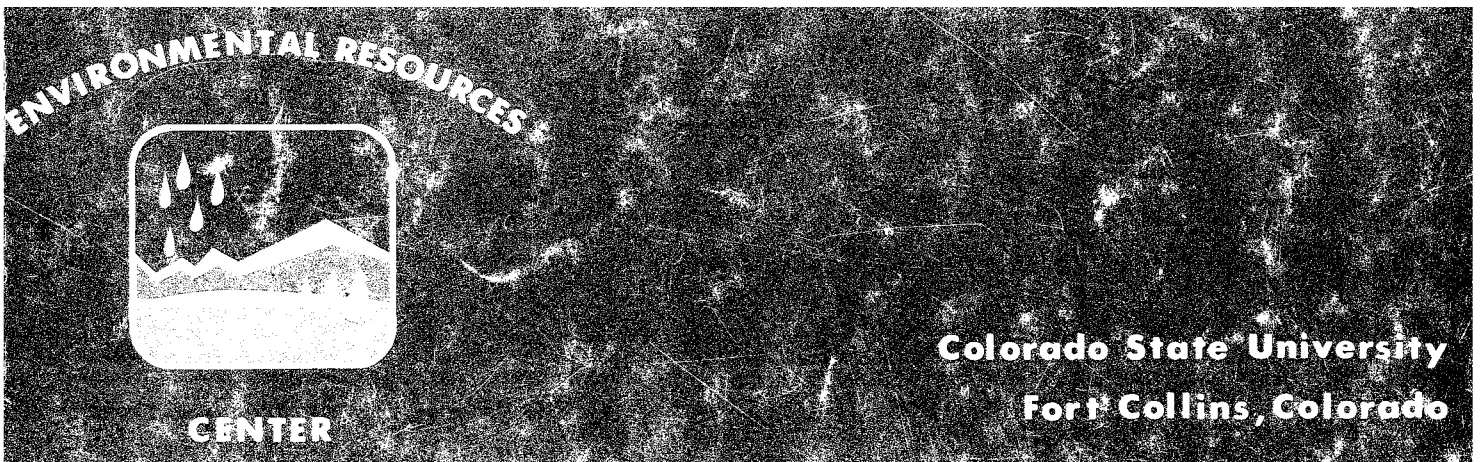


**INSTITUTIONAL REQUIREMENTS
FOR OPTIMAL WATER QUALITY
MANAGEMENT IN ARID URBAN AREAS**

by

**Wynn R. Walker, Gaylord V. Skogerboe,
Robert C. Ward, and
Thomas L. Huntzinger**

June 1973



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INSTITUTIONAL REQUIREMENTS FOR OPTIMAL
WATER QUALITY MANAGEMENT
IN ARID URBAN AREAS

Summary Completion Report
OWRR Project No. B-071-COLO

by

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ABSTRACT

INSTITUTIONAL REQUIREMENTS FOR OPTIMAL WATER QUALITY MANAGEMENT IN ARID URBAN AREAS

Water management strategies in arid urbanizing regions require careful evaluation of alternatives for supplying future demands and controlling water quality. Mathematical models were developed which describe the interrelationships among various institutional factors in order to delineate the requirements for implementing optimal policies. The first of two study areas selected to test the utility of the models is Denver, Colorado. This area is an excellent example of an area where the conditions of water scarcity and increasingly stringent water quality standards are critical. The Utah Lake drainage area in central Utah is the second region considered. In this region, water quality management is necessary to insure the continued use of water in the downstream population center of the state. Together these models produce results useful in determining the optimal strategies for water management in arid urbanizing areas. A generalized summary is presented to integrate these findings into a West-wide evaluation of this problem.

Walker, Wynn R., Skogerboe, Gaylord V., Ward, Robert C., and Huntzinger, Thomas L. INSTITUTIONAL REQUIREMENTS FOR OPTIMAL WATER QUALITY MANAGEMENT IN ARID URBAN AREAS. Technical Completion Report to the Office of Water Resources Research, U.S. Department of the Interior. Report AER72-73WRW-GVS-RCW-TLH28, Environmental Resources Center, Colorado State University, Fort Collins, Colorado. June 1973.

