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OPERATIONS RESEARCH STUDY OF WATER RESOURCES

PART I: METHODOLOGY AND PROBLEMS IN AN URBANIZED ARID ENVIRONMENT[1]

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ABSTRACT

The methodology of operations research is judged in relation to its utility to water resource management in an urbanized arid environment and to the study of worth of data for such management. Conditions for existence of a managerial problem are reviewed as is the multilevel structure of the decision process, including decisions on social goals for Western water use. Worth of data can only be judged in relation to a particular use to meet a social or managerial objective. The role of data uncertainty on the decision process is reviewed in the light of past water decisions and present and future problems.

KEY WORDS: operations research; social objective; managerial objective;
water decisions; arid regions

INTRODUCTION

It is the objective of Part I of this paper to review briefly the philosophy of systems analysis or operations research and to present "problems" of water resource development and management in the urbanized arid areas of the Southwestern United States; special attention is given to the development of efficient data collection systems for prediction and control in hydrology and water resources.

The second part of the paper, to be published at a later date, will show how this operations research approach has been applied to specific problems in the Tucson basin, Arizona.

GENERAL PHILOSOPHY

Operations research is the application of the scientific method to problem identification and problem "solving" by systematic evaluation of the consequences of a range of alternative courses of action for realization of design and social goals. Some call it the future science of action. We choose to define our philosophy in the context of systems engineering: the practical application, maturation, and convergence of (a) general systems theory, (b) operations research, (c) human factors (including social and economic sciences), (d) probability theory and mathematical statistics, (e) engineering mathematics, (f) computer science and numerical analysis. The interaction of these subjects in the context of a case study for the Tucson basin has been developed by the authors in earlier papers (Kisiel and Duckstein, 1968; Duckstein and Kisiel, 1968).

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[1] Part of this material was presented as a paper June 6, 1969, before the International Symposium on Aridlands in a Changing World, American Association for the Advancement of Science, University of Arizona, Tucson, Arizona. Paper No. 70064 of the *Water Resources Bulletin* (Journal of the American Water Resources Association). Discussions are open until April 1, 1971.

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IDENTIFICATION OF PROBLEMS

The general objective of our research has been to interact the methodology of systems engineering with identifiable "problems" of hydrology and water resources management in an urbanized arid environment. It is important to ascertain if in fact problems exist. The answers may be conditioned by one's value structure, professional background, level of responsibility for decision-making, and knowledge. However, our responsibilities to the profession are anticipatory and include improvement of existing professional practice. It is generally conceded by hydrologists that methodology for prediction of hydrologic phenomena in aridlands and urban areas requires considerable improvement. Such methodology is at least a necessary condition for water management. Furthermore, because water management is undertaken in a social context and for present and future generations, we believe in the desirability and merit of quantifying what is quantifiable now in the spectrum of economic and social variables that enter the decision-making process. Thus, it is our judgment that challenging problems exist in the application of systems methodology. Implied is our view that theory complements intuition (Feller, 1957) and that nature exceeds human intuition. Our emphasis is on an integrated systems approach with the Tucson area as a field laboratory for improvement of methodology.

Publicized problems include provision of an economical, palatable, and safe water supply for present and future generations, efficient management and allocation of existing water resources, and the control of floods in the urban area and natural river channels.

Typical problems include: (a) Allocation of water such that the supply will be utilized for the "best" interests of all concerned; since the concept of "best" depends on the viewpoint, someone must decide how to allocate water between conflicting interests; this is where operations research may help in classifying the choices using, for example, the concept of collective utility (Lesourne, 1964). (b) Efficient use (economically and engineering-wise) of treated sewage effluent; for example, exchange of effluent for groundwater that was to be used by farmers and mines and which thus becomes available for domestic use. (c) Comparative economic analysis of technically feasible schemes to recharge aquifers when only intermittent flows are present.

In this context, it is meaningful to relate the above to the necessary and sufficient conditions for the existence of a problem as given by Ackoff (1962): (a) an individual (decision maker or manager of central water resource agency) has a problem, (b) an outcome or objective that is desired by the decision maker, (c) at least *two unequally efficient courses of action* which have some chance of yielding the desired objective, (d) a state of doubt in the decision maker as to which choice is "best," and (e) an environment or context, consisting of factors not under the decision maker's control, of the problem. If the above is intellectually acceptable, then it is clear that the earlier defined problems meet these conditions. Our general systems approach is mission-oriented to the extent that it generates information (of value to problem solving) as a result of development of methodology.

