Chapter 6
Modeling and Water Resource Issues

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Chapter 6

Modeling and Water Resource Issues

Government agencies normally use water resource models to address specific resource problems under their jurisdiction. While most problems and model applications have unique aspects, it is possible to generalize about the kinds of problems most frequently encountered in water resource management — and the analytic techniques used to understand them. This chapter describes 33 of the Nation's most prevalent water resource issues, briefly assesses the modeling capabilities associated with each of them, and evaluates the model types used to analyze them. Previous chapters have focused on generic issues and problems involving water resource models; this chapter deals with specific water resource concerns and the capacity of models to address them. It is provided as a layman's introduction to the relationship between models and real-world water resource issues.

Water resource concerns can readily be grouped according to four major subject areas: 1) surface water flow and supply; 2) surface water quality; 3) ground water quantity and quality; and 4) economic and social models. The areas differ significantly with regard to levels of current knowledge, kinds of issues addressed, and types of models and levels of modeling expertise currently available. Each is discussed in a separate section of the chapter.

The first three subject areas deal primarily with physical processes, and are described according to a common format: 1) introduction; 2) types of models; 3) issues addressed; and 4) evaluation of currently available models. Each subject-area model evaluation follows a format that reflects the problems addressed, processes modeled, and mathematical techniques most commonly used within each scientific discipline. The last area, economic and social models, deals with the social science information needed to support water resource decisionmaking. Models of social sciences processes differ fundamentally from those of physical processes, and are extremely diverse; consequently, a larger subjective component is involved in evaluating them. No formal evaluation of economic and social models was undertaken for this study.

SURFACE WATER FLOW AND SUPPLY

Introduction

Managing surface water today virtually requires the use of a wide range of computer-based analytical techniques, ranging from sophisticated models that forecast the probable frequencies and extents of serious floods, to relatively simple computer models for simulating the operational characteristics of farm irrigation systems. All of these models provide information to help assure that water will be available when and where needed, or will not intrude when or where it is not wanted. Models permit the analyst to: 1) make reasonable predictiom of natural events, and 2) estimate the favorable and adverse cosequences of man's attempts to improve the reliability of' freshwater production, distribution, and use Syst ems.

Water resource models are widely applicable to problems in policy, planning, operational management, and regulation of the Nation surface water resources. Existing models are widely used to *plan* and *operational~ manage* most water availability y and water use problems. Model use is not as common for policy and regulatory activities, partially because existing models are not well adapted to decisionmaking in these governmental areas, and partially because such decisions have traditionally been based more on qualitative than quantitative criteria.

Models used to analyze surface water flow and Supply problems can be subdivided into two broad categories, for which both current model capabilities and future promising roles are somewhat different. For each of the two broad categories-water availability and water use—four specific problem areas are discussed later in this section. Although these problem areas are not all-inclusive, they encompass the major surface water quantity problems facing the Nation. Each problem area is specific enough to permit discussion of successes and failures in the use of models, and development of recommendations for appropriate model uses. An evaluation table for the models used in each problem area is presented later in this chapter (see table 7).

To introduce the modeling techniques that apply to surface water flow and supply issues, applicable model types are discussed below. Generally, the model types are not limited to one specific problem area—each model type may be applicable to several issues. References, keyed to over 30 model classes, are provided in appendix D to this report.

Availability of Water

Water availability analysis-which encompasses but is not limited to the sciences of hydrology and meteorology —uses models extensively. While models are less frequently used in policymaking than for planning and management, numerous examples of model use for determining water availability can be cited throughout private industry and at all levels of government. In fact, a major problem in using models to analyze a given water availability problem is the difficulty of selecting—from among the plethora of available models—the most appropriate model for the problem at hand.

Determining the availability of surface water requires analyses of the *hydrologic cycle,* typically including calculations of streamflow magnitude, duration, and frequency; and the temporal and spatial variations of these streamflow characteristics. A specific problem may require analyzing one or more of these characteristics at a single point along a stream—for instance, to determine the extent of a flood plain—or it may require coordinated analysis at a large number of locations in a watershed (e. g., to operate a series of multiple-purpose reservoirs).

Solving problems of water availability, however, requires more than understanding and modeling the hydrologic cycle. Many problems arise because of the need to *alter natural hydrologic processes* for a variety of reasons: to reduce flood hazards; to reduce the risks of drought and low streamflow; to

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change the timing and distribution of streamflow; and to improve management of this increasingly scarce renewable resource for a variety of beneficial purposes. Certain types of human intervention in natural hydrologic processes can be modeled reasonably well, but many types of modifications and controls introduce conditions that may be too complex to simulate or forecast accurately. In dealing with water availability problems, one must distinguish between the capability to model *natural proc-*

esses, and current capabilities to model the effects of *human management* efforts on these processes.

Water Use

Models have been used less frequently to analyze water use than to analyze water availability. Except for agricultural irrigation needs in arid areas of the Western United States, water availability has historically been so much greater than water use that there was little or no requirement for sophisticated analysis. Consequently, almost no effort was expended on developing models to analyze water use. In recent years, however, increasing demand for relatively large quantities of water—e. g., for energy development—and the droughts of the 1960's in the Northeast and the 1970's in the Midwest and West, have stimulated the development of models for planning and operations/management. Nonetheless, these recent developments are not yet reflected in widespread adoption of water use models.

Water availability and water use also differ in the kinds of information they require for model construction. Most problems of water availability are concerned with physical principles and relationships that are reasonably well understood, and are consequently easier to model successfully, while most water use problems involve not only physical factors but also *social and economic* factors—many of which are less well understood. The lack of knowledge about interrelationships among economic, social, and physical factors is compounded by a lack of data on social and economic factors related to water use. Social and economic models are discussed in more detail later in this chapter.

Types of Models Used in Surface Water Flow and Supply Analysis

Of the wide array of models used to analyze various aspects of surface water flow and supply, the most important ones fall into two broad model classes—process models and *statistical* models. Process models simulate or describe the flow of water through a watershed or water body using known, physical relationships. Statistical models use empirically derived relationships—often with no inherent physical meaning—to estimate the probability of a flood or drought, the magnitude of a flood peak, or even regional water use demands.

Watershed Process Models

Watershed process models follow the movement of water from the time it reaches the Earth as precipitation until it flows into a lake or stream, reaches a ground water aquifer, or evaporates back to the atmosphere. Models used to describe the dynamics of water over three distinctly different types of land areas are described in this section: 1) watershed simulation models, which describe the movement of water over large, nonurban areas; 2) agricultural soil/water interaction models, which are designed to specifically address agricultural water problems; and 3) urban runoff models, which describe the movement of water through urban areas.

Watershed Simulation Models.—Simulation models describing the movement of water over large, nonurban areas are used to estimate flood peaks, low flows, and volumes of water available to users. They are most useful where historical streamflow data are sparse or nonexistent. These simulation models are powerful planning tools that come far closer to replicating measured flows than was previously possible. Four types of processes must be included in watershed simulation models: 1) the movement of rainfall into and through the soil; 2) ground water flow to streams (called baseflow); s) the loss of water to the atmosphere from evaporation and evapotranspiration from plants; and 4) in colder climates, snow accumulation and snowmelt.

Watershed soil/water process models are used to replicate water movement into and through the soil for: 1) estimating flood peaks during storm events; 2) estimating water supply on an annual basis; and 3) estimating low flows during dry periods. Current models are most reliable for estimating low flows and total annual runoff volumes, and less so (but still acceptable) for calculating short-term flows and flood peaks.

During low-flow periods, except in very humid climates, water enters streams primarily by seepage through the soil profile or from aquifers. Most *baseflow models* do not use advanced ground water modeling techniques to estimate flow rates, but

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rather use observed flow patterns during long dry periods as an estimate of ground water flow to streams. They are quite adequate for estimating baseflow during floods, and reasonably good for estimating low flows.

Evaporation from water surfaces and *evapotransPiration* from plants are modeled to simulate the soil-drying process. The drier the soil, the more precipitation will infiltrate and be stored during the next storm. The results are more reliable for watershed-wide average soil moisture than for specific locations within the watershed, but are difficult to validate because of the scarcity of field data.

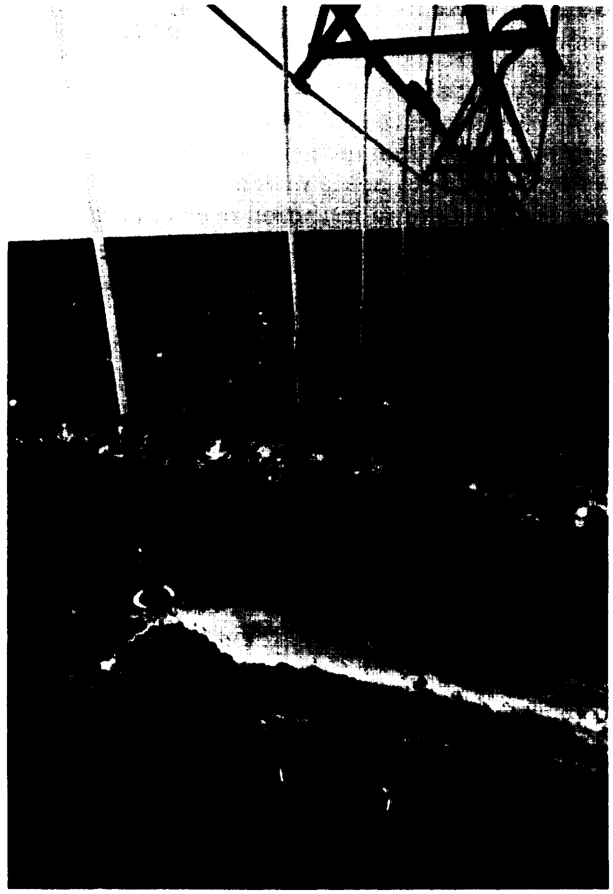
For areas where snow remains on the ground for more than about a month, the processes of snow *accumulation* on the ground and *snowmelt* in the spring must also be considered. Total runoff volumes from snowmelt can be simulated quite well for forecasting water availability during the following summer, but models are not very reliable for simulating snowmelt flood peaks (magnitudes are bad and timing is worse), because of the difficulty of predicting spring weather conditions. However, in areas where the snowmelt occurs relatively slowly, the models are adequate for most purposes.

Agricultural Soil/Water Interaction Models.—Simulation models similar to the watershed process models described above have been developed to assist in agricultural water conservation. Four types of models are currently available:

Soil/water process models are sometimes specialized to estimate moisture conditions in a small plot, rather than average conditions over an entire watershed. These *P!ot--size soil/water process models* are used for agricultural water management and land-use decisionmaking. This approach has potential for improving crop management decisions, but these models are not yet very accurate.

Models that analyze the effects of local climatic variation on *@ant water use* are valuable for allocating available water supplies. Acceptable results are obtained on an annual or seasonal basis, but estimates of shorter term demands (less than 1 month) are unreliable.

The extent and duration of the soil's capacity to hold irrigation water for plant use has been modeled to assist in farm water management and irrigation



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system design. Results from *irrigation water demand models* are generally reliable for estimating average annual water use, but poor for estimating how use is distributed over the irrigation season.

In areas where excess water is a problem, soil moisture can be reduced by subsurface tile or ditch drains to make the land more productive. *Land drainage models* estimate flow rates for system design and residual field moisture conditions for cropping decisions. These models achieve adequate to good results.

Urban Runoff Models .—Urban runoff models generate simultaneous flows from many small urban watersheds, and aggregate them into flood flows for specified downstream points. These models are sophisticated tools for urban flood plain management and for designing and operating urban storm-water control systems. They have received widespread use over the last few years and promise a great deal for the future.

Stream Process Models

Stream process models begin describing the movement of water at the point where watershed process models end—once the water enters a stream, lake, or reservoir. In this section, two topics are discussed: 1) models that describe the flow of water through streams, lakes, and reservoirs, used primarily for flood control; and 2) models that describe the movement and erosion of sediments (called alluvial processes) within water bodies.

Channel Process Models.—Channel process models describe the flow of water through streams, lakes, and reservoirs. They are often used for reservoir operations during flood conditions and for flood plain management. In general, they provide very reliable results when accurate information on channel and flood plain geometry is available. The following models are included in this category:

F[ood channel routing models are used for operating flood control facilities or issuing warnings during flood emergencies. These models provide quite reliable estimates of changes in flow depth and velocity as water moves downstream in well-defined channels. However, the estimates are less accurate for larger floods where streams overflow their banks, and are particularly unreliable where flows spread out over large flat areas.

When flows enter a lake or reservoir they increase both water depth and outflow through spillways or other outlet controls. *Lake and reservoir routing models* are accurate enough to size spillways to ensure dam safety and for controlling spillway gates to minimize downstream flood damage.

Flood plain management relies heavily on accurate mapping of flood hazard areas. Models can estimate flood heights and—when combinecl with accurate topographic maps—the geographic extent of flooding. The most accurate results from *flood inundation models* are achieved when the stream flows between stable channel banks, and the least reliable estimates are obtained on broad flat flood plains where flows are deflected by small obstructions and are spread in random patterns from one event to the next.

Special channel routing models are used to determine the downstream areas that would be inundated if a dam failed. The reliability of *dam failure models* is uncertain, because few historical records are available on the hydrologic conditions existing at the time of failure.

Alluvial Process Models.—The dynamics of channel erosion and sediment deposition have been described through modeling techniques. The results, however, are approximate, and a great deal more research is needed to make these models reliable. Two important problem areas include reservoir sedimentation and channel erosion:

Re.sewoir *sedimentation models* have been developed for determining the amount of sediment washed into a reservoir that is deposited on the bottom, thus reducing its water storage capacity. These models do not have the accuracy desired for estimating useful reservoir life, unless supported by empirical relationships from reservoir surveys.

Flowing water can erode the channels through which it flows and deposit sediment loads downstream. Problem locations can be identified by using *channel erosion and deposition models*, but the results are not reliable enough for channel design or maintenance management.

Statistical Models

When causative mechanisms are not well enough understood to construct process models, or the expense of developing or using process models is not justifiable, statistical models are often used in their place. Statistical models can be used whenever enough data are available to estimate the relationships between factors of interest—without having to understand the underlying physical processes.

Three types of models are presented in this section: 1) statistical flood models, which yield results similar to combined watershed and stream process models; 2) flood and drought frequency analysis, used for sizing flood control or water supply projects; and 3) water use statistical relationships, which are used to estimate demands for water.

Statistical Flood Models .—Statistical models—simpler in approach than the process models discussed earlier—have been developed to estimate flood flows and areas of inundation. These tools are useful for structural design or reservoir operation in situations where more sophisticated continuous simulation models are not justified. Three common approaches—flood formulae, regional flood formulae, and unit hydrography models—have been extensively used.

Flood formulae are simple equations for estimating flood peaks from watershed characteristics. They have been used for years to help design small structures, but can only be recommended for relatively small projects. Much more reliable for structural planning are *regional flood formulcw.* These equations are derived statistically using historical data and can be used for estimating flood peaks on streams throughout hydrologically uniform regions.

Another approach, called *unit hydrography mode/-ing,* is based on the assumption that a given amount of runoff from a given watershed will always result in similar flood patterns. These models have long been used to establish flow patterns for designing flood control reservoirs. The results are reasonable for reservoir design to prevent flooding by a storm event of specified size, but less than desirable for reservoir operation.

Flood and Drought Frequency Analysis.—Several approaches are available for estimating the frequency of occurrence of floods and droughts. The purpose of these models is to determine the economically optimal size of flood control or water supply projects. The available statistical models provide reasonable to good results for most applications.

Flow frequency models analyze historical series of flood peaks, flood volumes, or low flows to provide an estimate of the maximum or minimum flow magnitudes to be expected, on the average, no more than once every 10 years, 100 years, or some other period. The reliability of these models improves with longer record lengths. Once the statistical characteristics of streamflow have been determined, *annual data generation models* can generate annual runoff sequences that match the size, probability distribution, and other patterns of historical flows for use in determining reservoir capacity. The results are generally good for monthly, seasonal, or annual time periods.

