and provide electricity. Operational problems included controlling erosion and sedimentation into the reservoir and allocating water during dry periods. Verhaeghe, et. al. (1989) developed a model to evaluate water availability and operations during dry periods and to predict sedimentation rates. The model included a simulation component to replicate the hydrology of the basin under current management practices under fixed demand and varying demand scenarios; an optimization component to maximize electricity generation subject to water requirements during critical and average flow conditions; and a simulation component to track sedimentation rates.

Canter (1991) discussed the importance of water quality considerations that arise as a result of water development projects in the tropics in reference to the Amazon River in Brazil. He recommended that models are needed to study all phases of water development: planning, construction, transition, and operations; and discussed the importance of monitoring water quality throughout development to allow for calibration and verification of the working model. He discussed the effect of the change in water quality within thermal stratums, chemical cycling, biological cycling, bacterial content, gasses, evaporation, sediments, dissolved solids from both point and nonpoint sources. The paper provided a summary of models used by U.S. Army Corps of Engineers, commented on how modeling should be done. No new model was presented.

Water quantity and quality

Water quantity and water quality issues in the Colorado River Basin in the United States have been examined in a series of studies. In an early study, Howe and Orr (1974) used linear programming methods and a regional input-output model to estimate the direct and indirect income lost from upper basin agricultural acreage reduction as an alternative to traditional salinity control methods. Production activities in the upper mainstem of the Colorado River Basin were divided into 33 economic sectors. A reduction in acreage was simulated and the input-output model was used to determine the direct and indirect economic effects to the economic sectors, and a hydrosalinity model was used to estimate the effect on water quality (salinity). Gardner (1983) modeled the Colorado River Basin and applied linear programming methods to evaluate the opportunities for federal cost sharing with upper basin farmers as low cost means of reducing total salt load into the river basin. In a subsequent study, Lee (1989) examined a wide range of options for controlling salinity from multiple sources. Salinity control options included water conservation, shifts in cropping patterns, acreage reduction, and water transfers. The objective was to select the mix of control options to achieve the level of water quality that maximized returns to water uses in the river basin under various river flow scenarios. A detailed description of the physical model appears in Lee et al. (1993). The model was solved with nonlinear and stochastic programming methods. Oamek (1990) and Booker and Young (1993) examined the economics of interbasin water transfers from upper basin agriculture to lower basin urban uses to meet rising urban demands as a lower cost alternative to construction of new water projects. Booker and Young presented an institutional model of water use, flows, quality, and physical and institutional constraints. A range of "efficient" transfer quantities was ascertained under alternative specifications of the benefit function.

The Trent River in the U.K. provides irrigation water, navigation, municipal and industrial water supply, hydroelectric power, flood protection, commercial fishery, and recreational uses to users in England and Wales. Due to rising pollution levels and increasing demand for clean water, a plan of action and a series of development projects were proposed. Newsome et. al. (1972) developed a model to determine the minimum capital investment required to meet rising demands. Their model included: water transfers, pumped reservoir storage, estuary storage, and sewage treatment. Brewin et. al. (1972) developed a model to predict changes in Trent River water quality from development, effluent loads, river retention, increased diversions, and power generation. Water quality characteristics considered were: biochemical oxygen demand, temperature, and aeration. Within the model, the river was characterized as a series of discrete states, and the state of the river was characterized as a function of effluent emissions at or below that required to achieve minimum water quality standards. Dynamic programming was applied to determine the least cost method of achieving each state. The global optimum was defined as the river state that could be achieved at the lowest total cost.

Water quality

For the Axios River Basin in Greece, water quality is important to consumptive uses, recreation, fishing, and maintenance of natural reserve areas. van Gils and Argiropoulos (1991) specified a water quality model to replicate the concentration of pollutants in the river. The model allowed for sources and sinks, dispersion, degradation, transport, and chemical and physical processes. Alternative management strategies included: a 50% reduction in pollution levels, a reduction in agricultural acreage, and a 100% increase in municipal and industrial waste loads and disposal of partly treated wastewater. With a cumulative frequency distribution derived from monthly flow records, the model was used to determine the probability of violating water quality standards under each alternative strategy.