The above problems imply at least four identifiable levels of decisions: (a) goals for a social unit, (b) regional or basin-wide water policy consistent with the goals, (c) integral operation and design of water systems, and (d) design of individual facilities. This multilevel structure indicates that more objective evaluation and more optimal decisions are possible, in general, as one progresses down the spectrum to more concrete detail. The above sequential decision process has an irreversible character in that serious miscalculations or errors propagate their disorder into all subsequent decisions, both major and minor, in space and time. It is well known that detailed operations studies after authorization of small and large water resource projects frequently reveal either that the regional water policy is ill-conceived, incapable of being fulfilled, or too costly in its implementation. The challenge is to pursue the above multilevel decision process via systems analysis at minimum cost.

Because systems methodology includes a plethora of possible approaches to all kinds of problems, it is not a very trivial step to translate the procedures into a form suitable for problem-solving. Furthermore, there is no computer program that will "solve" all problems in all geographic and social settings. An excellent in-depth study of urban water resources research by the American Society of Civil Engineers (1968) emphasizes this point as well as the high cost of a combined engineering-economic systems analysis of urban water problems in one pilot urban area. Estimates were $15,900,000 for an engineering systems analysis for a six-year period and up to $675,000 for economic systems analyses over a three-year period. The objective would be development of a systems methodology for solution of urban water problems that is transferable to other urban areas and that will be directly usable by civil engineering consultants and urban planners. While this is a most worthwhile goal, it is apparent that one weakness exists in the approach: the study of the urban water subsystem has been decoupled from a regional study of the total urban system. Nonetheless, the above study is a milestone and a beginning. With the above backdrop it is evident that a comprehensive operations research study, even of urban water problems is no small task and a long-term effort.

Relevant to an understanding of social goals (at least as related to water) is the fact that the water situation in Arizona and elsewhere in the West reflects a paradox. Water problems of Western cities are embedded in the larger problems of the competition for water in the Western U.S.A. Whereas western water planners traditionally have assumed that water was the "limiting resource" in economic growth, the use of water by any one individual is not really constrained at the municipal level. Transplanted Easterners in many instances desire lawns and other appropriate vegetation that is consumptive of water. No rationing of water is imposed; it is true that in many eastern communities water is not even metered and that any rationing is imposed because of an inadequate storage or supply stream rather than a shortage of water resources.

The costs for future water development are not anticipated by accumulation of capital reserves through higher pricing of water or other taxing strategy. The presumption is (a) that the necessary capital will be provided by the Federal government for large-scale water development and by the voting public through approval of bond issues for local capital improvements for future supply, and (b) that technological advances will always insure a cheap source of water into the indefinite future. To be sure, substantial effort has been expended in the Tucson area to reclaim wastewater more effectively (over 31 percent of wastewater or 12,000 acre-feet is being reused) and to absorb private water utilities as a necessary step toward central and metropolitan control of the water resource. The above-mentioned presumptions seem to condition, as well, the thinking of the business, industrial, and agricultural community. The business community desires economic growth; but it is not clear that they choose to compute the long-term social costs, including future water needs, accompanying that growth, as recently stressed by White (1969) in the context of the role that banking institutions can play in pressuring for economic efficiency in water use.

Even though water is a necessary condition for industrial development in any community, the rank given to water depends on the industry. However, the mining industry's annual use of groundwater in southern Arizona, which is roughly one-half that of municipal use, is literally consumed in ore processing, is steadily growing, and is a serious source of concern to those responsible for water supply, notwithstanding the traditional factor of safety assigned to future projections of water use. In view of the low quality of some of the ore, it would appear that control of pumping by a state agency or by a pricing or tax mechanism would adversely affect the mines and thus employment.

Thus, one may ask whether it is better to use existing water resources at such a rate as to maximize economic growth and, thus, employment or to conserve a portion of the resource for future generations who may not have the necessary technological breakthroughs or economic wherewithal to provide for basic needs. Is it better to keep the water in the bank or to use it at a pace dependent on the social discount rate? The majority assumption is that, because past generations have been able to manage under the above philosophy, future generations will have even greater capabilities. However, the question is not academic in view of rapid population growth. Thus, intermingled in a very intricate manner are three criteria: economic efficiency, distributional equity, and growth.