Another important use of statistical models is for assisting reservoir design. By accounting for all inflows (stream and precipitation) and outflows (evaporation, uncontrolled releases, and project water delivered) over long time periods, capacity requirements for designing reservoirs and rules for operating them during dry periods can be determined. *Reseruoir water accounting models* provide excellent results if reliable data are available to describe inflow and storage volumes.

Water Use Statistical Relationships.—Water use demands (use as it would be if unconstrained by supply shortages) are estimated either from historical data or simulation models. Two types of models have been applied on broad regional scales:

Regional water use relationships statistically estimate peak, annual, and seasonal variations in water use rates. Their results are generally adequate for estimating the volume of water needed over long periods, but not for estimating peak demands.

Annual use generation models, similar to models that simulate streamflow, have potential for generating estimates of monthly to annual water use. These results may then be combined with supply estimates for the same period to improve water supply reservoir design or operating procedures. However, reliable models of this type are not widely used.

Water Availability Issues

Flood Forecasting and Control

Floods rank among the most prevalent of natural hazards. About half of the Nation's communities, and nearly 90 percent of its largest metropolitan areas, are located in flood-prone areas. Despite expenditures of more than $13 billion for flood control over the last 50 years, flood damage continues to rise each year. Residential, commercial, and industrial development in flood-prone areas outstrips our ability to provide protection, while the economic value of existing damage-susceptible property increases as well.

Available models and the hydrologic data required to operate them are generally adequate for flood control planning and management. Even in situations where hydrologic records are not as extensive as designers require, statistical methods and digital simulation models provide sufficient information for designing flood control and protection structures.

Although there are isolated cases of design deficiencies in flood control projects, most of the hundreds of existing projects function as planned. When flood damage occurs in "protected' areas, it is generally not due to faulty flood forecasting or to failure to operate flood control projects properly. Rather, damages occur because the flood magnitude exceeds the degree of protection provided by the project. However, when flood magnitudes exceed the project's protective capabilities, accurate forecasting becomes essential for minimizing loss even if it cannot *prevent* loss. A poor forecast of a flood exceeding the control structure's capacity can cause serious mismanagement, and greatly increase the resulting damage. Improvement is needed in the accuracy with which flood characteristics are predicted once the event is under way.

While models and predictive methods for flood control planning and management are generally satisfactory for design, engineering, and routine operation of traditional areawide flood control structures, flood control planners are increasingly concerned with nonstructural measures for reducing flood damage. Consequently, new needs for models and data aimed at nonstructural approaches have arisen. Many of these measures are regulatory in nature, and frequently address areas considerably smaller than those associated with larger scale structural projects. As a result, many traditional flood control models are not suited for planning and managing nonstructural approaches. These traditional models are based on a " macrohydrologic' scale, in which model assumptions and data requirements are scaled to hydrologic analyses for relatively large watersheds. However, when these models are applied to the " microhydrologic' scale, they are often *fuuncl to* be inappropriate, either because detailed data are not available at the microscale level, or because the macroscale assumptions are not consistent with conditions on the smaller scale.

Good hydrologic analysis on a microscale basis requires considerably more data than macroscale analysis; consequently, geographic consistency in data on soil types, vegetation, land use, precipitation, and surface runoff is considerably more important in microscale analysis. As a result, the models being developed for microscale analysis frequently depend on the availability of spatial data bases—i.e., sets of computerized "maps' with a geographically consistent set of data on an area's physical characteristics. Although the needed data are frequently available on printed maps, the effort required for digitizing and maintaining the data significantly limits widespread use of these models at present.

Model use for the regulatory aspects of flood control has been extensive in both flood plain management and flood insurance programs. Two basic types of models—flood inundation models and flood frequency models—have been widely employed. Flood inundation models are used to delineate flood hazard areas. When properly used, the available models are relatively noncontroversial. However, problems have occurred when the analysis is performed for part of a stream at one time and for adjacent parts at another time, with the result that the flood hazard areas fail to coincide at the boundaries of adjacent areas. Since the primary purpose of this analysis is regulatory in nature—identifying areas subject to flooding so that appropriate restrictions in use can be implemented—it is not surprising that even minor inconsistencies in flood hazard area delineations are major sources of controversy.

A larger source of controversy has been the use of statistical flood models to determine the magnitude of flood associated with a specified recurrence interval (usually 100 years). Each of the half dozen or so major flood frequency theories (and the models based on them) produces somewhat different results in a given setting, even when the same data set is used for all cases. In some instances the different theories give considerably different results, so that estimates of the size of a 100-year flood, for instance, may vary by a factor of two or more. With that large a variation in flood magnitude, there is an attendant, but usually somewhat smaller, variation in flood hazard area—since the amount of land subject to development restrictions varies with the estimate of the 100-year flood magnitude. Flood frequency estimates at different points on the same stream using different models (or even at the same point using different models) often produce different results, causing a tremendous amount of confusion and controversy. Since the differences are not due to error in calculation, but to fundamental differences in the assumptions of the models, the differences are essentially irreconcilable. The need for consistency was a major factor in the Water Resources Council's decision to recommend a uniform technique (or model) for use by Federal agencies in performing flood frequency analyses. That decision has eliminated some, but not all, of the controversy.

Low-Flow and Drought Forecasting

Low streamflow is caused primarily by physical phenomena, while droughts result from the joint occurrence of low streamflow and high demand—a condition due to social and economic causes as well as physical ones. Modeling capability for forecasting and managing low streamflow per se is as highly developed as for flood forecasting. However, from the point of view of drought management, which requires an ability to modify both water availability and water use, the available models are less satisfactory.

The major difficulty in forecasting low flows stems from problems in choosing appropriate statistical procedures for determining how often to expect low flows of a specified volume and duration. Most of the theories used in hydrologic probability analysis are based on the concept of independence—the idea that two or more "events' are totally unrelated to one another. In the case of low streamflow, analysts are normally concerned with the quantity of streamflow during a specific period of time. Frequently, however, the specified period is part of a more extended period of low flow produced by general climatological and meteorological trends. For this reason, it is difficult to ascribe probability estimates to low-flow "events.

Perhaps because of the difficulty of determining low-flow probabilities, a common practice in planning and designing facilities for low-flow management has been to design for the ' 'drought of record, i.e., the most severe low-flow period experienced in recorded history in a given watershed. Because of natural variation and differences in the length of available hydrologic records in different watersheds, the "drought of record' in some watersheds is very severe—perhaps with an estimated recurrence interval of 300 years or more—while in other watersheds the drought of record may have a recurrence interval of 20 years or less.

When the drought of record is used as a design standard, some facilities are inevitably underdesigned and others are overdesigned. Thus, while failures of flood control structures are rare, serious inaccuracies in low-flow management facilities are relatively common. Although alternative methods have been developed for calculating streamflow sequences of long duration based on statistical analysis of relatively short historical hydrologic records, planners have been reluctant to accept designs based on statistical methods that differ substantially from designs based on the "drought of record. " Considerably more work is needed on the use of statistical methods for planning, designing, operating, and managing low-flow control facilities.

Public policy for dealing with low-flow problems has focused more on water availability y policy than on water use in low-flow periods—except with regard to competition among uses (irrigation, hydroelectric power, municipal water supply), which will be discussed in the following subsection on streamflow regulation. Little use has been made of models for regulatory aspects of low-flow management, except where interstate compacts or judicial decisions have forced governmental entities to apportion low flow among competing users. In general, available models seem to be adequate for these needs.

Streamflow Regulation

The Nation has invested billions of dollars in facilities to regulate streamflow for a variety of purposes: to reduce flood damage; to generate hydroelectric power; to provide stable navigation channels; to provide dependable surface water supplies for municipal, industrial, and agricultural uses; to improve fish and wildlife habitat; and to provide recreational opportunities. Federal agencies alone have constructed hundreds of structures that regulate streamflow for one or more of these purposes. Thousands more have been constructed by other governmental entities, private enterprises, and individuals. Most of these facilities are passive; i.e., they require little, if any, operational management (other than routine maintenance) to accomplish their intended purpose. Levees, ungated diversion structures, and small dams with ungated spillways are typical facilities that require minimal operational management.

Hundreds of these existing facilities, however, are not passive. They are large, complex structures serving many purposes and requiring intricate daily, hourly, or sometimes even minute-to-minute operational management to achieve their intended purposes. Myriad conditions, criteria, and data must be identified and evaluated each time an operational decision is made. Some operational criteria are based on fixed conditions (e. g., those that ensure the safety of the structure) while others are based on changing phenomena (e. g., current and future weather conditions). Operational management is further complicated in multipurpose projects because some purposes are competitive (a decision favoring one purpose has an adverse effect on some other purpose), while others are complementary (a decision favoring one purpose has beneficial effects on other purposes). Operational management problems are even more complex in watersheds where two or more multipurpose projects exist. In this case, decisions for each project must be coordinated so that the projects themselves function in a complementary fashion.

Over the past decade, computer models that give the project manager much greater flexibility than previously used fixed operating rules have been developed. Thus, it is now feasible to model the operation of single projects or large systems of interconnected projects.

Many fixed operational rules have been replaced by models that permit day-to-day decisionmaking that can more effectively consider several objectives of a project (or projects) simultaneously. Most of the current models include only hydrologic inputs and outputs, and the physical operation of a project or system. Economic, social, institutional, and environmental factors affecting operational management are only considered indirectly, or evaluated outside the model. Despite their limitations, these models have the capacity to improve both short- and long-term operational management decisions and plans.

More recently, modeling capabilities for operational management of streamflow regulation structures have expanded to include mathematical optimization models and—in a few instances—online, real-time models used for controlling major portions of a system's operation. Some simulation models have also been expanded to analyze economic, institutional, and environmental factors. However, data acquisition (particularly for real-time operation) and model calibration are substantial obstacles to widespread use of the models currently available for large systems; many operating entities do not have sufficient computer capabilities and personnel to use the most sophisticated models available for onsite operational decisions.

Instream Needs

Determining instream flow needs differs from other water availability problems in that instream flow needs are frequently linked to water quality rather than water quantity requirements. The two most common purposes for establishing instream flow requirements are to preserve and protect aquatic and riparian ecosystems, and to comply with statutory, contractual, or institutional obligations to maintain the necessary streamflows.

The common practice of specifying instream needs in terms of water volume dates back to the earliest days of water resource development in this country, when allocating water to meet these needs was labeled "low-flow augmentation. While it was recognized that many of the objectives of low-flow augmentation were related to water quality characteristics rather than to water quantity per se, virtually all of the analytic techniques available for planning and managing strearnflow regulation were quantity oriented,

In the mid-1960's, knowledge of water quantity/water quality relationships and computer modeling capabilities simultaneously reached the point where it became possible to model many important water quality characteristics in reservoirs and streams. The first such models dealt with the two best understood quality characteristics—temperature and dissolved oxygen. These two characteristics were considered to be particularly important because they are involved in virtually all physical, chemical and biological processes occurring in streams.

By the early 1970's existing models were capable of assisting planning efforts to meet instream needs based on water quantity requirements, and providing information for some policy and regulatory aspects of instream-needs analysis. However, the available models could not, in most cases, produce results commensurate with requirements for operational management. New models that show promise for meeting the requirements for management decisions have recently begun to appear.

The role of models in policy and regulation of instream flow is limited by a lack of knowledge about the qualities of instream flow required to ensure the survival of fish, wildlife, and other aquatic and riparian biota. Many existing instream requirements are based on extremely limited information concerning biological survival and tolerances. Most existing standards establish a single value for instream needs, so that in essence a pass-fail condition exists. In policy and regulatory work, tradeoffs are critical components of analysis, and tradeoff analysis is severely hampered when degrees of success and failure cannot be analyzed. Improved understanding of relationships between instream flow and biotic life would greatly enhance the utility of existing models in policy and regulatory areas.

Water Use Issues

Domestic Water Supply

Domestic water suppliers in this country usually assume a utility responsibility —i.e., that of a regulated monopoly—in their service area. In effect, they agree to provide services to all users within the service area according to an established rate structure, and to assure, insofar as possible, that the service is equally available and dependable for all users. This does not preclude the possibility of establishing service classes or priorities for various categories of users (e. g., differentiating between purely domestic use and industrial use), but such practices are much less common in the water supply industry than in the electric power industry. Because of this ' 'utility' philosophy, water agencies have traditionally worked much harder to secure additional supplies than to control or manage demands.

In many instances, domestic water use projections have consisted solely of projecting changes in population and applying established per capita demand factors to the projected future population. In some cases projections have been somewhat more sophisticated. Some analysts recognize that per capita consumption is affected by changes in demography, technology, and lifestyles, and attempt to adjust current per capita consumption estimates to reflect anticipated changes in these factors. However, only a modest amount of data is available on which to base such adjustments.

As growth in domestic demands and competing uses diminish the relative availability of water, water utilities will have to develop and evaluate alternatives for obtaining additional supplies, or strategies for allocating available supplies among competing users. Models can be used to establish pricing policies, user priorities, and other economic and technological aspects of system expansion. Models can also play a useful role in examining the likely responses of various sectors (domestic, commercial, municipal, and industrial) to strategies that might be used to achieve targetted reductions in use.

If priority use and pricing systems come into widespread use, models will be needed to assist in determining the conditions under which use priorities should be implemented, and the amounts of water that should be made available to each user class.

When additional supply capacity is deemed necessary, models can be used for planning efforts to develop and expand water distribution systems. These models focus primarily on the hydraulics and economics of the distribution system itself rather than on water use characteristics.

Irrigated Agriculture

Model use in the area of irrigated agriculture has a relatively long history, and has grown more rapidly and is more widespread than for other water uses. Since irrigation occurs primarily where rainfall is deficient, farmers have had to be more conscious of the importance of water and of the need to manage a limited supply. Uses of models have ranged from determining the need for irrigation water and timing applications for specific crops, to developing policies for allocating water among users in times of water shortage. Models are also used to plan, design, and operate water distribution systems for large irrigation projects.

Some of the models available for planning and operational management of irrigation water are extremely sophisticated. They enable users to consider water requirements of individual crops over an entire growing season or for specific intervals within the growing season. The models can also gage the effect of precipitation on the amount and timing of needed irrigation water. Some of the most sophisticated models permit users to consider options to defer applying water or to reduce the amounts of water applied during periods of water shortage. These models provide information on the risks of crop failure or the likelihood of reduced crop yields, thereby helping farmers to apportion limited supplies among various crops. Such models also provide information on the economic consequences of buying and selling water entitlements.

The availability of these models to farmers involved in irrigated agriculture will be even more important in the future, as competition between irrigation and other nonagricultural water uses increases in the Western States.

Other Offstream Uses

Water is also used for such purposes as cooling in thermal electric power-generating plants; process water and cooling in coal gasification, shale oil production and other energy extraction and conversion processes; hydraulic mining; and for use as a transport medium in slurry pipelines. Many of these uses require withdrawals of large quantities of water from rivers and streams. In some cases (e. g., evaporative cooling, slurry pipelines, and interbasin transfer) not only are the withdrawals large, but the use is "consumptive' '—i.e., the water withdrawn is lost from the stream system from which it was withdrawn. In other cases (e. g., once-through cooling, mineral extraction, and energy conversion), while withdrawals are relatively large, the use is not consumptive because the water eventually returns to the stream after use. In some of these cases, however, the quality of the returned water is substantially altered and the water may not be fit for many other uses.

Models are currently available to assess the effects of offstream uses on water quantity and to assess such common water quality characteristics as temperature and dissolved oxygen changes. However, improvements in models are needed for assessing the economic and environmental implications of water withdrawals and potential water quality changes due to offstream uses.