The Densu River in Ghana provides water for approximately 2 million people, and also serves as the primary recipient of all domestic and industrial waste in the basin including a food cannery. The warm tropical waters tend to be polluted all year around. Laramie et. al. (1989) specified a steady-state hydrological model to capture physical, chemical, and biochemical activity from point and nonpoint pollution loads and their effect on the water quality in the river. Water quality constituents included: chloride, dissolved oxygen, and BOD. Using monthly flow and quality data the model was parameterized for the wet and dry seasons of the year.

Nutrient loads from fertilized agriculture in the Martna watershed in Estonia is accelerating the eutrophication of Matsalu Bay. Krysanova et. al. (1989) developed a model to evaluate alternative management practices in the river basin. A series of four differential relationships were specified to: capture nutrient transfer from the drainage area, water movement through the soil, nutrient balance in the soil, and nutrient concentration and movement in the river. The model was used to simulate the effects of fertilizer application rate, application method, application timing, and acreage of fertilized crop planted on nutrient loads into the bay.

Wastewater, sewage, storm runoff, and irrigation return flows pollute the Tong Hui and the Liang Shui Rivers in Beijing, China. As a result, water quality is below drinking standards, fish and wildlife habitats are threatened, and recreational uses are severely limited. To determine the effectiveness of sewage treatment on water pollution levels, a simulation model was developed. For modeling purposes, the river system was divided into discrete sections and defined in terms of its boundaries and sewage loading, sewage treatment, biological oxygen demand and dissolved oxygen within each section. Mass and energy conservation were assumed. Sewage treatment measures were grouped into "plans" representing various levels of control. The treatment plans were simulated, and the benefits in terms of savings from improved water quality were compared to the costs. The plans were ranked based on their estimated net present value under various discount rates (Hufschmidt, 1986a).

After completion of the Ubolratana Dam on the Nam-Chi River in Thailand, rapid settlement into the upper watershed area resulted in heavy logging, slash and burn cultivation, and consequently, erosion and transport of pesticides and fertilizers into the reservoir. Sedimentation lowers the value of the reservoir by reducing its capacity to produce electricity, store water, provide flood protection, and serve as a fish habitat. A model was developed by Hufschmidt (1986b) to evaluate the net benefits from soil erosion management of the watershed over a 50 year period. Sedimentation rates were captured with a mass conservation model, and the cost of sedimentation was assessed as the value of lost reservoir productivity lost. Two alternatives were evaluated: employment of watershed management to reduce erosion, and the status quo, no additional management and increasing erosion. Given the costs of watershed management and the small returns to the basin from reduced sedimentation, results showed that erosion control in the upper Ubolratana yielded no net benefit.

Recreational demand for water

In arid regions, efficient allocation of scarce water resources to competing uses can yield large economic benefits. In the Pecos River Basin in New Mexico, recreational uses compete with irrigated agriculture for available water, and competition is highest during the dry summer months. Ward (1989) estimated the implicit value of water in recreational uses for four reservoirs in Pecos. Assuming that the user value of a "site" (a reservoir with water) must sufficiently exceed the cost of travel to the site, the value of water in recreational uses was estimated statistically using survey responses from households in the surrounding area. Results showed that the value of water was four times higher in recreational than in agricultural uses, indicating that an "entry" fee to recreational uses could potentially provide sufficient funds for purchasing water from agriculture uses to keep the basins full during the summer months.

Country-wide water use planning

Börlin (1971) developed a model to aid decision making in country-wide water use planning, to be used as a template for research in other developing countries. The country-wide model was divided into five submodels: demographics, agriculture, employment, water, and income. The agricultural submodel included irrigation potential, agricultural policies, resource availability, and farmer behavior. An additional subregional model consisted of two endogenous variables: population and labor force; and five exogenous variables: employment, wages, consumer demand, river basin, and land. The population demographics were assumed to change over time with the rate of birth and death. Model results were restricted by constraints on the choice variables. The model specification allowed for analysis of a wide range of development projects. A hypothetical project mentioned was construction of a dam which would include multiple project phases over time, construction, capital, and operation and maintenance costs, and on-farm costs, and the effect of water development on regional employment. One concern with country-wide models is that they are limited only to cases where the country comprises only one river basin. In the case of interbasin water transfer, models must include impacts on the basin of origin.

