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[SYMPOSIUM]

SOME IMPORTANT RESEARCH PROBLEMS IN THE WATER RESOURCES FIELD

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Although some of the research efforts focused on the hydrologic cycle have been stimulated by the simple desire to probe the unknown, most of the research in the water resources field seeks a payoff in terms of improved water resources planning and management. The agency planner and system operator are particularly concerned with payoff. How will the research help in day-to-day planning and operation?

From this point of view there seem to be a few particularly pressing areas of research need in order to improve decisions with respect to water resources development and management. Some of these problems have been discussed, mentioned, or implied in the preceding articles. The purpose herein is to amplify and emphasize.

I

UNCERTAINTY

The first problem area is that of handling uncertainty in water resources system planning. Uncertainty stems from the difficulties in estimating future population and industrial development, future demands for water and water-related products and services, changes in technology, future political decisions, and from hydrologic uncertainty. As examples of changing demands, in recent years water-based recreation and water quality improvement have become increasingly important when compared with flood damage reduction and irrigation.

Adequate procedures have been developed by which the consequences of hydrologic uncertainty can be estimated.[1] With respect to other facets of uncertainty the most common suggestion has been to modify the interest rate used in system planning. There appear to be other procedures for coping with uncertainty: first, incorpora-

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[1] See particularly M. B. Fiering, Synthetic Hydrology—An Assessment, Paper Delivered to the Western Resources Conference, Ft. Collins, Colo., July 1965.

ting flexibility in water resources systems; second, analysis of alternative patterns of demands over time; and third, changing the end product-time focus of water resources planning.

Flexibility can be achieved by several means. First, flexibility can be achieved by stage or phase construction. Second, flexibility can be achieved by modifications in the original construction of facilities, for example, by incorporating multiple outlets in a reservoir. Third, flexibility can be achieved by shifting the mix of outputs and the use of storage capacity, in effect changing system operating procedures. Stemming from the above are unanswered questions: What are the benefits which can be attributed to the provision of flexibility? What types of facilities are most amenable to stage construction? What legal problems are involved, and how might they be surmounted, in changing over time the mix of outputs from water resources systems? It should be emphasized that flexibility is a problem not only in system planning, but also with respect to operation of water resources systems once they are in existence and with respect to organizational arrangements for both planning and operation of water resources systems.

A second possible procedure for handling uncertainty involves the analysis of alternative growth patterns over time. For a given area for which water resources development is being planned, alternative patterns of demands over the time period for planning would be estimated, ranging, for example, from high to low. For *each* demand pattern, the optimal system, however defined, would be determined. These systems would then be compared. The result might be that the optimal systems for all demand patterns would contain the same units for the initial period, *i.e.*, from time zero to fifteen years. One would conclude that these would be the logical initial units to install, because they appear able to produce the desired outputs under a range of conditions. On the other hand, it might turn out that there would be no identical system components, though this result appears relatively unlikely because the alternative demand patterns probably would not diverge widely in the short run. Given no identical components, the investment decision would have to be based on some estimate of the most likely demand pattern. The possible utility of analyzing alternative demand patterns in this fashion needs investigation.

Alternatively, one growth pattern would be selected and the optimal system determined for it. Then alternative growth patterns would be imposed on the optimal system previously defined and the corresponding system outputs, benefits, and costs determined. If the results with the alternative patterns were within the range of error related to the optimal system, one could assume that the system components were relatively insensitive to variations in demands. On the other hand, how would the planning decision be made if the optimal system for the originally selected growth pattern resulted in sizeable *negative* net benefits for the other growth patterns and no one growth pattern was more likely, in a statistical sense, than any other?

The two foregoing procedures are related, and in fact lead to the third, namely, shifting the end product-time focus of water resources planning. Traditionally, the procedure in water resources planning has been the production of a plan for development of the water resources of a given area to meet water needs, however estimated, over some relatively long period of time, such as fifty years. The typical procedure has been to delineate all of the units which will be needed over the entire time period.