Policy and regulatory functions are greatly affected by the lack of adequate modeling capability in this problem area. The volume of some proposed offstream uses—e. g., coal gasification or liquefaction and oil shale processing—is so large that decisions regarding them are likely to affect the economies and ecologies of large regions and involve a considerable number of governmental jurisdictions. Information from models would be of great value in resolving the controversies and inter-jurisdictional disputes that will inevitably arise.

Efficiency and Conservation

Models for dealing with water use efficiency and conservation are considerably different from models used in other aspects of water management. With the exception of irrigated agriculture, water users in this country have not emphasized efficiency and conservation except during periods of critical water shortages. Consequently, there is no substantial body of knowledge regarding efficiency and conservation strategies and their economic, social, and environmental consequences. Some data exist on specific conservation practices and their effects in isolated pilot programs under ' 'normal' conditions, and *some* data exist on a wide range of conservation practices and effects under emergency conditions. However, it is doubtful that the existing data base and knowledge (other than for irrigated agriculture) provides a sufficient basis for developing the models needed for policy and planning functions.

Pertinent economic models—e, g., models to determine the effects of water pricing on use—are discussed in "Social and Economic Models" of this chapter.

Evaluation of Currently Available Surface Water Flow and Supply Models

Table 7 presents evaluations of currently available surface water flow and supply models. Each water resource issue is subdivided into specific model applications; for example, under the issue of ‘flood forecasting and control, the capabilities of models vary for the seven applications addressed. Models are rated from A to F, with A indicating that modeling for this purpose does a good job in supplying the needed information, and F indicating that the state of the modeling art for this purpose is generally unsatisfactory.

Table 7.—Surface Water Flow and Supply Model Evaluation

Issue	Information required for applications	Overall rating
Water avaiiabiiity:		
1. Flood forecasting and control	a. Flood peaks for channel and bridge design	B
	b. Flood hydrography for reservoir design and operation	c
	c. Simultaneous flood hydrography for flood control system design and operation	c
	d. Flood depth mapping for flood plain land-use planning	c
	e. Effects of land use on downstream flows for upstream land-use planning	c
	f. Flood peaks after dam failures for emergency preparedness planning	D
	g. Soil moisture conditions for land drainage design	c
2. Drought and low-flow river forecasting	a. Low river flows for off stream uses	c
	b. Timing of drought sequences for estimating cumulative economic impact	B
	c. Soil moisture conditions for precipitation-supplied uses	c
3. Streamflow regulation (including reservoirs)	a. Runoff volume for maximum obtainable yield	A
	b. Runoff time patterns (within and among years) for reservoir sizing	B
	c. Simultaneous runoff volumes in regional streams for regional water supply planning	c
4. Instream flow needs:		
Fish and Wildlife	a. Low river flows for estimating fish support potential	c
	b. Within-year timing of low flows for fish lifecycle matching	B
	c. Timing of drought sequences for estimating minimum reservoir or lake levels	B
	d. Flow velocities within streams for estimating effects on fish species	c
Recreation	a. Low river flows for sustaining recreation capacity and esthetic appeal	c
	b. Timing of flow sequences for matching with recreation periods	B
	c. Runoff time patterns (within and among years) for estimating the impact of fluctuations in lake levels	B
Navigation	a. Low river flows for determining waterway capacity	c
	b. High river flows for determining navigation interference	c
	c. Formation of surface ice for determining navigation interference	D
Hydroelectricity	a. Timing of flow sequences for estimating run-of-the-river generating capacity	B
	b. Runoff time patterns (within and among years) for designing streamflow regulations	B
	c. Simultaneous runoff volumes in regional streams for regional generating system planning	c
Water use:		
5. Domestic water supply	a. Timing of water use for delive~ system design	D
	b. Water pressures throughout delivery system for delivery system design	c
	c. Volume of use for sizing supply facilities	B
	d. Return flow volumes for designing wastewater collection systems	c
6. Irrigated agriculture	a. Timing of water use for delivery system design	c
	b. Volume of use for sizing supply facilities	B
	c. Return flow volumes for drainage system design	B
7. Other off stream uses	a. Volume of industrial use for sizing supply facilities	B
8. Water use efficiency	a. Effect of increased use-efficiency on return flows for evaluating conservation measures	c

Rating Key:
A Modeling of the physical process at the current state-of-the-art does a good job in supplying the needed information.
B Information between adequate and good.
C Modeling does an adequate job for most purposes.
D Information between unsatisfactory and adequate.
F The supplied information is generally unsatisfactory.

SOURCE: Office of Technology Assessment.

SURFACE WATER QUALITY

Introduction

Billions of dollars are spent annually in the United States to protect the quality of surface waters. Unless carefully managed, residual wastes from municipalities, industry, and agriculture can seriously interfere with many beneficial water resource uses. Water quality models are used extensively in Federal, State, and local efforts to maintain and improve the quality of the Nation's surface waters.

Water quality models serve two general functions. The first is to provide basic scientific insight and understanding about the relationships between material inputs and water quality changes. These relationships are expressed in the form of mathematical equations that interrelate and synthesize observations. The second function is of an engineering nature. Once confidence in these relationships is obtained, the equations can be used to help manage, plan, and make policy. Given the present state of scientific knowledge and engineering development, existing models can generally provide a limited basis for water quality decisionmaking.

Mathematical models of water quality are most frequently used for planning, to some extent for policymaking, and to a lesser degree for day-to-day operations and management. Their most common use is to determine the degree of treatment required for a specific wastewater discharge in order to achieve or maintain a desired receiving water quali - ty. Other uses include determining the magnitude and effects of urban runoff, and assessing the effectiveness of alternative measures for preventing soil erosion and the resulting sedimentation within water bodies.

Because models simply quantify existing scientific knowledge about water quality, a basic understanding of the processes that underlie model equations and assumptions is helpful in assessing model capabilities. The next section, ' 'Types of Models Used *in* Surface Water Quality Analysis, describes the current state of scientific knowledge about determinants of water quality, and examines how well this knowledge is incorporated into present water quality models. Later, the state of the art of water quality modeling is discussed on an issue-by-issue basis, analyzing 10 major problems under the general categories of point and nonpoint pollution sources. The section entitled "Evaluation of Currently Available Surface Water Quality Models' assesses currently available model types. Evaluations are made both according to the characteristics of the models themselves, and for the 10 major problems to which they may be applied.

When considering water quality concerns, four basic questions face the analyst:

1. What is the *quantiy and quality* of the water and residuals coming from each point and nonpoint source?
2. How are these materials transported *to* the receiving waters?
3. How are these wastes transported *within* the receiving water?
4. What processes *transform* waste residuals within a water body?

Given the response of the system, the analyst must further consider the following quest ions:

- What deleterious effects do these wastes have on beneficial uses?
- Do existing standards reflect the magnitude of the effects?
- What control alternatives are available, how well do they perform, and how much do they cost?
- Are these control alternatives politically, economically, and esthetically feasible?

All of the above information is needed for management, planning, and policy decisions. Models are available, in varying degrees of detail and accuracy, to help the analyst address each of these questions.

The common basis for the majority of water quality models is the principle of "mass balance. Water and any material inputs from natural or human sources are followed: 1) from their point of origin; 2) as they travel to the water body; and 3) as they travel within the water body. The models account for biological, physical, and biochemical reactions that occur, and additions of water or materials.

To run these models, users must provide quantitative estimates of the characteristics of the watershed and the receiving water body. Source quantities, constituents, and other pertinent characteristics must be enumerated, and the numerical coefficients that describe the above reactions must be known.

Water quality models have one aspect that is both a vice and a virtue—most provide an absolute numerical value for any given variable such as the concentration of a pollutant. While it is desirable to have such a number, often no indication of the possible error is given. In practice, most water quality projections are subject to large errors and must be validated with field observations.

However, water quality models are still very useful in planning contexts, for example, because relative effects of control alternatives can be analyzed with sufficient confidence for many purposes. Model projections, when combined with the professional judgment of water resource analysts, are often the best information available to aid the decisionmaker in evaluating alternatives.

Types of Models Used in Surface Water Quality Analysis

All water bodies are affected by inputs from natural sources and human activities. The accuracy with which models can estimate relationships between these inputs and the water quality response determines their utility for management, planning, and policy purposes. Thus, current levels of scientific and engineering knowledge about these relationships form the basis for assessing surface water quality models.

Water quality models can be divided into three components that describe:

- source of materials;
- transport to and within the receiving water; and
- processes occurring within the receiving water;

The first component estimates the inputs of substances through human activities and natural phenomena; the second, the hydrologic and hydrodynamic regime of the water body and its watershed; and the last, the biological, chemical, and physical processes that affect water quality.

Source of Materials

Water bodies may receive point source discharges from municipal, industrial, and agricultural activities; dispersed or nonpoint source runoff from these same areas; natural inputs from undisturbed watersheds; and additional chemicals from rainfall.

The chemical characteristics of effluents from municipal sources are well known with respect to both average values and their variations. This is also true for many industries that generally produce one or a few products, such as the pulp and paper, canning, and steel industries. However, industries that produce a variety of products, such as organics, synthetic chemicals, and pharmaceuticals, produce discharges that are more difficult to characterize.

Information on agricultural and feedlot sources of waste is meager, but has been improving in recent years. Irrigation return waters pose difficult problems, particularly in the mid- and far-western regions of the country where high background concentrations of salts of natural origin prevail. The time-variable nature of return flows, which are both point and distributed, introduces additional complexities. Our social and scientific awareness of these problems is relatively recent; consequently, the historical data on these sources are minimal, and many gaps remain in current knowledge of the governing phenomena.

The ability to quantify pollutant loadings from a variety of sources is critical, particularly with respect to differentiating between point sources, which are readily controllable, and nonpoint sources, which are relatively difficult to identify and control. Assigning realistic values to distributed nonpoint sources is very difficult, given the present state of knowledge and data, Current models provide at least some assessment of the problem.

The most significant information gap lies in quantifying toxic substances from nonpoint sources or from residues of toxic materials created by past activities, e.g., from riverbeds and from landfills that leach into water systems.

Transport to and Within Receiving Waters

Point discharges are transported by pipes, open channels, or other conveyance devices from the point of origin to the receiving water on a regular basis. Nonpoint discharges move through storm drainage systems, via overland flow, and through subsurface flow to the receiving water as a result of rain events. Consequently, the quantities of materials entering water bodies from nonpoint sources are much more difficult to predict.

Most surface water quality models include a surface water flow submodel as part of the program, since in most cases it is necessary to predict runoff and flow quantities before making quality estimates. Many of the models discussed in the previous section on surface water flow are used as components of surface water quality models.

Pollutant transport by rivers and streams is, in general, better understood than transport within lakes. Transport in streams depends primarily on flowing water; within lakes, and some complex river systems, movement of pollutants occurs by diffusion and dispersion as well—difficult processes to model. In addition, a longer and more extensive data base is available for streams than for lakes.

Transport in streams can be approximated by simple one-dimensional models—the one dimension being the direction of flow. Under certain conditions, simple models can adequately simulate transport in lakes, but often more complex two- and three-dimensional models are necessary. The state of knowledge and computational techniques are such that only the most proficient analysts can use these models.

The above remarks apply to situations that are not highly time dependent. When water quality analysis must incorporate such factors as storm surges from combined sewers or rapidly changing river flows, the models must be considerably more complex. These models are still in the developmental stage and their results are only marginally useful at present.

Processes Occurring Within the Receiving Water

In general, the chemical, physical, and biological processes of rivers and streams are better modeled than those of lakes. In addition, more extensive water quality data exist for rivers and streams, particularly for such constituents as dissolved oxygen and coliforms (bacteria used to indicate the presence of sewage).

Eutrophication (excess algae or aquatic weed growth) is another widespread problem. The nutrients that cause eutrophication originate from a variety of municipal, industrial, agricultural, and natural sources. While the state of the art permits some model-based assessment, data requirements are so extensive that these techniques are often impractical. Simplified approaches, involving the nutrients phosphorus and nitrogen, presently yield results that may be indicative and, in certain cases, adequate for the intended purpose.

For inorganic and organic chemical water quality, the present state of knowledge is mixed. The biochemical reactions of certain industrial chemicals are sufficiently understood to permit the development of reliable models. This is true for a wide range of chemical compounds of relatively simple structure, which are commonly present in industrial effluents and which are susceptible to the presently available treatment processes. While the reactions involving metals are not as well understood as those of the simple industrial chemicals, they have been developed to a degree that will permit at least a marginal analysis and projection.

On the other hand, for more complex compounds, many of synthetic composition, far less is known about reactions, byproducts, and removal by present treatment techniques. These substances, which inciude many toxic materials, may be modeled with simplifying assumptions, yielding reasonable projections in limited cases. However, on the whole, current methods of analysis are regarded as only marginally reliable, A similar assessment applies to complex metals when concentrations approach or exceed toxic limits. Water quality models that analyze these substances are presently being developed.

A second area of notable uncertainty is the accumulation of toxicants in the food chain leading to fish. Much research has been undertaken over the past decade to advance basic understanding of the problem, collect data, and develop models, some of which appear to be very promising. Preliminary

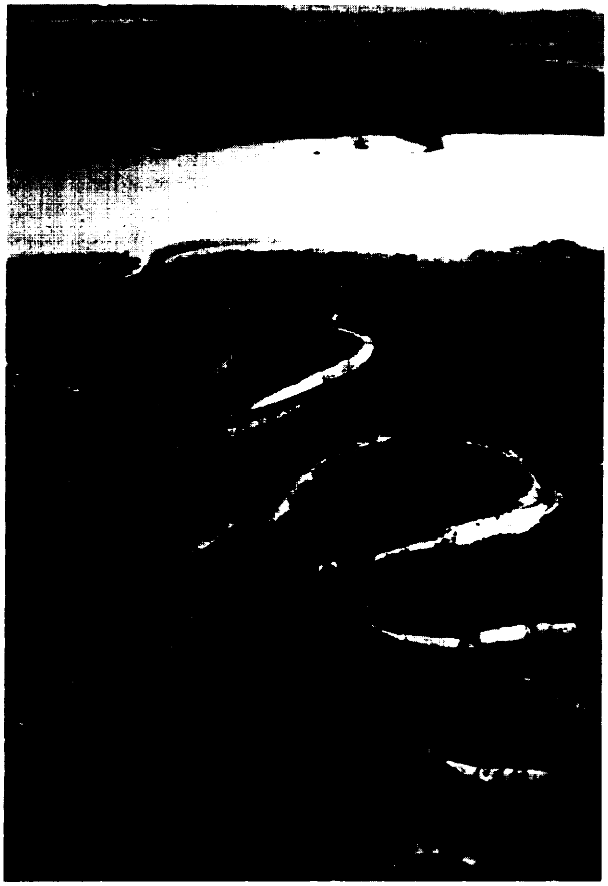

Photo credits: @ Ted Spiegei, 1982

Researchers are exploring natural capabilities to reduce nutrient levels in effluent flows as a potential means of tertiary sewage treatment. At left, water in a meandering stream is cleansed through contact with vegetation and reaerated on its way to the Hudson River; at right, a Florida cypress dome is fertilized with the nutrients in partially treated effluents from a 150-unit mobile home park. Models are available to estimate the effectiveness of various treatment methods in removing such nutrients as phosphorus and nitrogen, and to assess the effects of nutrients on biological processes in lakes and streams

food chain and fisheries models are available; however, these are in a relatively primitive state. Although they may provide some insight and understanding, they are neither sufficiently calibrated nor adequately validated for management purposes.

The same may be said for aquatic ecosystem models that describe changes to aquatic plant and animal populations subjected to water quality stresses. Ecosystem theory-the basis for such models—is still in a developmental stage. However, the results of laboratory studies on the effects of specific pollutants on sensitive organisms have been incorporated into water quality models with some success.