Multiple use planning

As a result of industrial pollution and agricultural runoff, the quality of water in the Maumee River Basin in Indiana, Michigan and Ohio ranges from acceptable to very poor. Due to population and industrial growth in the area, water supply shortages are expected by year 2000. Basin water transfers are considered the best alternative to increased development. In addition to providing a reliable supply of municipal and industrial water, goals in managing the basin's resources include: land use planning, erosion control, water quality improvement, maintenance of fish and wildlife habitat, increased opportunity for recreational uses, and drainage and flood protection. To simplify the analysis of this large basin system and to reduce the dimensionally of the problem to be solved, Haimes et. al. (1977) decomposed the basin system into a series of smaller subsystems, each assumed to be independent of the others. Each subsystems was optimized separately. The subsystem results were joined by linking variables and equations to represent the problem to be solved and to obtain the system-wide solution. Three basic alternative plans were synthesized. One emphasized economic development (more recreational opportunities and flood protection) another emphasized environmental quality (reduced biological oxygen demand and erosion), and a third represented the status quo. Model results revealed the tradeoffs the community and decision makers would have to face in selecting between competing projects and conflicting goals.

BARRIERS TO EFFECTIVE PLANNING AND MANAGEMENT

Although use of models for integrated river basin development and management is desirable, real world constraints limit their application and utilization. Main barriers to effective use of river basin models include information, physical, and institutional barriers.

Informational barriers

Insufficient economic data, data limitations, and poor information about the cultural, social, and political norms of the existing population often hinder development of an effective planning strategy. Additionally, short sighted development goals, insufficient budget for planning, and poor appreciation of the importance of good planning are further impediments to effective management of river basin resources.

Physical barriers

The physical nature of a river basin can confound efforts to manage the basin's resources. Because basins are irregular and receive water flows from multiple sources, difficulties are often encountered when attempting to divide a basin into discrete, manageable subunits. Further, the stochastic nature of the water supply makes prediction and control of the water problematic.

Interbasin transfer. Temporal and spatial variability are usual barriers to integrated river basin development. The possibility of interbasin transfer has implications for the planning of all regional development projects while providing flexibility and stability in water supply. Sometimes the geography is such that it does not allow large scale interbasin transfer of water, and sometimes the geopolitics is such that it does not accept the results from the integrated approach.

Institutional barriers

Although economic models can indicate opportunities for improvement in river basin planning, development, and management, existing institutions and conflicting policies may pose insurmountable barriers to more effective management. Grigg and Flemming (1980) discussed the United States' policy on water quality management. As stated in the Federal Water Pollution Control Act of 1972, the water quality management objectives are to maintain United States waters, give the States an expanded role in implementing water quality programs, and to assure that programs are equitable across all states, geographic regions, and industries. This third objective by definition rules out many economic approaches to water quality management such as marginal pollution taxes and transferable discharge permits; that give low cost polluters a comparative advantage over other polluters.

Application Barriers

As was correctly indicated by Tanji (1981), many models are formulated and applied to specific problems, and are not amendable to more generalized problem situations. If a model is to be applied from one problem situation (or location) to another, the model generally needs modification, calibration and validation. These modifications are associated with additional cost (e.g., in terms of time) to the potential user. This cost may become a barrier to effective use of the model even if it is the best that fits the problem needs.

SUMMARY

This review of work on river basin modeling has shown that there are a wide range of approaches for specifying a model for river basin planning, development, and management. Economic, engineering, biological, political and integrated approaches can all reveal potentially useful information to the river basin planner or manager. The key is to determine the most pressing problems at hand, to determine if the intended use of the model is to better understand the problem, to help identify potential solutions, or to be used as an ongoing tool in river basin management and operations; and finally to assess the amount of resources in terms of time, budget, expertise, and public and government participation, that will go into the model development and interpretation of the model results.

For a description summary of the key features of the models reviewed in this paper, the interested reader is referred to Table 1.

Some prerequisites for an appropriate application of an integrated river basin model may include:

1. A water resources information system using hydrometric data collection stations from key locations;
2. A rainfall-runoff model with soil and groundwater components;
3. A channel routing model with conveyance losses;
4. A reservoir operation model;
5. Agricultural, industrial, residential, and environmental water demand functions;
6. An engineering model to calculate infrastructure feasibility alternatives;
7. A water resources simulation model that incorporates the models in 1-6;
8. A linkage to a macroeconomic type model that translates the outcome from the water resources simulation model to monetary values and optimizes a river basin objective function subject to physical, institutional and political constraints.
9. One important component that has not been discussed in the models that were reviewed here is a social assessment model of relocation. Although river basin development is intended to improve human welfare, some development requires relocation of inhabitants. Development models should account for human effects such as relocation and other transitory costs.