Because of the dynamic nature of water needs, the units of a water resources system are required in some sequence over time, rather than all at once. At the same time, because of various uncertainties, the nature, magnitude, and sequence of demands and the corresponding system units required to meet the demands, may change quite radically, even in the short run. As a consequence, perhaps the end product-time focus of water resources planning should not be on an overall plan to meet needs for some lengthy period, such as fifty years, but rather should be on *the next unit or units* to be added. This is the approach used in power system planning.[2] This does not mean that the long term situation should not be assessed in planning, because the long range expansion pattern of a system in response to demands may influence the initial units to be added to the system. However, the emphasis should be on the required units for the immediate future rather than on a total overall plan for a relatively lengthy period of time.[3]

An important implication of the three procedures suggested above

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[2] See, *e.g.*, J. K. Dillard & H. K. Sels, *An Introduction to the Study of System Planning by Operational Gaming Models*, 78 A.I.E.E. Trans., pt. 3, at 1284 (1959).

[3] There may be some concern that a focus on the next added units would result in losing desirable reservoir sites. Because the approach suggested involves analysis of long run expansion patterns, desirable sites are identified. Such sites can be zoned for future use as reservoirs, development rights can be purchased, or the sites can be purchased outright. A decision with respect to a future reservoir site can be based on a comparison of the present value of the costs of current purchase of a relatively undeveloped site plus returns foregone until use of the site as a reservoir, versus purchase of a developed site at a later point in time.

for handling uncertainty is that planning must be carried on continuously. The analysis of the next increments to be added to a water resources system in a given area in response to changing demands, political decisions, goals, and changing conditions cannot be accomplished by an agency that is given only an irregular responsibility, with respect to time, to assess the area's water problems, as in the once-in-a-decade planning efforts of the Corps of Engineers in the Columbia Basin. The planning agency must be responsible for, and organized to perform, the continuous planning process, where the end product of that process is a series of more or less periodic decisions about the next investments to be made.

Although continuous planning may be more difficult than "one-shot" planning, the former permits much more flexibility in planning and more responsiveness to changing conditions. Flexibility involves not only those aspects mentioned above, but also the consideration of various nonstructural alternatives for meeting demands for water and water-related products and services. An agency producing "one-shot" plans for an area once every ten or fifteen years is in a poor position to keep abreast of, and to note the effectiveness of, such measures undertaken within the area as flood plain zoning and flood warning systems, public and private waste treatment measures, local pricing policies, and in-plant changes. As a result, the tendency is to propose structural means, such as reservoirs and levees, for water resources development.

Equally important, continuous planning enables more responsiveness to changes in politically determined goals for water resources development. It also enables faster response to changes in the criteria to be used in water resources planning, such as changes in the interest rate.

There probably are other procedures for handling uncertainty in water resources planning. For whatever they may be, and for the ones noted herein, what is needed is an assessment of their practicality and feasibility.

II

RELATIVE ACCURACY OF DATA

Related to uncertainty is a second problem, the relative accuracy and precision of the data used in water resources planning. An axiom in the scientific world is that the analyst should choose his techniques of analysis in relation to the accuracy and precision of the data involved. Similarly, the strategy of planning should be conditioned by the relative accuracy and precision of data, particularly where there are a number of variables involved for which the data have differing degrees of accuracy and precision. Thus, where the economic variables, for example, projections of demands and benefits over a fifty-year period, are known to have a wide range of potential error compared to the hydrologic data or to the reservoir capacity and cost data, and at the same time are the dominant factors influencing system plans, there would be little point in allocating large amounts of manpower and time to refining hydrologic data to a high degree of sophistication.

What is needed are some studies of the relative accuracy and precision of data relating to various types of water resources systems.[4] Such studies would provide data of value in water resources planning in at least two respects. First, knowing the relative accuracy of the various types of data involved and their relative importance in planning as measured by the contribution to the error in the final result, a better allocation of the resources available for planning can be made. For example, in an area where industrial water withdrawals comprise the bulk of the outputs and flood damages are relatively minor, and the accuracy of the data relating to industrial withdrawal is much less than that relating to flood damage, it would not be logical to allocate more man-hours to refining flood hydrographs than to analysis of the economies of industrial water utilization.

Second, given information on the accuracy and precision of data, more rational decisions can be made with respect to the degree of refinement of the overall planning effort. For example, how far should the search for the "optimal" system be carried? To what extent will short-cut methods of analysis yield answers within the established range of error? Use of highly sophisticated methods of analysis may be unjustified where data accuracy is low. Rational planning depends on a knowledge of the relative accuracy and precision of the data involved.