Nonpoint Source Issues

Urban Runoff

Urban runoff (along with agricultural runoff) is one of the most difficult waste discharges to control because of its intermittent nature and varying quality. Federally mandated control and management of urban runoff has created the potential for increased use of urban runoff models.

At present, urban runoff models are most helpful in planning, primarily for water quality management and comprehensive areawide planning. The best examples lie in the section 208 programs of the Clean Water Act—particularly the Nationwide

Urban Runoff Program. Such planning is designed to provide each State and the Environmental Protection Agency (EPA) with information on point source and nonpoint (including urban runoff) treatment needs and the effectiveness of treatment methods. Urban runoff models such as EPA's Stormwater Management Model and the Corps of Engineers' STORM can simulate the quantity and quality of runoff from a specified runoff area and can be used to compare the effectiveness of alternative control strategies. These models may also be linked to receiving water models to gage the effects of urban runoff on receiving water quality.

Urban runoff models can also play an important role in Federal and State agency policy decisions. Federal agency construction grants allocations, and requests for such funds by State agencies, could be based in part on estimates of the volume and quality of point source and nonpoint source wastes in a specific area, the effects of these wastes on the receiving water, and the effectiveness of nonpoint source control in alleviating the problem.

Urban runoff models do not appear to have attained the credibility necessary to be used as regulatory tools at this time. These models require an extensive local data base, and such information is usually unavailable, except for cities in which specific studies have been performed to develop, calibrate, and test such models.

Erosion and Sedimentation

Models of erosion and sedimentation are developed primarily by such Federal agencies as the Corps of Engineers, the Soil Conservation Service, the U.S. Geological Survey, and, to a lesser extent,

Photo credit: U.S. Department of Agriculture

Two years of low rainfall on the Big Canyon Ranch near Sanderson, Tex., greatly reduced plant cover levels, setting the stage for extremely high runoff rates on the draw pictured above after rainstorms hit an area 30 miles away. Plant cover is a major determinant of soils' abilities to absorb moisture and resist erosion; runoff and erosion models consider cover levels as one of many factors in estimating flows and sediment transport

EPA. Extensive use is made of erosion and sedimentation models by Federal, State, and local agencies concerned with river management. Construction agencies use these models to assist in operational management, e.g., in dredging navigation channels and operating reservoirs. Sedimentation is a critical factor in reservoir management, as it can reduce a reservoir's useful volume. River authorities must have information on rates of sedimentation and ways of alleviating or minimizing sedimentation to operate their reservoirs most efficiently.

Local, State, and Federal agencies concerned with forestlands, rangelands, and farmland management continually seek better ways to minimize soil erosion. They employ models to guide the selection of effective management techniques.

A primary concern is the large amounts of nutrients (especially nitrogen and phosphorus) contained in eroded soils. Soils reaching waterways may impart those nutrients to the water, potentially causing nuisance algal growths or other symptoms of eutrophication.

Probably the greatest utility of erosion and sedimentation models lies in the area of planning. For example, the Corps of Engineers employs such models to plan and design erosion control structures along rivers and coastal areas and to estimate the extent of sediment accumulation over the life of a reservoir. The Soil Conservation Service uses erosion models to plan erosion control programs on farmlands and forestlands.

Because toxic chemicals often adhere to river sediments, sediment transport models are used to predict the movement and fate of toxicants accidentally released into waterways. EPA relies on water quality models incorporating sediment transport submodels to follow the transport of Kepone down the James River to the Chesapeake Bay. The agency is using this information to plan monitoring programs and subsequent mitigation programs, if needed.

Salinity

Several factors may cause the buildup of excess salinity in surface waters. One major source is irrigation return flows. To maintain a favorable salt balance in agricultural soils, farmers may apply more water to their crops than is required for plant production. The additional water leaches out excess soil salts that may either flow overland to surface waters or percolate to the ground water. The erosion of soils with high salt contents, such as the marine shales found extensively in the West, and the input of salts from natural sources, such as brines, also contribute to excess salinity. Finally, the concentration of salt in surface waters can increase due to evaporation, reductions or diversions in flow, and plant transpiration.

Salinity, as a physical process, is one of the best understood pollution problems, and relatively easy to model, Many models exist to predict salt concentrations in agricultural drainage as a function of crop, soil type, and irrigation practice; downstream salinity concentrations; and the effects of excess salinity on crops, metal deterioration, soap consumption, and health. A well-developed data base complements these models.

Models are widely used to develop management strategies for salinity control. They can provide managers with information on the effectiveness of control options for reducing downstream salt concentrations. In addition, these models are useful for evaluating the likely effects of proposed regulations. From a planning standpoint, these same models are used to develop areawide salinity control plans and can aid in setting funding priorities to implement these plans.

In the ares of policy, salinity is an important aspect of international water rights issues and treaty obligations between the United States and Mexico. In particular, the salinity of the Colorado River has been a major international issue for some years. The increase in salinity of the Colorado from saline return flows before it leaves the United States is a major problem for water users in Mexico. Models have been used to determine whether planned consumptive uses from the Colorado Basin will allow the United States to meet its treaty obligations for delivering water at or below a specified salinity.

Agricultural Pollutants

Agricultural pollutants are found in runoff from irrigated and nonirrigated agricultural lands and pastures. The pollutants include soil particles eroded from the land; organic substances from decaying vegetation, animals, and feedlot waste; nitrogen and phosphorus from commercially produced fertilizers as well as from animal waste; and pesticides that have been applied but are not yet degraded. These pollutants find their way into nearby receiving streams, where their effects must be assessed.

Agricultural pollutants are generally considered to originate from nonpoint sources; animal feed lots, however, are considered point sources. Like other point sources, the latter must be treated to meet effluent and receiving water standards according to sections 301 and 303 of the Clean Water Act. Nonpoint sources are eventually to be controlled as well, but standards and guidelines for implementing controls have not yet been promulgated.

Mathematical models aid in assessing the instream effects of these point and nonpoint sources —such analyses play an important role in regulating pollution sources. The models for tracking organic materials and their effects on oxygen resources in streams are well developed, well documented, and easily usable by personnel with appropriate analytical skills and knowledge of water quality management principles. Such models should also withstand the scrutiny of litigation. Models for nutrients and pesticides, however, are not used as broadly as models that predict levels of dissolved oxygen.

Mathematical modeling of agricultural pollutants finds extensive use in planning. Models have been used primarily for section 208 studies of areawide pollutant problems and water treatment needs. Such studies enable States and EPA to establish priorities for treatment, based on estimates of the effects of point and nonpoint sources on receiving waters.

Not only do Federal and State agencies use mathematical models for the kind of planning mentioned above, but they also use these models to determine the effectiveness of treating agricultural pollutants, recommend funding levels to Congress, and propose legislation for controlling agricultural pollutants. In these cases, mathematical models may be the only means of linking the pollution source to effects on the receiving waters—a connection that is important in estimating the benefits of regulatory programs.

Photo credit: @ Ted Spiegel, 1932

Agriculture can also serve as a means of treating certain water pollutants. Lubbock, Tex., utilizes a 3,000-acre farm as its tertiary disposal facility, employing nutrient-laden waters to irrigate and fertilize crops

Airborne Pollutants

Since the enactment of the 1971 Clean Air Act, mathematical models have been used as regulatory tools by Federal and State agencies that are assigned responsibility for air pollution enforcement. Such models determine the relationship between discharge and downwind exposure concentrations of common air pollutants such as sulfur oxides, nitrogen oxides, and particulate. Some of these pollutants are transferred from the air medium to water and thus contribute to water pollution. Such materiah include windblown dust, hazardous **substances,** and compounds that may eventually produce acid precipitation.

The transfer of pollutants from air to water has received increasing attention in the last few years.

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Hazardous substances in incinerator effluents and windblown erosion from landfill sites are problems for which mathematical models may be used to anticipate and formulate control strategies. Models of short-range pollution transport (less than 200 km) are currently available. The potential consequences of acid precipitation, and of the deposition of heavy metals, radioactivity and other hazardous materials from powerplant air emissions, may require Federal and State agencies to assess future water quality problems resulting from increased energy production. Models of long-distance pollution transport, and of atmospheric processes that may produce acid rain, are in early stages of development.

Point Source and General Issues

Wasteload Allocation (Point Source)

Wasteload allocation refers to the process of determining the amount of some waste material that a particular discharger is allowed to release by analyzing the relationship between discharged amounts and resulting concentrations in the receiving water. This cause-effect relationship may be determined after the fact through sampling programs, or before discharges occur with the help of mathematical models.

Water quality models find their most appropriate regulatory roles in estimating waste treatment needs for compliance with the Clean Water Act. The act sets forth two criteria for water quality standards: 1) effluent requirements for regulating ' 'end-of-pipe" discharges, as specified in section 301 of the act; and 2) receiving water standards, as specified in section 303 of the act. Discharges who meet effluent standards may be required to provide further treatment if resulting waste discharges cause higher-than-acceptable receiving water concentrations. Wasteload allocation models determine the maximum allowable level of discharge for individual producers in order for pollutant concentration levels in receiving waters to be at or below existing standards. Removal techniques to meet these limits can then be selected.

Mathematical models for this procedure are well developed and documented, can be adapted to receiving waters of different types, can be easily used by regulatory staff, and are reliable enough to withstand judicial scrutiny. Waste allocation is particularly complex, however, when a number of discharges reach a common receiving water near the same point. In such cases, the allowable wasteload can again be determined by a mathematical model, but assigning wasteloads equitably among the contributors must be a legal and administrative decision.

Water quality models have been used extensively in planning for treatment needs throughout the Nation. As part of section 208 of the Clean Water Act, point and nonpoint wasteloads were to be determined for segments of the Nation's waterways. Mathematical models were used in these cases, first to estimate current loadings from the point and nonpoint sources, and then to estimate the impact of these loadings on the receiving stream. Based on the magnitude of these effects, the need for wasteload reduction was determined. Then, based on the ratio of point source to nonpoint source discharges, Federal and State agencies could estimate where the greatest water quality improvement could be achieved at the least cost.

Probably the most dramatic and exemplary policy-level application of these water resource models was undertaken by the National Commission on Water Quality. The commission, mandated by Congress as part of the 1972 Federal Water Pollution Control Act Amendments (Public Law 92-500), undertook a number of assessments of the social, economic, technical, and environmental impacts of implementing the other sections of the act. Among the commission's responsibilities were a set of water quality studies to evaluate the act's impact on some 40 specific areas around the United States. Water quality models were used extensively in these studies and were, in fact, necessary to carry them out. Study results indicated that the effluent regulations of the 1972 act should be altered to reflect more realistically attainable levels of treatment in the allotted time periods. The work of the commission contributed to policy changes within EPA, and influenced congressional formulation and passage of the 1977 Clean Water Act (Public Law 95-21 7), which incorporated many of the commission's recommendations.

Wasteload allocation models were critical to the commission's ability to demonstrate the consequences for the Nation's receiving water quality of

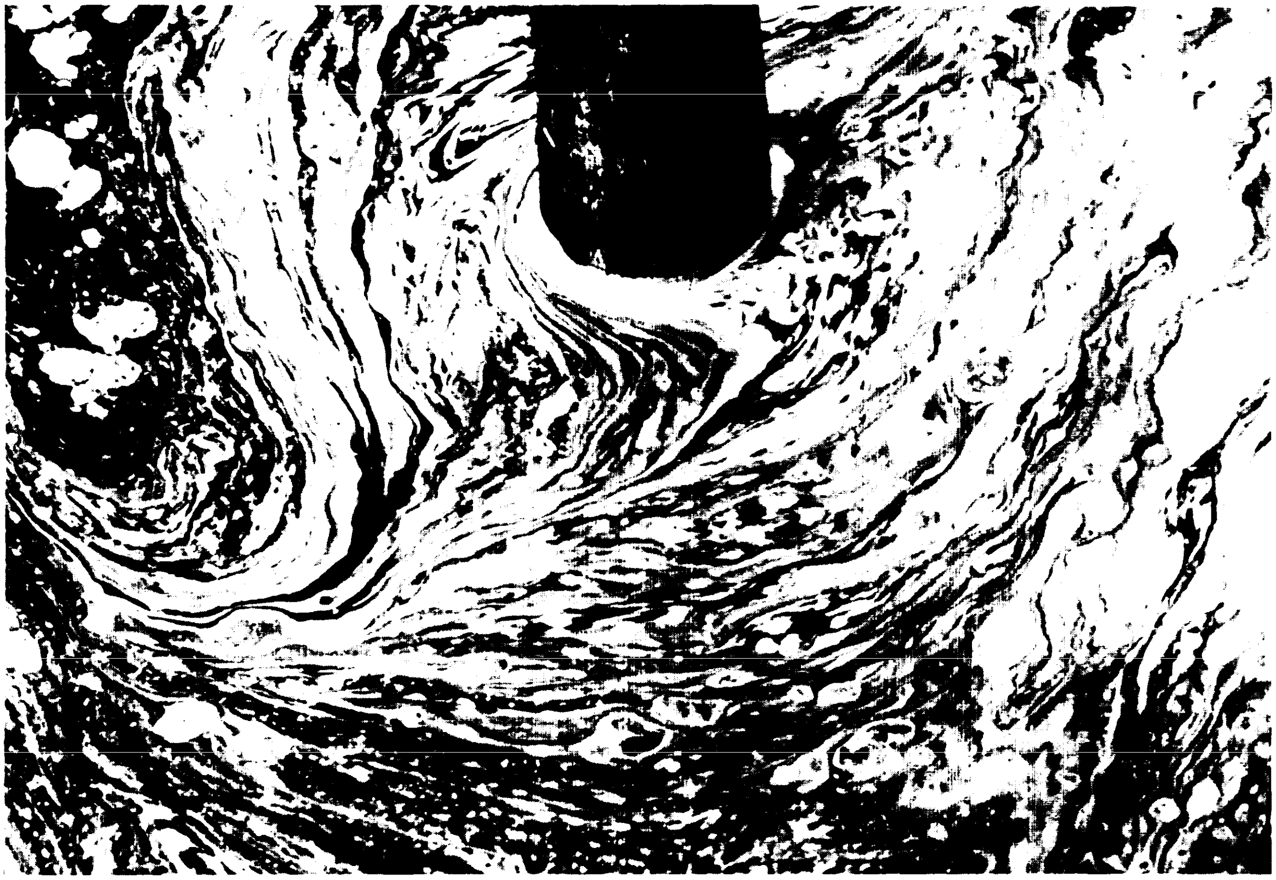

Photo credit: EPA-DOCUMERICA, Doug Wilson

Untreated water from a pulpmill in Puget Sound, Wash.

implementing the 1972 act. The study also revealed some shortcomings in then-current modeling capabilities, however. Contractors performing work for the commission relied primarily on dissolved solids and dissolved oxygen models; models for nutrients and toxic materials were applied in only a few situations, largely because existing data bases were inadequate for calibrating and validating them.

Thermal Pollution

Thermal effluents are among those regulated by the Clean Water Act. Effluent limits have been set for thermal wastes as well as for allowable temperature increases in receiving waters. Zones of influence and resulting temperature increases from thermal effluents can either be monitored directly or predicted with mathematical models.

Mathematical models for thermal wastes range from fairly simple one-dimensional models to more complex two- and three-dimensional models. Most of these models have been developed through the support of EPA and the electric utility industry and have been applied in many locations. Most regulatory staffs can operate the simpler thermal waste models, but the more complex multidimensional models require well-trained staff.

The electric utility industry uses mathematical models extensively in applying for construction and operation permits for nuclear powerplants through the Nuclear Regulatory Commission, and in preparing environmental impact statements as required by the National Environmental Poiicy Act of 1969. Under the latter act, the permittee must show the extent of the environmental impact of its facility, in particular the impact of the thermal waste. Such effects are routinely forecasted by using mathematical models.

Toxic Materials

Compounds that cause some injury to humans or other organisms of concern are classified as toxic materials. Such materials are not necessarily lethal, but may be compounds that produce such sublethal effects as cancer, birth defects, or reproductive failure.