KEYWORDS - agricultural wastes, institutional constraints, mathematical models, optimization, systems analysis, urbanization, wastewater treatment, water management (applied), water quality, water supply.

PREFACE

This is a generalized summary of three reports developed as completion reports for the research project, "Institutional Arrangements for Optimal Water Quality Management in Arid Urban Areas." The purpose of the study was to develop procedures which quantify the effects of institutional constraints on water management in arid urban areas. The results of the project are of particular interest due to recent projections that many urban areas in the West will have exhausted their raw water supplies in the next few decades. Currently, these arid areas are looking at available alternatives for meeting future water demands.

The original project proposal delineated that a model of an arid urban area would be developed and then applied to the Denver metropolitan area and the Utah Lake drainage area in central Utah. Due to the length of the material developed for each portion of the study, and the fact that readers interested in the Denver area may not be interested in Utah Lake, or vice versa, the final completion report for the project was divided into three separate reports. The reports are referenced as follows:

Walker, Wynn R., and Skogerboe, Gaylord V. MATHEMATICAL MODELING OF WATER MANAGEMENT STRATEGIES IN URBANIZING RIVER BASINS. Technical Completion Report to the Office of Water Resources Research, U.S. Department of the Interior. Report AER72-73WRW-GVS25, Environmental Resources Center, Colorado State University, Fort Collins, Colorado. June 1973.

Walker, Wynn R., Ward, Robert C., and Skogerboe, Gaylord V. EVALUATION OF URBAN WATER MANAGEMENT

POLICIES IN THE DENVER METROPOLITAN AREA. Technical Completion Report to the Office of Water Resources Research, U.S. Department of the Interior. Report AER72-73WRW-RCW-GVS26, Environmental Resources Center, Colorado State University, Fort Collins, Colorado. June 1973.

Walker, Wynn R., Huntzinger, Thomas L., and Skogerboe, Gaylord V. COORDINATION OF AGRICULTURAL AND URBAN WATER QUALITY MANAGEMENT IN THE UTAH LAKE DRAINAGE AREA. Technical Completion Report to the Office of Water Resources Research, U.S. Department of the Interior. Report AER72-73WRW-TLH-GVS27, Environmental Resources Center, Colorado State University, Fort Collins, Colorado. June 1973.

This summary report presents a brief review of each report, which is then followed by a discussion of the general findings of the total project as they relate to the key issues facing water management in arid urban areas.

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SECTION I

INTRODUCTION

Due to the increased production in the agricultural sector of the United States in the past seventy years, there has been a basic shift from rural to urban living. Regional urbanization has been accompanied by new problems in administering natural resources such as water. For example, the demands for water of suitable quality have greatly affected the usefulness of water supplies in several areas. As a result, new sources have been actively sought and the feasibility of employing technological advances to amend marginal supplies has been investigated.

In addition, the intensity of water uses in conjunction with growing demands have created serious water quality degradation. These problems are difficult to remedy because the institutional mechanisms developed to allocate and manage the water resource have not been altered sufficiently to effectively meet the requirements of rapid urbanization.

Objectives

The purpose of this study is to investigate the feasibility of alternative water management strategies which could be implemented to alleviate the mounting problems of water shortage and water quality deterioration.

More specifically, the objectives as originally stated in the project proposal are:

1. To develop more effective programs for achieving water quality goals in areas which are rapidly changing from rural to urban in character, and which are faced with critical water shortage problems as well as serious water quality problems.
2. To determine the extent to which present institutions would prevent implementation of these programs.
3. To identify needed changes in water quality and water quantity management institutions, policies and practices.
4. To develop model programs for management of water quality in water short urban areas.

Scope

Administering water resource utilization in rapidly urbanizing areas encompasses numerous individual aspects of significant importance. Two of these have been selected for this study:

1. Coordination of the supply, distribution, and treatment of water in the metropolitan setting;
and
2. Regional integration of agricultural and urban water pollution control.

Since the first topic is an important subproblem of the second, consideration of these two problems allowed this study to evaluate the specific institutional requirements for optimizing water management decisions in urbanizing areas. Two regions where the conditions are particularly suitable to the objectives of this study are the Denver, Colorado metropolitan area and the Utah Lake Drainage area in central Utah.