As for agriculture, the evidence is that the modern Arizona farmer consistently responds to water scarcity according to the theory of production economics (Martin and Young, 1969; Kelso and Jacobs, 1967). Marginal producers gradually depart the farming business, other producers substitute water saving systems such as pipelines or concrete ditches when water is scarce and expensive, marginally profitable crops are replaced by more productive crops, and marginal lands are put to rest. Furthermore, there is evidence that irrigated lands may be transferred to municipal or industrial use if the price is right, thus releasing water to these high-income producers (Kelso and Jacobs, 1967). This economic fact is important because irrigators withdrew about 55 percent of the annual average of 165,000 acre-feet from 1962-1966 and municipalities only 35 percent. The common assumption is that agriculture is vital to the economy; on the other hand, if the large volumes of water used for irrigation were available to industry, would the requisite industry be on hand to make economic use of that water? This raises a controversial point about the secondary and tertiary benefits accruing to primary agricultural production. Martin and Young (1969) argue that input-output analyses of the additional income generated by each type of crop do not support the agriculturist's point of view that agriculture is the keystone for the state's economy. The paucity of social data and assumptions inherent in input-output economic analyses conspire to confound an objective evaluation. Yet, it is clear that past trends favor increased assimilation of agricultural water resources by the municipal and industrial sector.

The view of the municipal sector is well reflected in a recent address by the Director of Tucson's Department of Water and Sewers (Tucson Daily Citizen, 1969) who insists that it is inequitable to require the city to pay $55 per acre-foot for Central Arizona Project water plus about $20 per acre-foot for treatment (including softening) in the face of present well pumping costs of $4-5 per acre foot. He argues that this would leave the cheap supply to other users, such as mines and farms and, as a result, suggests that a pump tax, conservancy district with taxing powers, or some other mechanism must be found to spread the cost. It is clear that authorization of the Central Arizona Project has spawned a new set of problems concerning water allocation and cost sharing within the State. Legislative action at the state level on the above matters is certainly necessary, and we must admit that far-reaching legislation may do much more good than technologic breakthroughs or sophisticated methodology. Yet, systems analysis can help to point the way to appropriate legislative action.

The key question is: Does any urbanized arid area have a regional water problem if the agricultural production is not essential to the long-run economy of the region? If it is essential, then what is the problem? To minimize cost of water source or to encourage growth? Can the community have both or the better part of both "worlds," particularly when water is at least a necessary condition to society? The first problem is "solvable" in the context of existing methodology for cost minimization; the second problem has little to do with water if agricultural production is not important for the long run and if the figures on benefits accruing to municipal and industrial use of water are believable. It must be emphasized, however, that problems as seen now may not be problems of the future.

Because water resource management is one instrument for stabilizing the man-environment relation, it is important to ask how limiting water is to the Western (or Arizona) economy. On the basis of economic efficiency criteria, Young (1969) answers the question negatively, that is, water is not a limiting factor. This does not necessarily get at the question of distributional equity and growth. The former is a question of social goals and the systems analyst's role is to find the cost and worth of each feasible alternative to reach that goal as exemplified in the book by Davis (1968). The latter requires many assumptions about the future (see Davis for a quantitative approach to these uncertainties). Migration into aridlands (Mann, 1966; Smith, 1966; Richardson, 1966; Aschman, 1966) is a positive feedback element imposed onto existing resource systems. It generates further economic growth, more water competition with irrigated agriculture, and political pressures for large interbasin transfers (Howe, 1968). Requests for ste [illegible] appropriations for construction of the Central Arizona Project are presently justified, in part, on the basis of a crisis that the absence of CAP water would generate in agriculture (Tucson Daily Citizen, 1969). This project, among others, is caught in the dimly perceived and ominous shifts on the horizon in public opinion and governmental policy with respect to aridland agriculture (Thorne, 1966). Thorne (1966) foresees "little doubt that traditional allocation procedures will be changed to facilitate easier transitions in water and land use as justified by economic and social goals (and) that these transitions will result in reduced water and land resources for agriculture." These trends toward relative avoidance of consumptive use of water suggest a period of relative crisis or stress on the economy of certain Western aridlands, similar to the one experienced during the Northeast drought (Richardson, 1966). However, Richardson (1966) states that avoidances of consumption "does not promote growth and is not typical of dynamic growth of modern civilization or of aridlands flora and fauna." To save water for future use raises questions about the present or temporal worth of water in space-time, a problem formally considered in engineering economics and operations research and in the context of groundwater management by Burt (1967), using dynamic programming and the calculus of variations. These tools are part and parcel of the overall methodology imbedded in the general systems model (Kisiel and Duckstein, 1968; Duckstein and Kisiel, 1968). Such a formalism for goal-seeking systems embodies important phenomena in complex physical, biological and social systems, such as aridlands, as given by Milsum (1968): (a) growth and positive feedback, including tendencies toward steady-state or zero growth rate, (b) oscillations in the weather, forests, and human values, (c) psychological and man-machine-nature interactions, (d) minimal principles, and (e) extreme value statistics. The emphasis on the importance of extremes is in response to dissatisfaction with the economist's use of mean values in his projections for regional patterns, with the earlier-mentioned importance of detailed operations studies of groundwater and surface water systems to the planning process, and with the history of the failure to consider extremes of Colorado River flows (National Academy of Sciences, 1968). The overall direction of this study in the long-run is in the spirit outlined by Smith (1966): "(to) analyze the environmental intensities (so as) to make them more explicit for decision . . . (and to establish) the link . . . with a process and organizational structure for decision." Recent steps in this direction include a more formal economic analysis (other than cost-benefit analysis) of water problems by Duckstein (1968) in a study for the World Health Organization, and a hydrologic appraisal of Arizona's legal code for control of groundwater by Reetz (1969). All of this is in the spirit of the comprehensive report on the alternatives for water management in the Colorado Basin (National Academy of Sciences, 1968).