Toxic materials are regulated under several statutes, including the Clean Water Act, the Toxic Substances Control Act of 1976 (Public Law 94-469), the Resource Conservation and Recovery Act of 1976 (Public Law 94-580), and the Safe Drinking Water Act of 1974 (Public Law 93-523). Regulation under this last act is discussed in the section entitled "Ground Water Quantity and Quality." Although control is focused on technology-based standards, mathematical models have potential roles in enforcing portions of these acts. As with other pollutants, effluent requirements have been established for point sources based primarily on removal techniques. However, receiving water criteria must be met as well. Modeling for toxic material concentrations may be required at some future time to determine further treatment needs if receiving water standards are not being met.

While legislation exists for control of nonpoint source toxicants, implementation has been given low priority. As controls are applied, however, ground and surface water quality models could play an important role in determining the cost effectiveness of alternative control measures, Mathematical models can also be used to design monitoring networks so that stations can be best located and sampled to gain maximum information from monitormg.

As with other issues, mathematical models for toxic materials have greatest utility in the planning process. Models can be used to anticipate problems, and to test different management approaches for removal effectiveness and managerial efficiency. Since regulations for controlling liquid and gaseous sources of toxic substances are currently being implemented, and those for hazardous solid wastes have recently been issued, models for planning long-term toxic material control should find widespread application.

Drinking Water Supply

The Safe Drinking Water Act is the principal Federal legislation regulating the quality of drinking water. It, along with State statutes and local ordinances, regulates the quality of public drinking water. Regulations apply to water quality at the end of the treatment process; consequently, streamwater quality models have no roles per se in regulating drinking water under this act. However, toxicology models, which relate concentrations of various hazardous substances to human health risks, are used to aid in setting standards. These models use differing methods for extrapolating data from animals to humans, so that resulting estimates of human risk may diverge widely. The OTA report, *Technologies for Determining Cancer Risks From the Environment*, provides an assessment of toxicology models.

The quality of the raw water is an important factor in supplying high-quality water for human consumption. Where raw waters are degraded by upstream users, water quality models can be used to predict water quality at the point of intake to determine the level of treatment needed. In particular, water quality models are used in determining when intakes should be closed due to contaminants originating upstream. For example, a spill of carbon tetrachloride in the Ohio River several years ago forced water users downstream to close intake structures at appropriate times to avoid contaminating the water supply. Models were used to predict when and how long the carbon tetrachloride would be in the vicinity of the intake structures.

Water Quality Impacts on Aquatic Life

Models for predicting water quality impacts on aquatic life involve two steps: 1) estimating concentrations of those materials that may affect aquatic life (positively or negatively), and 2) comparing calculated concentrations with accepted criteria to judge the consequences of those concentrations to the ecosystem. This latter step is seldom incorporated into the model structure, and requires professional judgment by aquatic ecologists.

The models used to assess impacts can vary from very simple models for calculating the effects of concentrations of selected materials, to very complex models incorporating several different types of pollutants and their effects on numerous organisms. The complex models are the least reliable, due to the lack of data to support many of the necessary assumptions and the great difficulty in calibrating and validating them. Both types of models require considerable professional judgment in applying the results to field situations.

Models to determine water quality impacts on aquatic life are primarily of value in the planning process. This is due to the kinds of applications that can be made of these models, the current state of their development, and the number of areas for which data are adequate to apply them.

Aquatic life impact models can be usefully applied if a theoretical analysis of the aquatic system is coupled with coefficients derived from controlled laboratory experiments. Examples include models of the movement and effects of Kepone in the James River, of polychlorinated biphenyl (PCBS) in the Hudson River, and of PCBS in the Great Lakes. Both the Kepone and PCB models facilitate impact assessment by allowing researchers to compare exposure concentrations to tolerable levels, while the P(2B models can predict alterations in populations if toxic interactions are included. These models have been used to forecast the effectiveness of alternative remedial actions, and thus help provide a basis for future regulatory activities.

Evaluation of Currently Available Surface Water Quality Models

A model's level of complexity and its degree of availability provide the basis for a simple scheme of classification. Accordingly, four generic types of models are outlined below, and their basic capabilities are summarized. In the evaluation table (table 8), these four generic model types are rated according to their utility in analyzing five major aspects of each of the 10 issue areas discussed above. The evaluation table also assigns an overall rating for modeling sophistication in each issue area. Using a potential scale of zero to 10, actual assigned ratings range between 1 and 9, indicating the uneven level of current modeling capability for surface water quality analysis.

Type Z is **a** standardized procedure or technique that may be routinely performed without a computer. It involves simple mathematical equations, statistical techniques, and graphical procedures. Examples include use of the Streeter-Phelps stream model for evaluating dissolved oxygen downstream of point sources (although this is often programed into complex models), and evaluating lake eutrophication potential with diagrams or regression equations. While the procedure does not involve a computer, it is not necessarily unsophisticated. On the contrary, some "desktop' procedures are mathematically quite sophisticated, whereas some complex digital computer models are nothing more than a programed version of intuition. Finally, a Type I model may still require considerable time and effort and the use of computational aids (e. g., hand calculators) to be fully operational.

Type II is a computerized version of a Type I model. This may avoid the tedium of routine calculations and greatly expand the amount of data that can be processed. The level of complexity of the analytical technique, however, is still low.

Type III is a procedure that is sufficiently complex that a computer is required for its use. Such models generate numerical solutions for sets of mathematical equations that could not be solved prior to the advent of modern computers. Many individuals, consultants, universities, industries, and public agencies have constructed such models.

Type IV is the same as a Type III model except that it is termed operational, meaning: 1) documentation (e. g., user's manual, description, and theory) is available; 2) the program has been well tested and its credibility established by groups other than the model developer; 3) the program is available and accessible to interested users (this does not preclude proprietary models); and 4) user support is available either from the model developer or from other groups. Although several hundred large water quality models are described in the **literature, less** than 100 can be termed operational. A Type IV model can thus be used by others with relative ease.

Table 8.—Surface Water Quality Modei Evacuation

Issue	Generic type: I No computer, not complex	II Computer, not complex	Ill Computer, comDlex	Iv Computer, complex, operational	Overall level of modeling sophistication
Nonpolnt source pollution and land use					
Urban runoff:					4
Source/generation	C	C	B	B	
Transport to receiving water	—	A	A	A	
Transport in receiving water		C	B	B	
Impacts on beneficial use	;	C	c	C	
Control options/costs	B	B	B	B	
Erosion and sedimentation:					4
Sourcelgeneratlon		C	c	C	
Transport to receiving water	:	—	c	—	
Transport in receiving water	B	—	c	—	
Impacts on beneficial use	B	—	—	—	
Control options/costs	A	—	—	—	
Salinity:					9
Source/generation	A	A	A	—	
Transport to receiving water	A	A	A	—	
Transport in receiving water	A	A	A	A	
Impacts on beneficial use	B	c	c	—	
Control options/costs	A	—	—	—	
Other agricultural runoff:					3
Source/generation	c	C	B	B	
Transport to receiving water	—	B	A	A	
Transport in receiving water	—	c	B		
Impacts on beneficial use	c	c	c	:	
Control options/costs	B	B	B	B	
Airborne pollutants:					6
Source/generation	A	A	A	A	
Transport to receiving water	A	A	B	B	
Transport in receiving water	c	c	c	—	
Impacts on beneficial use	c	c	c	—	
Controi options/costs	A	A	A	A	
Water quality (other than nonpoint sources and land use)					
Wasteioad allocation:					7
Source/generation	A	A	A	A	
Transport to receiving water	A	A	A	A	
Transport in receiving water	A	A	A	A	
Impacts on beneficial use	c	c	c	C	
Controi options/costs	B	B	B	—	
Thermai poiiution:					9
Source/generation	A	A	A	A	
Transport to receiving water	A	A	A	A	
Transport in receiving water		A	A	A	
impacts on beneficial use	:	C	c	c	
Controi options/costs	A	A	A	A	
Toxic materiais:					1
Source/generation	c	C	c	C	
Transport to receiving water	—	—	c	C	
Transport in receiving water		—	c	C	
Impacts on beneficial use	z	—	c	—	
Controi options/costs	c	—	c	—	
Drinking water quaiity:					2
Source	A	—	c	—	
Treatment		—	c	—	
Impacts on beneficial use	;	—	—	—	
Water quality impacts on aquatic iife	B	—	B	B	3

Key: A Reliable, credibie modeling may bereadily used for most problems ofthis subissue. Some models maybe suitable forreguiation and design,
B Same as C, but some models may beuseful for planning andrelated purposes, and suitabie for determining relative effects.
C Modeling Ispossible. Credibility andreliability of results is lowdueto weaknesses in the database.
— Modeling of this type is not usually performed.

Overall level of modelng sophistication:
O No models available.
10 Routine use of models of all types,

It is not possible to state categorically that one type of model is to be preferred over another—in particular that a Type IV model is to be preferred over a Type 1. The appropriateness of an analytical tool depends on the particular problem and objectives of the analysis. In the most general terms, Type III and IV models have greater potential for accuracy and credibility than do Type I and II models. But there are many instances in which data and theoretical formulations are so lacking that the use of a complex computerized model is simply not warranted, even if one already exists. For example, the fate of toxics in the environment is of immediate concern to the public, but the various parameters and coefficients that describe the sources, sinks, and transformations of these chemicals are so ill-defined that the sophistication of toxic model formulations far outstrips the present data base. Simpler procedures are often much more credible.

The evaluation table presents a summary of informed opinion regarding the utility of models in analyzing specific issue areas. Overall, models are currently judged most successful for the issues of salinity, wasteload allocation and thermal pollution. The weakest issue is toxics, due mainly to the lack of data necessary to determine the changes these substances undergo in receiving waters.

Successful modeling for a given issue requires a good deal more than the application of sufficient modeling expertise. To model the governing principles of physical processes, the principles themselves must be well understood. Scientific understanding of biochemical phenomena related to water quality is not sufficiently advanced to permit highly accurate modeling; the governing principles of temperature, on the other hand, are relatively well documented. Data constraints place a further limitation on the utility of models—processes that are thoroughly understood can be accurately modeled only if data are available to predict conditions for the location under study. This evaluation accounts for these factors in assessing model utility, rather than simply assessing the state of the modeling art in itself.

GROUND WATER QUANTITY AND QUALITY

Introduction

Ground water systems, unlike surface water systems, are completely concealed from view; consequently, conceptual, physical, or mathematical models are the only way to achieve an understanding of their potential yields and responses to natural or man-related stresses. Simple ground water problems may be analyzed using physical hydraulic concepts and assumptions, perhaps expressed in simple paper calculations. However, more complex applications require the use of large amounts of data, gathered from multiple test wells at many different times. The only way to integrate this information involves using computers that are capable of solving hundreds or even thousands of complex mathematical expressions simultaneously.

Public agencies that issue water use permits or otherwise manage regional ground water resources must rely on models to forecast effects of ground water use. Applications range from day-to-day management of a community's ground water use to long-range Planning for maximizing the utility of an entire aquifer. Models can be designed, for example, to calculate how pumping from a new well might affect local ground water levels, or to predict how far contaminants might move in a given period of time. However, models can also be designed to answer more complex questions about potential quantities of recoverable water in regional ground water systems as more and more wells are drilled and pumped. These evaluations can provide information for regulatory decisions regarding allowable limits on total ground water use, optima] pumping rates and placement of new wells, or controlling subsurface waste injection that may contaminate ground water.

The principal types of situations for which models are used include:

- changes in ground water availability;
- changes in ground water levels due to pumping from wells, land drainage, or injecting water into an aquifer;

- changes in ground water flow caused by alterations in surface water flow patterns;
- movement of contaminants through ground water systems from waste disposal or encroachment of saltwater; and
- settlement or subsidence of the land surface due to withdrawals of ground water.

The greatest limitations on the effective use of ground water models are not computer size or accuracy, but: 1) the basic understanding of physical and chemical processes in ground water systems; 2) the cost of collecting sufficient field data to describe the characteristics of the ground water system; and 3) the availability of well-trained personnel. In general, ground water quality models are much less reliable than ground water flow models. While models are widely used to address ground water availability questions, many ground water quality models have not yet been proven reliable enough for routine regulatory application.

Types of Models Used in Ground Water Resource Analysis

Ground water models are usually classified according to the physical and chemical processes they describe. The two major types are: 1) ground water flow models; and 2) contaminant transport models. Generally, ground water quantity and yield problems are analyzed with flow models, while ground water quality issues require the use of contaminant transport models. The two major model types are examined below, and ground water quantity and quality issues are analyzed in "Ground Water Quality Issues. " Lastly, the section evaluates the utility of currently available ground water models.

Ground Water Flow Models

Flow models determine rates and patterns of fluid movement through soil or rock. Both the type of fluid and the nature of the soil or rock are used to further characterize the flow model. Types of fluids modeled include water only, water and air, or water and an immiscible fluid (a fluid that does not mix with water, such as gasoline). The soil or rock types may be either porous or fractured material. Flow in *porous media is* primarily through interconnected voids (open spaces) between individual grains. An example of this type of material is sandstone. In *fractured media,* water cannot move through the rock as in porous flow, but moves through cracks or cavities in the rock. In general, better estimates of flow can be made with models for porous media than for fractured media.

Saturated flow models consider the flow of water only. These models assume that water completely fills the open spaces between soil grains or rock. Data used in these models include: 1) inherent characteristics of the system, such as the transmissivity (ability to transmit fluids) and storage (ability to store fluids) characteristics of the rock or soil; and 2) changes imposed on the ground water system, such as water entering or leaving the system. Results from the model consist of calculated fluid pressures or water levels at time intervals for specific locations in the ground water system. Saturated flow models are used for almost all types of ground water quantity applications.

Above the *water table,* the open spaces between soil grains or in rock voids contain air as well as water. A model that considers a mixture of air and water simultaneously is called an *unsaturated~ow model.* Data requirements for unsaturated flow models include all of those needed for saturated flow models plus data describing the reduction in transmissivity (resistance to water flow) due to the presence of air. Besides fluid pressures, the models also calculates variations in the amount of air contained in the pore spaces. Unsaturated flow models are useful for small-scale problems such as crop irrigation or water flow adjacent to landfills.

Multifluid models deal with the simultaneous flow of immiscible fluids in the soil or rock—e. g., a gasoline-water or oil-water model. These models are similar to unsaturated flow models, except that gasoline rather than air is the second component of the fluid mixture. Multifluid models can help to assess the consequences of fuel tank leaks or oil spills on land.

Contaminant Transport Models

Contaminant transport models analyze the movement, mixing, and chemical reactions of contaminated water in the native water and the soil or rock through which it flows. Like flow models, transport models are also classified by fluid and

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media types, as well as by the chemical reactions considered.

Three major processes control the movement and changes in concentrations of pollution in ground water: 1) movement due to ground water flow (called advection or convection); 2) the mixing of ground waters having different levels of contamination (called hydrodynamic dispersion); and 3) chemical reactions. Contaminant transport models are normally classified according to whether they consider chemical reaction. Two major types of models are generally recognized: 1) conservative transport models, which do not consider chemical reactions; and 2) nonconservative transport models, which do.

Nonconservative transport models can simulate a variety of possible chemical reactions. For example, models may consider the fate of water-borne pollutants that become fixed or adhere to the soil or rock surface, thereby coming out of solution and not moving with the water. However, while these and more complex reactions can be addressed in theory, in practice, chemical reactions are **normally** either ignored or are approximated by simple equations. Simple equations are used because the precise mechanisms for the chemical reaction are generally unknown or are too complicated to be used in field applications.

Data required for both conservative and nonconservative transport models include the hydrologic data discussed previously for flow models, as well as data describing mixing and chemical reactions. Models generally calculate projected concentrations of the various pollutants as they vary over time and space.