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Table 1: Descriptive Summary of Models Reviewed

Model Use	Source	River basin	Model Characteristics							Issues addressed												
			Economic, Engineering, Biological, Political				Intertemporal, Stochastic, Multiple objective			Demand, Growth, Supply			Municipal and Industrial, Agriculture, Energy, Flood protection, Recreation					Water quality, Environmental quality, Health			Fishery, Navigation	
			E	n	B	P	I	S	M	D	G	S	M	A	E	F	R	W	H	E	F	N
planning	Laramie et al (1989)	Densu RB, Ghana		●	●			●					●	●				●				
	Börlin (1971)	OECD	●	●			●			●	●		●	●								
	Canter (1991)	Amazon RB, Brazil		●	●													●	●	●		
development	Bulkley and Maclaughlin (1966)	Maule RB, Chile				●								●	●	●						
	Regev and Lee (1975)	Russian RB, CA, USA	●				●									●	●					
	Tavares (1981)	Guadiana RB, Portugal	●				●				●	●	●	●								
project evaluation	*Hufschmidt (1986a)*	*Liang Shui and Tong Hui Rivers, Beijing China*	●	●	●		●						●	●				●		●		
	Hufschmidt (1986b)	Nam-Chi RB, Thailand	●	●			●					●		●	●	●					●	
operations	Verhaeghe et.al. (1989)	Tana RB, Kenya		●				●		●			●	●	●			●				
	Dandy and Crawley (1992)	Murray-Darling, Australia	●	●					●	●		●	●					●				
managment	Haimes, et al (1977)	Maumee BR, USA	●	●	●				●	●	●		●	●		●	●	●		●	●	
	Ward (1989)	Pecos RB, New Mexico, USA	●							●				●			●					
	Brewin et al (1972) Newsome et al (1972)	Trent RB, England and Wales	●	●	●		●			●	●		●		●	●	●	●			●	
	van Gils and Argiropoulos (1991)	Axios RB, Greece		●	●		●	●			●		●	●				●			●	
	Krysanova (1989)	Kasari RB, Matsalu Bay, Esotonia		●	●									●				●				
	Booker and Young (1993)	Colorado RB, USA	●	●			●	●		●		●	●	●	●			●				
	Gardner (1985)	Colorado RB, USA	●	●			●							●				●				
	Howe and Orr (1974)	Colorado RB, USA	●	●								●	●	●	●			●				
	Lee (1989, 1993)	Colorado RB, USA	●	●			●	●		●		●		●				●				
	Oamek (1986)	Colorado RB, USA	●	●						●		●	●	●								

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APPENDIX: U.S. ARMY CORPS OF ENGINEERS ON COMPUTER MODELS FOR WATER RESOURCES PLANNING AND MANAGEMENT

A report by the U.S. Army Corps of Engineers--USACE (1994) provides technical information on computer models used for water resources planning and management. The report is not focused on river basin models only. The purpose of this appendix is to provide the interested reader with selected information about the content of that report.

Chapter 2 of the USACE report provides information on organizations in the United States that develop, distribute, and support computerized water management models. These organizations include Federal agencies, national research institutes, and international agencies and research institutes.

Chapter 4 of the USACE report includes models for demand and supply forecasting in the municipal, industrial and agricultural sectors.

Chapter 5 of the USACE report includes computer models of water distribution systems. These models provide mainly hydraulic analysis of pipe networks.

Chapter 6 of the USACE report reviews ground water models mainly for simulation of movement of water and other fluids, and pollutant transport in porous media.

Chapters 7-10 of the USACE report review models that address river issues. The review includes models for watershed runoff, models of river hydraulics, models of river and reservoir water quality, and models to operate reservoir and river systems.

The USACE report includes an appendix which provides technical information of selected models. This information includes a contact address and phone number, information on model availability, documentation, computer configuration, capabilities of the software package, and application experience.

The report is available from the National Technical Information Service
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