III

INSTITUTIONAL PROBLEMS IN SYSTEM PLANNING AND OPERATION

Techniques need to be devised by which the decisions of private and non-federal governmental units affecting water resources sys-

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[4] A preliminary effort along these lines was made in H. A. Thomas & B. T. Bower, Relative Precision of Cost and Benefit Data (Harvard Water Program 1957).

tems can be integrated with the planning and operating decisions of federal, federal-state, or state agencies with region-wide responsibilities. Many facets of water resources that require integration if efficient development and operation of water resources systems are to be achieved, involve multiple decision-making centers. As demands for water and water-related products increase in any given area and impinge increasingly upon each other, the range of alternative combinations of possible system components for meeting those demands must be increased, if efficient development is to be achieved. Among these alternatives are such measures as internal recirculation by industries, flood plain zoning, flood warning systems, and ground water withdrawal and recharge.

The crucial and identical characteristic of these alternatives is that the implementation of such alternatives is generally outside the jurisdiction of the region-wide water resources agencies. That is, decisions whether or not to undertake such alternatives are made by local units of government—municipalities, counties, and the like, or by private production units. For example, efficient utilization of ground water resources requires that ground water withdrawals be integrated with surface water withdrawals and surface water availability. However, surface water regulation is likely to be controlled by a region-wide public agency, whereas ground water withdrawals are controlled by individual farmers, municipalities, or industrial firms. Similarly, a regional water agency may plan a development with certain assumptions about the use of the flood plain. If such uses are not controlled by the local units having the control power, in accordance with the system plan, then the system will not produce the planned output of flood damage reduction. Water and waste treatment plants involve decision-making units that differ from those controlling basin-wide reservoirs. The extent of reservoir development required in an area is a function of the way in which individual water users operate their in-plant water utilization systems. If such operations result in water utilization patterns different from those assumed by the planning agency, then the system will not achieve the benefits estimated in the planning.

The problem then is, what mechanisms can be evolved by which the public and private decision-makers external to the planning and operating agency can be induced to undertake those measures which will provide the optimal solution? Legal questions, problems of administrative organization, and possible instruments, such as withdrawal, effluent, and water utilization charges, are involved.

IV

OPERATING PROCEDURES FOR WATER RESOURCES SYSTEMS

The planning and operation of a water resources system requires the development of an operating procedure for that system. Simply defined, an operating procedure is a set of rules for withholding water in, and making releases from, surface and ground water reservoirs, and for initiating flood evacuation and flood proofing measures, temporary lagooning of wastes, incremental waste treatment measures, artificial re-aeration facilities, and the like, in relation to the hydrologic inputs and the output demands. A typical operation study involves imposing hydrologic inputs, both monthly stream flows and shorter period flows during critical periods, *i.e.*, flooding and low flows, on a water resources system through the period of analysis—50, 500, 1000, or more years, to determine the outputs which can be produced by the system. Ideally an *optimal* operating procedure, *i.e.*, one that maximizes the selected objective function, should be developed for each water resources system under investigation.

Where a water resources system has a single output, such as power, and where that output can be evaluated in dollar terms, an optimal operating procedure can be developed with *relative* ease; it has been done for many power systems. However, for multi-product or multi-output water resources systems where values for all outputs cannot be defined in dollar terms, at least on a monthly or an "instantaneous" basis, optimal procedures based on dollars have yet to be developed. Further, no success has been achieved to date in developing optimal operating procedures on a physical rather than an economic basis, that is, by expressing the worth of an acre-foot of water for power in terms of "*x*"acre-feet of water for municipal water supply, for recreation, for irrigation, and so on.

Recourse, of necessity, has been to relatively fixed operating procedures, that is, procedures in which the rules specifying releases are formulated in terms of only a few of the variables relevant to the system. For any water resources system, a number of such procedures can be developed. However, the number of possible procedures is virtually infinite and time and manpower limitations preclude investigation of more than a few of the possible alternatives. What is needed are more general operating procedures that would result in optimal operation for any of the many possible combinations of system units. Alternatively, simple rules could be developed by which a systematic appraisal of a large number of relatively fixed operating procedures would be possible.

Some of the major problems involved in the development of optimal operating procedures include the integration of nonstructural measures, operation during critical periods of floods and low flows, methods of flow forecasting to be used, and hedging. The operation of flood warning systems and the related flood fighting, flood proofing, and flood plain evacuation activities as integral parts of a water resources system exemplify the first.[5] For example, given a particular flow-flood damage relationship for a reach of river downstream from a reservoir, the operation of the reservoir for flood damage reduction is initiated by some level of flow occurring in the course of the operation study. The same flow or a subsequent higher flow would initiate the flood proofing activities, and so on. Both the withholding of flood flows in the reservoir and the related activities would achieve some degree of flood damage reduction.