Because ground water flow is a major factor affecting the movement of contamination, pollutant transport models are necessarily extensions of ground water flow models. As a result, a contaminant transport model is, at best, as reliable as the ground water flow model to which it is coupled. For small-scale contamination problems in material that is highly variable or is fractured, estimates of ground water flow may be inaccurate, thereby reducing the reliability of transport estimates.

In addition to ground water flow, the movement of pollutants is affected by mixing and by chemical processes, both of which are poorly understood. Since quality problems are more complex than quantity problems, models dealing with ground water quality are generally less reliable than those for ground water quantity. Quality models are also considered less credible than quantity models because of their recent origin and the relative unavailability of validated models.

Ground Water Quantity Issues

Available Supplies and Optimal Yields

Models are well suited for determining the hydrologic limitations on ground water availability, or on the yield of an aquifer. Hydrologists have developed several definitions of what constitutes an aquifer's yield. One definition, "sustained yield, " represents the maximum amount of water that can be removed from the system if inputs and outputs are to be balanced, with no net loss from the aquifer. The concept is based on the commonsense observation that water cannot be continually withdrawn from wells if the rate of withdrawal exceeds the natural rate of replenishment to the ground water system. A second definition, ' 'optimal yield, incorporates political and social considerations, and refers to an optimal plan for using a ground water system, whether on a sustained basis or not. This approach attempts to maximize economic objectives and to minimize environmental impacts through legal and social constraints on the use of the ground water supply.

Computer models can be very useful tools for estimating an aquifer's response to alternative development plans. Assuming that the geometry and water-bearing characteristics of the ground water system have been adequately described, the modeler uses equations to show, for example, how water naturally enters the system from infiltration of rainfall or streamflow, how water naturally escapes from the system through discharge into surface water bodies or through consumption by vegetation, and how the extraction of water from wells affects the overall water balance.

The response of a ground water system depends not only on hydrological conditions, but also on the manner in which the ground water is withdrawn for use. For example, locating wells too close to each other may cause large water-level declines near the well field, resulting in reduced yields, dry wells, or even subsidence of the land surface. Ground water flow models can be used to address problems such as the optimal design of a well field and the extent of available supplies, and to predict water-level declines due to alternative development schemes.

Although the most frequent use of ground water flow models is for water-supply management, these models can be helpful throughout the planning stages preceding management decisions. Models also provide a framework and guide for collecting and organizing data. By matching computed model results with observed system behavior, one can gain a better understanding of hydrologic and geologic conditions. Even with limited data, the hydrologist may use a model to test alternative hypotheses of how the system behaves.

For managing, regulating, and planning the use of ground water, models that determine available supplies and optimal yields are highly reliable. However, since ground water data are derived primarily from wells, aquifers that are relatively undeveloped often have an inadequate data base for estimating potentially available yields. As the system is developed, more data become available, and earlier modeling efforts can be modified to reflect this additional information. Thus, data collection and modeling activities must be coordinated with aquifer development if reliable information about the ground water system is to be available when it is most needed—when water withdrawals are large enough to significantly affect the aquifer.

Conjunctive Use of Ground and Surface Waters

Aquifers are commonly hydrologically connected to surface lakes and streams. Ground water frequently provides the base flow to streams—the streamflow that occurs even during dry weather. During periods of low rainfall, the base flow provided by ground water is a major determinant of both the quantity and quality of surface water. A decline in ground water levels may decrease the base flow and degrade surface water quality. In other situations, surface water may recharge the ground water system. In this case, a change in the quantity or quality of the surface water would affect the ground water.

Conjunctive use models analyze the interaction between ground and surface water systems. These models may provide information about both quantity and quality aspects of surface water and ground water interrelationships, and can be used to aid in the combined management of both water sources. Ground water flow models have been employed for many different conjunctive-use situations. A typical problem of this kind involves determining the effects on surface water flows of irrigating with pumped ground water distributed through irrigation systems. The ground water flow models used for these applications are essentially the same as those used to determine optimal yields. For conjunctive use, however, the components of the model describing the interaction between ground and surface waters become critical and are consequently more complex.

During the past decade, ground water flow models have frequently been used to solve conjunctive use problems. Model reliability is nearly as high as for ground water supply and optimal yield applications; confidence is somewhat reduced, however, because quantitative estimates of the interactions between ground and surface waters are difficult to obtain. Furthermore, the scale of the surface water problem (i.e., area of influence and speed of water movement) may differ from that of the associated ground water system. This may result in an accurate description of the ground water response but a less satisfactory description of local surface water responses.

Subsidence of the Land Surface

Under certain geologic conditions, particularly where thick beds of clay underlie the land surface, heavy withdrawals of ground water may lower ground water levels to such an extent that the clays partially dry out. In some situations these clays shrink or compact, resulting in settling or subsidence of the land surface, which may cause ruptures in pipelines, cracking of building foundations, or even surface water floods. The Houston Ship Channel in Houston, Tex., is a notable example—several adjacent residential communities have essentially been abandoned because flooding by tidal waters has resulted from land surface settlement.

To model these conditions, data are needed not only for the ground water system itself but also for soil mechanics and physical properties of clay soils under dry conditions. In addition, information is needed about the surface water systems in areas where subsidence may alter drainage areas and flow patterns.

Ground Water Quality Issues

A basic understanding of ground water flow is necessary for understanding ground water quality problems. Since pollutants entering a ground water system are carried along with the water flow, many of the factors that determine quantity relationships also apply to quality models. Problems of ground water quality are likely to dominate water resource issues in the 1980's. They fall into four broad categories: 1) accidental and negligent contamination from urban and industrial areas; 2) agricultural pollutants to ground water; 3) movement of pollutants into and through ground water from waste disposal; and 4) seawater intrusion.

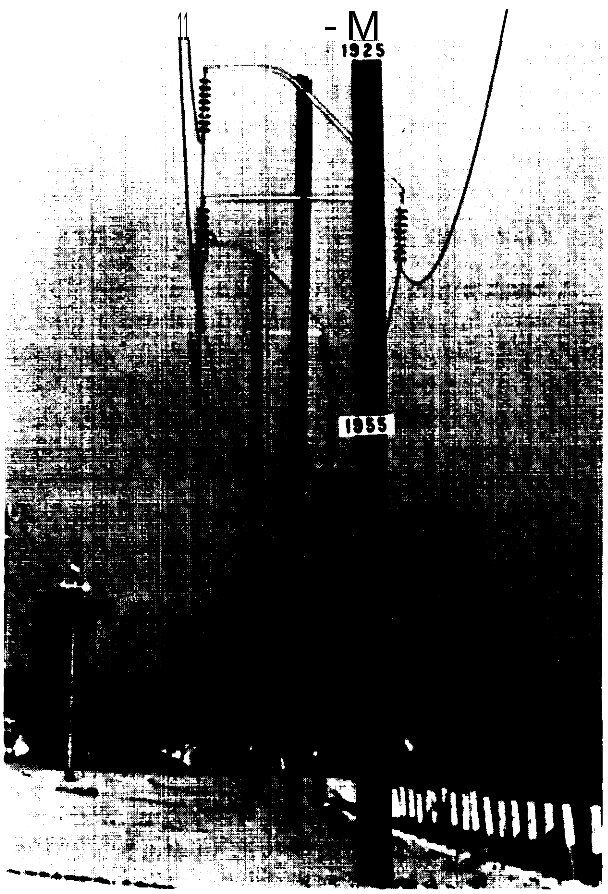
The disposal of wastes, in particular, involves major political issues for which the analytical capabilities of models will be useful. Wastes can be disposed of in the atmosphere, in streams and other surface water bodies, or into or on the solid earth. Each of these options has associated tradeoffs. Inland and onland disposal of either solids or liquids may contaminate ground water and cause wastes to be transported long distances from the original disposal site. Consequently, ground water hydrologists are being asked to predict the movement of contaminants to aid in designing waste-disposal systems to minimize contamination. The problem is perhaps best exemplified by the present search for a geologic disposal site for high-level radioactive wastes.

Accidental and Negligent Contamination From Urban and Industrial Areas

Unintentional ground water pollution is reported with increasing frequency. Regulatory agencies have particular difficulty in planning for emergency incidents of ground water pollution, due to the wide variety of possible contaminants and hydrogeological conditions. Contaminant transport models, in conjunction with careful hydrologic studies, can provide important information on alternative corrective measures.

This section deals with unintentional, nonagricultural contaminants to ground water. Three frequently occurring pollutant types will be discussed: 1) petroleum products; 2) industrial chemicals; and 3) road salts. For each of these, contaminant transport models can be used with varying degrees of success and confidence. Model capabilities are limited primarily by insufficient data on and understanding of the movement of contaminants through soil and rock. It is often necessary to drill numerous sampling wells to determine the extent of the contamination. Other information that is needed includes the amounts of contaminants released and the chemical reactions occurring in the soil.

Petroleum spills and leaks are serious sources of ground water contamination. Hundreds of thousands of gasoline storage tanks, thousands of miles of underground pipelines, and numerous tank trucks and railroad cars carry oil or gasoline throughout the country. Contamination from these sources is quite difficult to analyze with models. Models of the movement of oil or gasoline have been routinely employed for petroleum reservoir engineering, but have had limited application to ground water problems. Insufficient experience with these models limits their use for analyzing contaminant transport.



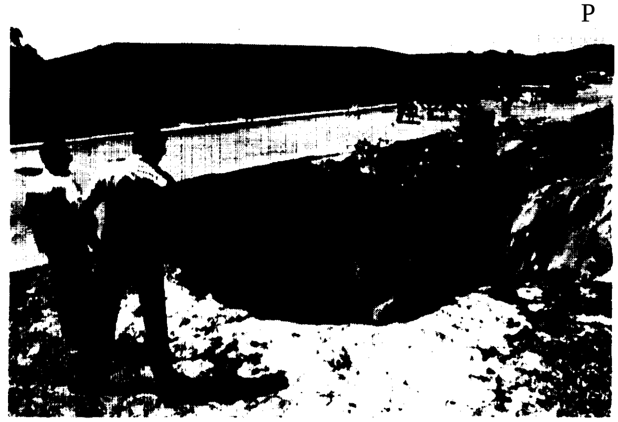


Photo credits: @ Ted Spiegei, 1982

Extensive ground water withdrawal can cause land to subside on small or large scales. At left, signs on telephone poles in the San Joaquin Valley, Cal if., show the sinking of the Earth's crust as a result of ground water use for irrigation since 1925. Florida sinkhole at right demonstrates a more dramatic local effect. At any scale, land subsidence in inhabited areas has enormous destructive potential; developing models to estimate the conditions under which subsidence will occur requires extensive knowledge of geology, ground water hydrology, and soil sciences

Although oil and gasoline do not generally mix with water, small concentrations of petroleum products may dissolve. These low concentrations may exceed acceptable water pollution standards. The movement of dissolved oil or gasoline can be analyzed by contaminant transport models once the nature of the dissolution process is known. These models can be used to gage the effectiveness of various cleanup procedures.

Toxic *industrial chemicals* can accidently contaminate ground water supplies in a number of ways—leaky storage tanks, tanker spills, or leaky holding ponds. The range of possible contaminants makes it difficult to use models to predict resulting pollutant concentrations. In general, for chemicals that dissolve in water but do not react with soil or rock, credible models can be developed if sufficient hydrologic data exist. However, for chemicals that are either immiscible with water or reactive with soil or rock, model reliability will be low, regardless of the amount of hydrologic data available. Still, for such reactive constituents, conservative or ' 'worst-case' predictions can be useful for assessing the maximum pollution potential, and can be generated by assuming that no reactions occur. In these cases, model results can aid in evaluating alternative remedial measures.

Large quantities of *salts* are applied to roads during icy conditions, primarily in Northern States. Road salt is highly soluble in water; thus, shallow ground water supplies near major roads may become contaminated. In recent years, recognition of this problem has led to decreased usage of road salt. While contaminant transport models can assess the potential for ground water pollution from road salt use, the problem is not generally considered serious enough to warrant the collection of the expensive field data needed to produce credible results.

Agricultural Pollutants to Ground Water

Agriculture, because it is so widespread an activity, is an important influence on the quality of ground water. Agricultural activities can affect ground water quality through: 1) salt buildup, and 2) contamination by herbicides and pesticides.

Salt buildup is caused in two ways. In semiarid regions, fields close to streams are commonly irrigated with both surface water and pumped ground water. As the water flows through the ground and returns to the stream, it accumulates salts from the soil that are further concentrated by evaporation from soil and plants. The water returning to the stream often has high salt concentrations and is sometimes unusable for irrigation by farmers downstream.

Salt buildup can also occur as a result of fertilizers, and, to a lesser extent, from storage or disposal of livestock wastes. Fertilizer is a serious source of pollution. Nitrates—a major component of fertilizer and a type of salt—are the most common cause of ground water contamination beneath agricultural lands.

The use of *pesticides and herbicides* has expanded significantly in recent years, When pesticides and herbicides are applied to the land, they migrate downward toward ground water supplies through the unsaturated zone. They generally move slowly, and undergo chemical changes in the unsaturated zone that alter their properties. Pesticides and herbicides that are "broken down' in this manner are often not harmful when they reach the ground water. However, the greater the use of pesticides and herbicides, the higher the likelihood of producing concentrations exceeding the biodegradation capabilities of the unsaturated zone. Serious ground water pollution can result in such cases,

Models of ground water flow and transport through saturated soil and rock are generally reliable when applied to these problems. Water quality variations in an irrigated stream-aquifer system can be reliably predicted with mathematical models, if sufficient data are available.

Flow and transport in unsaturated zones are less well understood; consequently, unsaturated flow models are less reliable than saturated ground water models. As yet, no model has been developed that incorporates all the physical, chemical, and biological processes occurring in the unsaturated zone. However, many problems involving pesticide-herbicide ground water contamination can be analyzed without a comprehensive model, Simplified models are useful for assessing the effectiveness of the unsaturated zone as a barrier to potential pollutants. Results based on conservative or worst-case assumptions may be helpful for determining the effects of agricultural practices on ground water.

Movement of Pollutants Into and Through Ground Water From Waste Disposal

Several methods are commonly used for onland waste disposal:

- landfills;
- surface spreading;
- surface impoundments; and
- injection wells.

Approximately 5 pounds of solid wastes per person are produced daily in the United States. Solid waste is normally reduced in volume by compaction and placed in *landfills,* which currently number over 150,000 in the United States. When rain enters a landfill and infdtrates through the refuse, byproducts of waste decomposition dissolve in the water, producing a liquid known as leachate. Leachate can be a serious problem in nonarid regions, where rising water tables infiltrate refuse, causing contaminants to migrate into the ground water system. Such leaching of pollutants may continue for decades or even hundreds of years. Models can be used to predict the effects of alternative engineering designs on the landfill hydrology, and to predict the transport of leachate into ground waters. These models are still in initial stages of development.

Much domestic waste in the United States is processed in secondary sewage treatment plants. A common practice for disposing of these waste byproducts is to spray liquid sewage on and spread sludge over the land surface. Surface *spreading* of sewage and sewage sludge may degrade ground water quality, both through salt buildup and from heavy metals that are not removed during secondary treatment. Since this practice is similar to fertilization, modeling capabilities and difficulties are similar to those described for agricultural practices.

Surface impoundments are pits, ponds, and lagoons in which liquid wastes are stored, treated, and disposed of. These wastes contain a wide variety of organic and inorganic substances. Over 170,000 impoundments are located in the United States—many of them contain potentially hazardous wastes. Few of these impoundments have a bottom liner, and few have means for monitoring ground water quality.

Contaminants that seep from impoundments may be modified in the soil by various chemical reactions, thus reducing their harmfulness; others may move into shallow ground water and cause pollution. Studies generally show that ground water contamination creates a contaminant plume that may be well contained locally, but might extend up to a mile or more from the impoundment, depending on ground water conditions.