EFFICIENCY OF DATA COLLECTION SYSTEMS

In a complementary, but more encompassing, research project, supported by the Office of Water Resources Research, U.S. Department of the Interior, the efficiency of data collection systems for prediction and control is under study. In many ways it is an operations research study of needs in water resources research and of existing data collection systems in the Tucson area and its surrounding environment. The methodology evolved in this study is intended for application in other geographic and climatic areas. The focus is on worth and information content of hydrologic and water resources data for a variety of design and managerial objectives. Implied is an evaluation of the growth of errors in space-time models of hydrologic systems and their subsequent effect on solutions of management models of basin-wide policy and operation of water resource systems. In addition to the uncertainties about the physical system (nature) and goodness of mathematical models of the physics, of concern are the uncertainties in our knowledge of the following:

a. Objective functions: their proper form and uncertainties in unit costs and independence of variables

b. Constraint functions

c. Demand functions for water in the agricultural, industrial, and municipal sectors

d. Social response to substantial changes in current water pricing policies

e. Social response to various schemes of cost allocation and sharing between the agricultural, industrial, and municipal sectors (pump tax, water conservancy districts with taxing powers, and others)

f. Secondary and tertiary benefits (and costs) associated with water use in each of the above sectors (input-output analyses)

g. Temporal constancy of the above factors

h. Quantitative forecasting of technological change, population, water demand, and economic growth over the next 5-50 years.

Our conception of the problem being attacked is best illustrated, as in Figure 1, by means of a cycle of steps that enter into any effort at solution of water resource problems. Two basic reasons exist for data collection: to understand and to manage more effectively our social and physical environment. With this in mind our research effort starts with a consideration of worth of data in terms of economic efficiency and information content; it then proceeds to a consideration of worth in terms of use of data to construct mathematical models of the physical system and water management schemes.

Worth of data can only be judged in relation to a particular use to meet a social or managerial objective. There is no absolute worth. We cannot anticipate all future use to which data might be put. In recalling the multi-level structure of decision-making, one can envision the need for more detailed data as one moves from the realm of decisions on social goals and regional policy to detailed design. However, this is not to imply that in all instances less data is required at the highest levels of decisions. A recent study by the National Academy of Sciences (1968) raises such questions about the goodness of the data and data analysis techniques used to analyze Colorado River flows and, in turn to decide on water allocation among the basin states in the 1920's.

Worth may be judged in terms of economic efficiency of the data collection system for decision-making. For example, if the managerial objective is to evaluate alternative strategies for natural recharge, questions arise as to the worth of additional data on movement of water through unsaturated porous media, on actual natural recharge along the natural channels in the basin, on the properties of porous channels, on precipitation at presently ungaged points, on chemical and biological quality of urban runoff, and on surface runoff at various points in the urban area and river channels. Thus, does one year of additional streamflow data in the urban area improve incrementally the prediction of the amount of urban water available for recharge and prediction of the timing of flow (hydrograph) as it affects diversion, recharge, or detention structures? Does it improve our ability to predict variability of flow volumes and other hydrologic (including chemical) variables as these influence the evaluation of management alternatives for capturing surface waters in an urban area? In economic terms, does investment of one additional dollar improve the mathematical model for prediction of the physical variable in question and in turn improve benefits accruing to management schemes based on that data? Ideally we seek to equate the marginal cost of data acquisition and analysis with the marginal benefit accruing to the data. However, the measurement of such costs is so much easier than the measurement of benefits. Proxies may have to be found for the latter. To invoke the formalism of information theory in relation to information-content of data is to strengthen the studies of economic efficiency of hydrologic and water resource data collection systems.