Operation of a water resources system during a critical low flow period is similar to that during a flood period. Initiated by some level of low flow, the operation of the system may shift from monthly time periods to daily time periods. Certain short-run activities, in addition to reservoir releases, may be involved. These "temporary" measures include overloading of water and waste treatment plants, *i.e.*, operation at above design capacity; under-irrigation, possibly accompanied by increases in other factor inputs on the irrigated area; specific controls on withdrawals; lagooning of wastes; additional application of chemicals in treatment plants; and artificial addition of oxygen to waste discharges or to the stream itself. The extent to which such measures are technically feasible, the cost functions related thereto, and the manner of integrating them into the water resources system, both in planning and actual operation, need investigation.

Monthly operation and short-run operation during critical periods, *i.e.*, floods and low flows, both require the forecasting of future inflows. For the former the problem involves what should be used as the anticipated inflow in the next time period, the next month or the next several months. Some of the alternatives are the mean inflow for the forthcoming period, the mean inflow modified by the serial correlation with the flow in the preceding month or months, and the mean inflow modified by the serial correlation with preced-

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[5] Various levels or degrees of flood plain zoning can be incorporated in water resources planning in the form of modifications of flow-flood damage relationships.

ing flows and a random component. The problem for critical flow periods is perhaps simpler, because the patterns of flows during floods and low flow periods can be fairly well characterized on the basis of historical behavior. Even so, the degree of refinement in flow forecasting justified for planning studies needs investigation.

Hedging involves the withholding of some portion of available water in the immediate time period in order to have more water available in a later period.[6] The purpose of hedging is to minimize overall economic losses from inadequate supplies of water by incurring several small deficits, *i.e.*, in several time periods, instead of a single large deficit in a later time period. The economic desirability of hedging is a function of the shape of the loss functions related to the various outputs involved—irrigation, municipal and industrial water supply, recreation, power, and water quality improvement. Research needs involve the development of operating rules for hedging in water resources systems and of short-run loss functions associated with temporary deficiencies in production of the desired outputs.

Thus there is a range of problems relating to operating procedures for water resources systems on which useful work can be done.

V

WATER QUALITY IMPROVEMENT BENEFITS

In recent years considerable attention has been focused on, and considerable pressure created for, so-called "low flow augmentation." This phrase is not particularly useful for rational planning of water resources development. The desired output is not an augmented low flow in and of itself, just as a desired output is not the reduction of flood peaks per se. The desired end product in the latter case is, of course, flood damage reduction. In the former case, regulation of flows to change the time distribution of the quantity and quality of water may be both beneficial and detrimental to various users. Lacking a better term, the phrase "water quality improvement" is used herein to designate the relevant output.

It is important to note that consideration of water quality improvement as an output from water resources systems should not be limited solely to low flow periods. With respect to water quality there may be detrimental effects from the reduction of high flows,

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[6] See A. A. Maass et al., Design of Water-Resource Systems 455 (Harvard Univ. 1962).

for example, where such reduction precludes scour of sludge banks or where the elimination of high flows modifies the environment for fish life in tidal estuaries.[7] Benefits may also accrue from reduction in high flows, *i.e.*, by reducing turbidity, which in turn reduces water treatment costs.

What needs to be developed are water quality improvement benefit functions related to various water quality parameters, such as chlorides, alkalinity, hardness, total dissolved solids, heat, and turbidity, for various users—industrial, municipal, agricultural, and recreation. The general nature of such relationships can be illustrated as follows. Given a paper mill with a demineralizer used to provide the requisite quality of water for the manufacture of paper, the efficiency of the demineralizer is a function of the quality of the intake water with respect to chloride concentration. Over some range of chloride concentration the demineralizer is able to produce the requisite quality of water at about the same unit cost. However, as the chloride concentration of the intake water begins to increase above some limit, the cost of producing the quality of water required begins to increase. A chloride concentration is finally reached where the demineralizer can no longer produce the required quality of water and production must cease or an alternative source of water must be utilized. The incremental costs associated with incremental increases in chloride concentration need to be evaluated.