Actions that can be taken to alleviate contamination of ground water include:

- lining the impoundment with plastic, impervious clay, asphalt, or concrete;
- constructing collection systems such as wells for recycling; and
- reducing the movement of contaminated ground water by means of hydraulic or physical barriers.

The effectiveness of these actions can be evaluated with mathematical models. The approach to analyzing contamination from impoundments is similar to that used for landfills.

Wastewater injection wells offer an alternative to disposal of waste at or near the land surface. As of mid- 1973, at least 278 industrial wastewater injection wells had been installed in 24 States, and 170 of these wells were operating. Most were between 1,000 and 6,000 ft deep and had average injection rates of less than 400 gallons per minute. As with other pollution problems, chemical and biological reactions occurring within injection wells are the most difficult to model accurately. Nonetheless, models may still be used to estimate the impact of the injection system on the natural hydrology; this, in turn, may be used to design well fields and injection schemes.

Seawater Intrusion

Cities in coastal areas often withdraw large quantities of ground water for their freshwater supplies. This decreases the seaward flow of freshwater, which may cause saltwater to move into ground water reservoirs.

The movement of seawater into drinking water supplies in coastal areas is a serious and widespread problem. Models can aid in designing well fields and pumping schemes to minimize seawater intrusion. However, for cases in which the hydrology is complex, such as a layered ground water system in which flow characteristics among the layers vary greatly, modeling results are less reliable.

Evaluation of Currently Available Ground Water Models

In table 9, models that can be applied to each of the problems previously described are evaluated according to model types employed and the models' areal scale of analysis. The evaluations are for the general level of model development in each category, rather than for any specific model. A comprehensive list of models available for ground water analysis is provided by Bachmat, et al. [1]

Two major criteria are used to evaluate each model category: 1) model reliability; and 2) credibility of model results. Models are considered reliable if they can accurately describe the important chemical and physical processes. Credible results require both a reliable model and sufficient data to run that model. For some applications, models may be reliable, but the cost and difficulty of col-

[1] Y. B. Bachmat, et al., "Utilization of Numerical Ground Water Models for Water Resource Management," U.S. Environmental Protection Agency, report No. EPA-600 /8-78-Ol 2, 1978.

Table 9.—Ground Water Model Evaluation

spatial Considerations	Model types																			
	Site										Local						Regional			
Pollutant movement, if any	Flow only				Transport w/o reactions			Transport w/ reactions			Flow only		Transport w/o reactions		Transport w/ reactions		Flow only		Transport w/o reactions	
Flow conditions	sat P	sat F	unsat p	multi fluid	sat P	sat F	:;t F'	sat P	sat F	M P	sat P	sat F	sat P	sat F	sat p	sat F	sat p	sat F	sat p	sat F
Issues																				
Quantity—available supplies.	B	C									A	B					B	B		
Quantity—conjunctive use.	B	R									A	B					B	B		
Quality —accdental petroleum products.				R	B	c	R						C	R						
Quality—accidental road salt, ...					B	C	C													
Quality—accidental industrial chemical					B	C	C	C	R	–			B	C	C	—				
Ouality—agricultural pesticides and herbicides.					B	C	C	C	R	–			B	C	C	—				
Quality–agriculture salt buildup. .					B	C	C						B	C						
Quality—waste disposal landfills.					B	C	C	C	R	–			B	C	C	—				
Quality—waste disposal injection.					B	C	C	C	R	–			B	C	C	—				
Quality—seawater intrusion.				B	B	C	C						0	C					C	C

Key
Rows — issue and subissue areas discussed in text
Columns — model types and scale of applications; e g, the sixth column applies to a site-scale problem in which Pollutant movement is described by a transport model without chemical reactions under saturated flow condltlon in fractured media
Application scale
Site—models delaing with areas less than a few square miles
Local—models dealing with areas greater than a few square miles but less than a few thousand square miles
Regional—models dealing with areas greater than a few thousand square m!les
Abbreviations
w/—with
w/o—without.
sat—saturated ground waterflow conditions
unsat —unsaturated flow conditions
P—porous media
F—fractured or solution cavity media
Entr!es
A a usable predictive tool having a high degree of rellablllty and credlb!l!ty given sufficient data
B a reliable conceptual tool capable of short.term (a few years) prediction with a moderate level of crediblltty gwen suff!ctent data
C a useful conceptual tool for helping the hydrologist synthewze complicated hydrologic and quality data
R a model that is still In the research stage
— no model exists
Blank—model type not applicable to issue area

lecting data may prevent calculated results from being very credible. The ratings assigned for each model category are a composite of these two considerations.

The key at the bottom of table 9 describes the terms employed, and briefly summarizes the model rating scheme, the breakdown of model types, and the measurements used to define different levels of scale. Explanations of the rating scheme, and of scale and time considerations in model evaluation, are provided below:

Model Rating

A rating of "A" indicates that models are reliable and can be applied with credibility to a particular problem. It also implies that data necessary to use the model can be obtained at reasonable costs. Models with "A" ratings can be used effectively for making decisions on applicable problems.

Models rated "B" can be used for short-term predictions with confidence. The lower level of credibility implies that either some part of the processes described is not fully understood, or that data necessary to use the model may be too expensive or too difficult to obtain. These models can be applied to field problems if their limitations and capabilities are recognized. Further, if field data were collected on a continuing basis and incorporated into the model, model credibility would improve. Models with "B" ratings can also be used to investigate general problems (but not specific field applications). Conceptual investigations can be used in designing regulations and policy, e.g., for determining landfill siting criteria.

Models rated "C" have not been sufficiently validated for analyzing specific problems. Both expensive data collection and inadequate understanding of important processes are likely for these models. Models with "C' ratings have utility as conceptual tools for investigating general problems.

Models having a rating of "R" are still in developmental research stages. In the future, these models should earn a higher rating as they are validated through field use.

Models described by "-" are not presently available.

Area/ Scale. The credibility of ground water models is highly dependent on the geographic scale of the study area. Most models are designed to operate at the local scale (area greater than a few square miles but less than a few thousand square miles). Therefore, more confidence may be placed in models used for this scale.

Time Scales. Ground water models project future conditions for widely varying intervals of time. Generally, the longer the range of the prediction, the less reliable it is. Ground water models normally involve planning horizons of 20 to 30 years, and each model varies in its ability to forecast future conditions. For many hazardous waste problems, the time frames needed are much longer, sometimes ranging to hundreds of years. Results from such projections are much less credible than results from models used for problems with shorter time frames. While time frames are not specifically considered in the evaluations, the effects of different time projections on the credibility of model results must be considered in evaluating specific models.

ECONOMIC AND SOCIAL MODELS

Introduction

Many different types of models and analytic techniques are used to determine the economic and social consequences of water resource activities, to forecast consumer and industrial water needs, and to analyze water resources for comprehensive river basin planning and management. Social and economic models address patterns of human behavior using theories drawn from economics, sociology, social psychology, geography, and political science.

Economic models are used to estimate the overall effects of water resource activities and regulations at both the regional and national levels, as well as to forecast economic consequences to individuals and firms. For example, an economic model can forecast changes in an industry's water use as the cost of obtaining water changes, and determine the effect of such changes on industrial output.

Social models can project population trends, estimate water demands, and analyze the social structure of a given area. They can be used to identify the groups likely to be affected by resource decisions, and their perceptions of these effects. Social models can be coupled with economic models to evaluate the societal implications of water resource regulations or projects.

The use of social and economic models is relatively new in the water resources field, as in other fields. Social and economic model use in water resource analysis has been prompted by two major regulations: 1) the Principles and Standards (P&S) of the Water Resources Council; and 2) the National Environmental Policy Act of 1969. The P&S are a group of publications that presently require consideration of the likely effects on environmental quality and national economic development of projects proposed to receive full or partial Federal funding. The P&S also require studies of the effects of proposed projects on regional development and on the social well-being of the affected area. The National Environmental Policy Act requires estimates of the social and economic effects of proposed projects. To make such estimates, social models can be used to identify the population that would be affected by the resource decision, and the extent of the likely effects. Economic models are also employed to determine the economic impacts of a project on individuals, firms and the region overall.

Several factors account for the increasing use of social and economic models. Models may provide the only available means of organizing complex information for examining the effects of an action or policy. Information derived from the conditions and scenarios assumed in a model can provide insights about the effects that may occur, and serve as a basis for common discussion of assumptions and probable outcomes. Finally, social and economic models can be used to compare the merits of proposals in terms of a particular objective, and help decisionmakers determine the costs and benefits of a proposed decision.

Both social and economic models are limited by the necessity of dealing with human behavior, which is not always predictable. Behavior is difficult to incorporate in a model except in an abstract way—identifying behavioral tendencies with in a probability of outcomes. Another problem, more prevalent among social models, is that they are data-limited. Available data often prohibit quantifying and analyzing all factors involved in determining the "public interest" in any given situation. Thus, "decision" models of social and economic factors can only be used as guides—they cannot be substituted for the human decisionmaking process.

Because of the difficulty in evaluating social science models, and their less advanced state of development, these models were not formally evaluated. Few social science models are widely adaptable; moreover, such models are difficult to validate by comparing predictions to results, as is routinely done for models of physical processes. Assessing the relative utility of these models requires comparisons of previous model applications under a variety of conditions by different analysts, and necessarily involves a considerable component of subjective analysis.

Basic Analytical Characteristics

Social science models are classified by the kinds of information they generate. Three major distinctions are used to identify significant characteristics: 1) descriptive v. normative; '2) macroscale v. microscale; and 3) efficiency v. distribution of costs and benefits.

1. Perhaps the most important dimension involves the distinction between descriptive and normative models. A descriptive model is an empirical and historical representation of 'what is. Descriptive models determine factual relationships as they exist or may be expected to occur. They are intended to include a minimum of subjective assumptions and biases.

   A normative *model* may be equally reliable and credible, but it focuses deliberately on "what should be. Normative models include substantial judgments and assumptions about goals and objectives. For example, a descriptive model of the Nation's economic output would simply report actual or expected levels of gross national product (GNP), while a normative model might include the assumption of a 5-percent annual increase in GNP as an economic goal. Most of the

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Water resources development can have tremendous effects on an area's ability to attract residents, industry, and related activity. Models are available to estimate how construction expenditures may directly affect local or regional economies, as well as how water facilities could affect subsequent development. In addition, models can describe how water-related development could affect demands for a wide range of public services, for example, schools, hospital facilities, roads, and other infrastructures

current social and economic models used in water resource analysis are normative, i.e., substantial a priori value judgments have been made about the goals, objectives, measures, and methods used in the model.

2. Scale is the second feature by which social science models can be categorized. Two distinct types are recognized—*macroscale models and microscale models.* Macroscale models address aggregate changes or activities. Macrolevel models include those that measure and forecast trends such as levels of national economic activity (e. g., GNP), money supply, international trade, migration patterns, etc. They are useful for providing national and regional analyses of water resource projects and programs.

   Microscale models focus on individual and/or enterprise-level behavior. They are often used in water resources for feasibility studies, environmental impact statements and other project-planning activities. Microscale models are used to address, for example, pricing, benefit/cost, social impact, and risk/benefit questions.

3. A third feature of social science models addresses the dual questions of *efficiency* and *distribution of costs and benefits.* Water resource policies or activities affect both economic efficiency and the distribution of costs and benefits. Efficiency is describable by economic models, while addressing the distribution of benefits requires a broader social analysis, Models of economic efficiency focus on means of increasing the gross supply

of goods and services. Distributive models trace changes in assets and/or income distribution among either resource owners (e. g., labor, capital, management) or major sectoral groups (e. g., farmers, industrial workers, the unemployed).

Types of Models Used for Economic Analysis

Four types of economic models are widely used for dealing with water resource issues: 1) input-output; 2) optimization; 3) econometric; and 4) simulation.

1. *Input-output models* are based on a detailed accounting of sales and purchases among each of the industries or sectors being studied. Information on purchases and sales is used to determine either the requirements for particular inputs (e.g., water) or the production of outputs (e. g., manufactured products).
2. Optimization models are used to determine the allocation of resources that best meets a previously specified objective (e. g., least cost), subject to some specified constraints. The technique is particularly well suited, therefore, to solving problems where both the objectives and the constraints are clearly defined. When more than one objective is considered, these models can describe the tradeoffs between the best solutions for each respective objective.
3. Econometric *models* are a less homogeneous group than the two previously discussed classes of models. The term is generally used to describe forecasting models, the structures of which have been carefully estimated from historical data. The large, national forecasting models (e. g., Chase, Wharton, Data Resource, Inc. (DRI), etc.) are of this type, as are many models tailored to regional and State needs. Econometric models are typically based on the following macroeconomic principles: 1) production determines income; 2) income determines demand; and 3) production, in turn, adjusts to demand. The interactions among production, income, and demand determine economic multiplier effects, which play an important role in economic impact analysis.
4. The fourth class of models is referred to here as *simulation models.* Economic simulation models are often input-output or econometric models that are adapted to examine the implications of different sets of assumptions. Simulation models describe the highly involved pattern of cause-and-effect relationships that operates within most social or economic systems. Once relationships are identified and the key factors have been quantified, the model is used to simulate the performance of a system over a period of time, under different sets of assumptions about the system's internal relationships and the values of external variables. Such models can calculate the incremental effects of price changes or improvements in production methods, for example.

Other Social and Economic Analytical Techniques

In addition to traditional economic analysis and the four model types identified above, an increasingly large set of social and economic analytical methods is being used in natural resource planning and policy evaluation. The methods are diverse, so they will be discussed here according to the kinds of relationships they are designed to explore.

A major consideration in planning and policy analysis is the size *and demographic structure of the population.* Demographic models, therefore, relate information about the present size and structure of the population to projected changes due to births and deaths or to population shifts. Most of these models deal with specific age, sex, and racial groups or cohorts, and are consequently referred to as cohort survival models,

Another set of analytical techniques has been developed to deal with the *demands for, and supply of infrastructure*—factors such as housing and public facilities and services. These techniques are used by planners to determine the fiscal impacts on governments —including both expenditures and collection of revenues—of providing various levels of infrastructure services, Standard models are available to carry out these infrastructure and fiscal impact calculations, although variations among jurisdictional units require adjustment for the particular unit of government being considered.

Once economic, demographic, and public sector behavior has been accounted for, a major remaining concern is the social structure of an area. Few computer models have been developed to analyze this problem, but progress is being made in defining social structure, and in understanding how it is affected by natural resource decisions.

The final major area of activity for socioeconomic analysis is the *integration* of the various economic and social concerns discussed above. The models discussed above provide measures of change in the economic, demographic, fiscal, and social environment. However, the significance of these changes ultimately depends on the perceptions and values of the people who will be affected by them. Current research is underway in identifying groups that may be affected by resource decisions, and determining their evaluation of the social and economic changes that may affect them. Methods for quantifying these analyses, however, are in relatively early stages of development.

Economic and Social Issues in Water Resource Analysis

Effects of Water Pricing on Use

Severe water shortages in many locations have prompted investigation into strategies for reducing the demand for water. Water use restrictions have commonly been used for managing water use, but other methods that rely on economic incentives (water pricing and conservation subsidies) have potential for reducing the consumption of water through nonregulatory approaches.

Water demand models, which predict the response of water demand to changes in water costs, have been developed for residential, industrial, and agricultural uses. The cost of using water, as considered by these models, includes both prices paid for water delivery and other acquisition and use costs, such as costs of disposing of used water.

Residential/ water demand models are based on actual household water use behavior. Consumer demand theory suggests that the quantities demanded are related to water price, consumer characteristics (income, family size), and factors such as the season, and extent of outdoor use. Data are collected on household water use and on factors which affect that use. Using statistical analyses, the effect of price can be isolated from the effects of all other variables influencing residential water use.