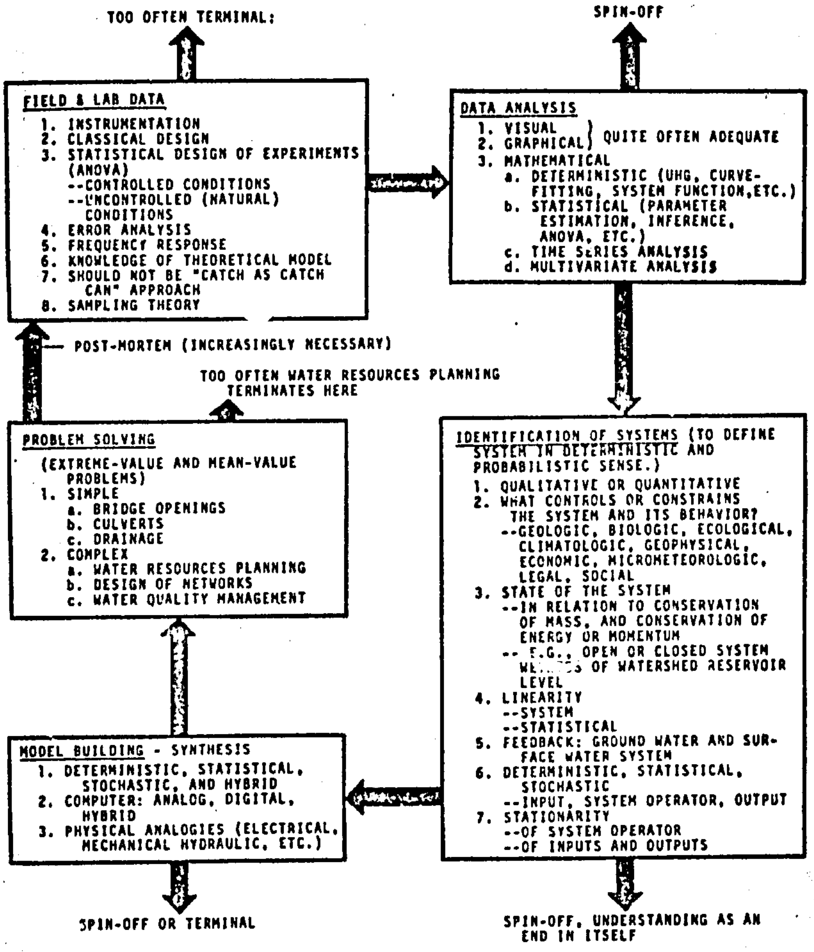

FIGURE 1. Cycle of model building.

In information-theoretic terms, we ask: does the variance of hydrologic variables and model parameters remain stable or does it change substantially as a result of the additional increment of data? If the former, then the information-content has been maximized and there is no need for further data collection if steady-state conditions exist into the foreseeable future; if the latter, new information is being generated, the phenomena are non-stationary in both space and time, and evaluation of the management alternatives is enormously complicated. Because only now are we beginning to acquire data on rainfall, runoff, and water quality in urban areas (American Society of Civil Engineers, 1968) it would be several years before one could evaluate the worth of the data in an empirical sense. However, computer simulation of hydrologic inputs and models of surface water and groundwater systems permits both a systematic study of worth of existing data and computer experimentation with a variety of models of the input and of the subsystems (Kisiel and Duckstein, 1968; Duckstein and Kisiel, 1968). In fact, because of the difficulties in unravelling the sources of error in a real-world context, computer experimentation on simulated physical models may be the only route presently available for seeking an objective evaluation of data worth. This is one of the uses to which the digital computer models of an aquifer and surface water system (including urban runoff) would be put.

CONCLUSIONS OF PART I

A framework for an operations research study of water resources problems in and near western cities has been given. Preliminary results for the Tucson basin, which has been used as a laboratory throughout this series of studies, will be given in Part II in a subsequent paper.

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