Two additional points relating to water quality improvement benefits should be noted. First, defining water quality improvement benefit functions is related to, and will be of help in defining, loss functions in relation to water quality.[8] That is, what economic losses are incurred, by various users in relation to various water quality parameters, when water quality is deficient, or below the "target" level, for short periods of time? It may well be uneconomic to provide the specified water quality 100 per cent of the time. The incremental output from 95 to 100 per cent certainty may require an incremental investment, for example, in reservoir storage to provide dilution water, in excess of the benefits derived. The benefits from continuously maintaining water quality at the specified level or the losses from failing to maintain that quality during short periods of time, *i.e.*, loss functions, require delineation.

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[7] With respect to potential problems relating to fish life in estuaries stemming from modification of the flow regime, see the discussion by B. J. Copeland, Proceedings, Invitational Seminar on Advanced Water Resource Topics 62 (Univ. of Tex. 1964).

[8] See Maass et al., *op. cit. supra* note 6, at 156-57.

There is an analogy between the evaluation of short run water quality improvement benefits and the evaluation of flood damage reduction benefits. With respect to the latter, flooding occurs only at intervals. Thus, flood damage reduction is an output from a water resources system which is not produced continuously. The same is true for water quality during short run periods of deficiency.

Second, in developing operating procedures for a water resources system, a general objective in a physical sense is to minimize the waste of water spills, *i.e.*, minimize the quantity of water that produces no "useful" output. A similar objective appears relevant with respect to water quality improvement. That is, a general objective is to minimize the time when *more* than the desired water quality is available because no benefits accrue to the additional increments of improved water quality.

VI

WATER RESOURCES PLANNING IN METROPOLITAN AREAS

In the most recent planning studies of metropolitan areas the interrelationship between land use and transportation has been explicitly recognized and considered.[9] The question arises whether or not a similar interrelationship exists between spatial patterns of land use and water supply and waste disposal facilities in metropolitan areas. For example, to what extent have the costs of water supply and waste disposal in metropolitan areas been increased as a result of sprawling urban development? Is there a relationship between water supply and waste disposal costs and such factors as the density and spread of metropolitan areas? To what extent can the provision of water supply and waste disposal facilities, à la transportation, influence the spatial pattern of development in metropolitan areas?

These questions can be raised in the context of given pricing policies and a given configuration of governmental units in a metropolitan area. However, both factors influence water resources planning and development in such an area. The role of charges in influencing water intake and the quantity and quality of waste discharges remains inadequately defined. How do various levels of charges affect water intake and waste water discharge, particularly

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[9] The Penn-Jersey Transportation Study is perhaps the foremost example. See also W. S. Pollard, Operations Research Approach to the Reciprocal Impact of Transportation and Land Use, Paper Presented to the ASCE Transportation Engineering Conference, Minneapolis, Minn., 1965.

with respect to industries? To what extent can peak demand charges influence the time pattern of water demands for domestic, commercial, and industrial users? To what extent can users shift their water utilization patterns to reduce peak demands and what incremental costs are involved in so doing?

The typical profusion of governmental units in metropolitan areas has precluded taking advantage of economies of scale in the provision of water supply and waste disposal. With respect to metropolitan Seattle, for example, evidence indicates that unit costs of waste disposal can be reduced very significantly through utilization of area-wide facilities.[10] A related question is whether or not the concentration of heavy water-using and water-polluting industries in specific, local sections of a metropolitan area can contribute to more efficient water resources development and management.

These questions all have important implications with respect to the efficiency of resource allocation and policy decisions in metropolitan areas. As such areas grow over time, water supply and waste disposal problems will become increasingly important and complex. These problems comprise a large and an important area for research.

CONCLUSION

Obviously, no attempt has been made in the foregoing discussion to cover the entire gamut of research needs relating to the planning and operation of water resources systems. Rather, an attempt has been made to delineate a few of what appear to be major and pressing problems. Occasional attempts to define research needs, as exemplified in this symposium, appear to be of use in helping to formulate worthwhile programs of research in the water resources field.

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[10] When Metro Seattle was initiated several years ago, there were 18 different sewage treatment plans operating in the area, treating about 12.35 billion gallons of sewage daily at an average cost of $55 per million gallons. After 1971, when the major trunk sewage lines are to be completed and all temporary treatment plants are abandoned, 105 billion gallons are expected to be treated annually at an average cost of about $10 per million gallons.