The models analyze actual consumer responses to water prices. However, because responses to prices vary among regions and among income groups over time, model estimates will be region-, time-, and income group-specific. These models are useful planning tools, provided that adequate data are available and that analysts recognize the theoretical and statistical assumptions underlying the model.

Industrial and agricultural! water demand can also be analyzed with mathematical models. Because large water users are often self-supplied, market prices for water in the conventional sense do not apply. However, analyses for these demand sectors are based on the costs borne for using water. These models consider the objectives and constraints that govern agricultural and industrial decisions about levels of production and amounts of raw materials to be used, including water. The influence of water price on use is inferred by examining the models' predictions of water use changes as water costs change.

These models are not based on observed responses to price change. Rather, they are simulations of responses that could be expected from ''rational' water users with objectives and constraints similar to those described in the model. To the extent that water users deviate from the objectives and constraints assumed in the model, model predictions will be inaccurate. A number of these models have been developed; however, their use requires highly skilled analysts and good data bases.

Both types of water demand models are useful tools for water resource decisionmaking. If properly developed, they can organize complex information about the factors that determine water use, and assess the importance of price relative to other factors in determining use. Information provided by such models is helpful for developing demand management strategies, including changes in prices of publicly supplied water (e. g., at municipal systems or Federal irrigation projects) or marketing of water rights, where market prices are determined by willing buyers and sellers. These models are useful for comparing alternatives, but are less reliable for provialing quantitative estimates of actual volume demands.

Cost to Industry of Pollution Control

Pollution control costs, like the availability and cost of water, are one of many factors affecting the profitability and location of industrial activity. Models are used to determine the effects of regulations on specific industries, as well as the impact of pollution control policies on the economy as a whole. Costs of pollution control can be assessed at both macroeconomic and macroeconomic levels. Macroeconomic costs are those associated with a particular firm or industrial group, and include direct expenditures for pollution control equipment, costs of changing production processes, and foregone production. Macroeconomic costs are gaged by calculating the effects of industry expenditures to meet environmental regulations on employment levels, the Consumer Price Index (CPI) and GNP.

Macroeconomic models are the most complex of all economic models. Their development and use requires highly skilled personnel. For example, the models of DRI, and Chase Econometrics, Inc., which are among the best known of this type, have been used to evaluate changes in macroeconomic variables in response to industry expenditures for compliance with environmental regulations. However, some analysts consider it inappropriate to use these models to measure ' 'costs of pollution control. While the models can predict movements in the CPI or GNP, they do not estimate the economic value of a cleaner environment (e. g., reduced health care costs, workdays lost due to illness, etc.) as an offset to the cost of pollution control equipment. The reliability of these models is difficult to test; their use depends largely on the plausibility of assumptions made about inputs and the lack of credible analytical alternatives.

A4zc~oecomrnic *moa!ds* of costs to industry for pollution control are most often optimization models, similar to those described in the above section on water demand. Models of this type can be developed for "typical firms" in specific industries. A baseline condition is first determined by applying the model without environmental regulations. Environmental regulations are then introduced as a constraint on the firm's resources and outputs. Proper interpretation of the results can provide estimates of the costs that firms incur as a result of regulations. Limitations and potentials of this type of model are similar to those of water demand models. Models of this type are used for determining the least-cost approach to environmental regulations. These models have been used to a limited extent by EPA in the water quality regulatory process. It is likely that greater use of these models will be made in the future, for reviewing existing or promulgating new environmental regulations.

Benefit/Cost Analysis

Benefit/cost analysis measures the value of a policy, program, project, or regulation in terms of economic efficiency. Procedures for calculating the benefits and costs of Federal water resource activities are outlined in the P&S of the Water Resources Council.

A relatively small portion of Federal activities in water resource protection and development is now covered by the P&S. Affected agencies (principally the Corps of Engineers, Soil Conservation Service, Bureau of Reclamation, and Tennessee Valley Authority) prepare estimates of some costs and benefits of their proposed investment projects. However, some of the most common Federal activities —e. g., waterway and discharge permits, and sewage treatment construction grants—are not required to prepare benefit/cost analyses.

Although economists have developed rigorous theoretical standards for determining the proper measure of both costs and benefits, even the most competent analysts face difficulties in conducting sound benefit/cost analyses. Many costs and benefits may be known, and yet be difficult to define or quantify accurately—in water resource activities, more incommensurable benefits tend to be encountered than incommensurable costs. Construction costs for building a dam or a sewage treatment plant, for example, are easier to estimate than the value of decreased likelihoods of flooding, or the value of cleaner water to downstream users.

When no professional consensus exists as to the monetary value of a benefit, or the probable cost of an activity, standards of accuracy for benefit/cost analysis are difiicult to establish. Estimating the value of less tangible benefits necessarily involves an element of subjectivity; consequently, such estimates are affected by the assumptions of the analyst. The choice of a particular time frame or discount rate, for example, while not imparting intentional bias, may heavily influence results.

As a general rule, benefits and costs of public projects are easiest to evaluate when the resources, goods, or services produced are traded in the market economy (e. g., power production). Benefits and costs are less easy to measure if the resource, good, or service either contributes directly to a good which is traded (e. g., irrigation water as a factor in agricultural production), or if the private market offers a comparable substitute for the public project's output (e. g., railroad transportation as a substitute for river transportation). Benefits and costs are very difficult to estimate for resources, goods, or services for which few market transactions exist (e. g., recreation, wildlife habitat). In these cases, the economic value of the public project cannot be inferred from observed market prices.

Institutional limitations on the alternatives that can be considered for achieving an objective constitute another constraint to effective use of benefit/cost analysis for Federal water activities. Benefit/cost analysis is most useful when it is used as a screening device for comparing alternatives. If an agency, for example, is restricted to funding flood control structures and cannot propose purchasing flood plain development rights as a nonstructural alternative, the full power of the analytical technique cannot be effectively used.

Benefit/cost analysis is often used to support normative arguments that no actions *should* be taken unless benefits exceed costs. However, such arguments are often rejected for two reasons: First, complete measurements of economic efficiency, benefits, and costs of public actions are limited by data and time for conducting the analysis. Therefore, a benefit/cost analysis will often not reflect all economic benefits and costs. Second, economic efficiency in resource allocation is only one of several possible aspects of the "public interest" which must guide decisions. For example, the distribution of these benefits and costs among the public can be considered as important as the relative amounts of these benefits and costs. Nonetheless, benefit/cost analysis is useful for comparing and screening alternatives according to their relative contribution to the Nation's economy.

Implications of Water Resources Policy for Regional Economic Development

The regional economic impact of water resource development is an important concern that is not considered in "standard' benefit/cost analysis. To the locality or region in which a water project is proposed, the regional economic effects may be as important as the costs or benefits to the nation as a whole.

Models have been developed that estimate changes in the level of local or regional economic activities (employment or income) and/or economic base (development potential) due to projects or activities. Standard models include various forms of simple economic base studies, as well as the more complex input-output models.

In the past decade, advances have been made in regional development models for analyzing economic, demographic, and community effects associated with water resources development. The Bureau of Reclamation, for example, has developed the Bureau of Reclamation Economic Assessment Model, an economic/demographic simulation model used in both planning and impact assessment procedures. Similar tools are used by the Corps of Engineers and by regional and State water resource agencies.

These models are used to evaluate the economic effects of direct expenditures made in a region to implement a program or build a project, and the continued effects of the spending generated by these activities. Such models simulate a complex and dynamic process, accounting for multiplier effects from expenditures made in direct support of the activity (wages paid to labor, goods and services purchases locally, etc.), and assist in comparing the impacts of alternative programs and projects on the regional economy. Such comparisons can be of value for both planning and policy.

The use of these models is feasible for most skilled analysts. The Water Resources Council has published multipliers developed by the U.S. Department of Commerce for simulation purposes. However, developing the models and multipliers themselves requires special skills and extensive data.

The results of these models must be carefully interpreted. Such models are based on data that represent the existing regional economy. If the water resource activity being evaluated significantly alters the region's economic structure, the model may be invalid. The smaller the public action relative to the regional economy, the more reliable model results will be. Moreover, these models should not be used with the implicit assumption that economic activity (e. g., a new industry) will be attracted to the area solely on the basis of increased water resources development. Many economists consider water projects to be uncertain means for redistributing income, stimulating regional development, or achieving employment stability.

Clarification of the regional economic stake in water development has been and can be further aided by careful model use. This type of analysis is best suited to planning activities, such as comparing scenarios for different alternatives. If such models are used to estimate impacts with more precision, they should only assess the impact of certain, direct expenditures resulting from the public action, and only for short (1- to 5-year) time periods.

Forecasting Water Use

Models for forecasting long-range water use range from simple extrapolations of past trends to complex models that project water use in response to changing social, economic, and technological conditions.

Simple models, often termed the ' 'requirements approach" to projection, have been favored by Federal agencies in the past. These models extrapolate historical growth rates in water use, by use category or for total consumption. The models can be modified to provide separate per capita use rates and population projections, which are then combined to produce a total water use projection. Under the latter approach, per capita use is projected to grow at historical rates and population projections are taken from separate demographic studies. The requirements approach has been called into question because it has failed to project actual water use accurately. The requirements approach also provides little assistance to the decisionmaker, since it does not indicate why water use changes over time.

To remedy these shortcomings, more complex economic forecasting models have been developed. Complex models are simply applications of the water demand models described above. First, the demand models are used to determine the relative importance of the various independent factors (price, income, technology, etc.) that determine consumption levels for each major category of water user. Second, future changes in these factors are projected and incorporated into a demand model to predict future demands for water. A disadvantage of the complex model approach is that it requires projections into the future for many factors, a difficult task requiring a large, credible data base.

Water use projections are only guides—' 'best guesses' about an uncertain future. The demand model approach does, however, serve a useful role in planning and policy. Models can be used to test the sensitivity of forecasts to different assumptions —e. g., they can identify and assess the consequences of overinvestment or underinvestment in water supply capacity.

Risk/Benefit "Analysis

The consideration of uncertainty in planning or policymaking processes is a significant recent development in water resources analysis. "Risk assessment, *or* ''risk/benefit analysis, is required by the revised P&S for situations in which uncertainty is an essential element of the planning process. Risk/benefit analysis deals with uncertain events so as to reflect both the expected outcome (in a probabilistic sense) and public attitudes toward uncertainty and risk. Public attitudes are particularly difficult to gage for those situations in which there are low probabilities of highly serious accidents.

Since the year-to-year and day-to-day variability of the hydrologic cycle encourages the presentation of information in probabilistic terms, risk analysis is a particularly suitable approach to water resources decisionmaking. A flood or a drought or a pollutant spill of a particular magnitude will cause quantifiable losses. Estimates of the probability of that size flood or drought or spill occurring transform the projected loss to a statement of risk. Safety is generally paid for with time and money. Projects and policies, with their associated costs, work to either reduce damages or the probability of an undesirable event. Judgments about acceptable levels of risk and what should be spent to reduce them are a part of the politics of water resources. Models can help in clarifying those choices.

Risk/benefit analysis organizes information so the decisionmaker can compare the reduced risk of alternative policies with the increased costs. The "benefit" side of risk/benefit analysis is generally a statement of net costs incurred by choosing a more costly alternative over a less costly one. These costs are calculated using estimation models similar to those used for benefit/cost analyses. The "risk' side of risk/benefit analysis is a statement of the probability and consequences of a particular action or occurrence. Consequently, risk/benefit analysis is not the sole domain of social scientists, but must rather be conducted by engineers, lawyers, and scientists from many disciplines.

Methods for estimating adverse health and safety risks are relatively new, but the cases in which these methods have been applied are relatively similar. One of the major shortcomings of this approach is the inadequacy of historical data to construct probability functions. Although subjective probabilities can be assigned by experts, such assignments can potentially impart biases to the analysis. The high degree of uncertainty about dose-response relationships, in particular, tends to reduce the credibility of quantitative estimates of risk.

Social Impact Analysis

The potential social impacts of water resources programs or projects have received increasing public attention in recent years. As a result, Federal agencies have begun to develop accounting methods for social-effects that consider two important factors:

1. The effects of **a** program or project fall unevenly on different groups. For example, some groups may benefit from increased employment, some may experience shifts in recreational opportunities, others may undergo tax increases.
2. The desirability of these effects will depend on the value structures of the groups affected. The impact of activities can be perceived differently by different groups.

These two factors mean that political decisions are likely to affect certain groups differently than others. Decisionmakers need to understand not only the effects of a project, but also what the effects will mean to the affected individuals.

Regional economic development models (described above) provide a basis for considering community-level effects—particularly effects on housing, on the demand for public facilities and services, and on the overall fiscal condition of local governments. Once these consequences of a project have been determined, consideration must be given to what the Water Resources Council has referred to as "social well-being. The remaining questions are of two kinds: First, what is the effect of the project on the social structure of an area? Second, how are the economic, demographic, community, and social effects of the projects perceived by the affected people? Models and operational methods to answer these questions are still in the research stage.

Current research indicates that social structure is definable in terms of: 1) the functional groups in an area; 2) the characteristics of the groups (e. g., size, attitudes towards growth); and 3) patterns of economic, political, and social interaction among the groups (e. g., employee/employer relations and political alliances). Questions can then be asked: Will a project introduce any new groups into an area? Will it in any important way affect the characteristics of existing groups? Will it affect the way in which economic, political, or social interaction occurs among the groups? Answers to these questions constitute the social effects of a project in the same sense that economic/demographic and community effects can be defined using the models and procedures outlined above.

The next step in social well-being analysis is to determine the significance of the changes to the people affected. This requires that the distribution of effects among the various groups be known and that their individual evaluations of these effects be determined. Specifying the distribution of the effects (economic, demographic, community, social) is usually possible once both effects and groups have been clearly defined. Effects can then be evaluated, largely through direct questioning of group members or knowledgeable individuals. This part of the social assessment process constitutes "public involvement.

In projecting the social impacts of various changes, models can be used to: 1) organize information on the social factors that are affected, and 2) qualitatively determine the direction of the impacts (positive, negative, or no change). Even this qualitative information can be useful to a decisionmaker. If a systematic approach is not used, the inventory of social impacts may be incomplete.

Unified River Basin Planning and Management

River basin models consider the simultaneous use of water resources and the competing values associated with those uses. Such models are one means of assessing the "value' of water for alternative uses—both for offstream purposes and recreational, wildlife, and water quality instream uses. These models form an analytical basis for examining alternative planning and management strategies for an entire river basin. River basin models require input from a large number of disciplines as well as information from economic and social models.

Two principles are central to unified river basin planning and management:

1. River basin planning stresses comprehensive analysis of the interrelationships among water resources and social and economic activity, rather than the project-specific focus of most planning activities.
2. River basin planning emphasizes monitoring and analyses on a continuing basis, instead of only at times when specific projects are being considered.

Since the methods applied in this area are similar to, or the same as, the methods discussed in the previous sections, all of the justifications and limitations discussed in those instances apply here.

The first models developed for unified river basin planning were river basin simulation models completed during the 1960's. These models linked water resources to economic activity and demographic trends. The Susquehanna River basin model developed in the early 1960's was the first of these efforts, and demonstrated the applicability of a systems approach to river basin analysis. The general example provided by that work has been repeated many times since.

Another related application of river basin analysis has occurred principally in the Western United States. Models have been developed to analyze the economic development implications of competitive demands for water among agriculture, energy-related mining or industrial development, and in recreational stream uses. Analysis of the implications of alternative allocation schemes has generally been conducted at the river basin or State level, using simulation models with hydrologic, econometric, and demographic components. Models of this kind were first developed for the purpose of analyzing different resource management strategies in Utah in the early 1970's with the Utah Process Economic Demographic Model. Similar models now exist in many States and, among other applications, are used to analyze water resource management alternatives.

Only in a few basins have there been modeling and data collection on the scale necessary to relate in detail both water quality and water demand to subregions and sectors. To do this comprehensively requires linking physical and social models that include many subjective inputs from citizens and/or decisionmakers.