The Denver, Colorado, area is a water-short, rapidly expanding urban center facing rigid water quality controls. Water supplies for the area are primarily obtained from sources in both the headwaters of the South Platte River Basin and the headwaters of the nearby Colorado River Basin. It appears reasonable to conclude from previous developments, that diverting more water resources from these watersheds to supply the expanding needs will induce extensive legal, social, and political controversy. A need therefore exists to evaluate the feasibility of alternative management strategies in this area and determine the nature and expense of the institutional constraints which may hinder implementation of more effective policies.

The Utah Lake Drainage area does not face serious water supply problems, but it does contribute significantly to a critical water quality problem in its downstream reaches. This region is the headwaters of the Jordan River, and is a major water source for more than half of

Utah's population located along an area known as the "Wasatch Front." The water demands along the Wasatch Front are comprised mainly of municipal and industrial uses, which require not only a sufficient supply but an acceptable quality as well. Efforts to minimize water pollution must therefore be regional in scope, which necessitates examination of practices and potential treatments in the Utah Lake drainage area. This study is thus concerned with the levels of water quality control achievable in the area and the optimal policies to accomplish such control.

In order to present the results of this study, four reports have been prepared. The first report presented the modeling procedures used in the study, while the second and third reports presented the results of applying the models to the Denver and Utah Lake areas, respectively. This report, the fourth, is a summary of the first three and a discussion of the major overall findings of the study.

SECTION II

SUMMARY

Modeling Procedures and Results

The comparison of alternative strategies for water management implicitly assumes some basis exists for comparison and, therefore, for rating one alternative better than another. Optimization, a term often used with mathematical models, would imply that the model can determine which alternative is the best based upon the chosen criterion.

Probably the most commonly used and widely accepted basis for comparing water management alternatives is one of the economic indicators. Among the more adaptable economic indicators are maximization of net benefits, minimum costs, maintaining the economy, and economic development. The use of each depends on the ability to adequately define tangible and intangible direct or indirect costs and benefits. In water resource development and water quality management specifically, the economic incentives for more efficient resource utilization are negative in nature. A large part of this problem stems from the fact that water pollution is a cost passed on by the polluter to the downstream user. Consequently, the inability of the existing economic systems to adequately value costs and benefits has resulted in the establishment

of water quality standards, however inefficient these may be economically. The immediate objective, therefore, of water resource planners and engineers is to devise and analyze the alternatives for achieving these quality restrictions at minimum cost. Thus, minimum cost is the criterion chosen for this study.

The search for an optimizing technique to evaluate the relative merits of an array of alternatives depends largely upon the form of the problem and its constraints. Each optimization scheme has its unique properties making it adaptable to specific problems, although many techniques when sufficiently understood can be modified to extend their applicability. Successful modifications of this nature are prevalent in current engineering practice, but some experience is required in using these methods.

Most conditions encountered in the field of water resources, urban water systems specifically, involve mathematical formulations which are non-linear in both the objective function and the constraints. Furthermore, the constraining functions may be mixtures of linear and non-linear equalities and inequalities. Without simplifying these problems or radically changing existing optimization techniques, it is possible to derive solutions based upon the "differential approach."

Most techniques for selecting the optimal policy do so by successively improving a previous estimate until no betterment is possible. These may be classified as direct

or indirect methods depending on whether they start at a feasible point and stepwise move toward the optimum or solve a set of equations which contain the optimum as a root. In a majority of cases, the differential approach can be used to describe the method. Thus, it is possible to understand a wide variety of procedures by knowing one basic mathematical approach.

Numerous applications of one form or another of the basic differential approach have been made in the field of engineering. Because of difficulties in programming "generality," nearly all of these applications have been somewhat specialized toward the specific geometry of the problem. The nature of this study necessitated two entirely different optimization analyses. Consequently, to avoid developing two models, it was decided to attempt the programming of a general differential algorithm.

The optimizing technique developed for this study is called the "Jacobian Differential Algorithm." Theoretically, it is a generalized eliminating procedure which is computationally feasible under a wide variety of conditions. As in all direct minimizing procedures, the algorithm involves four steps:

1. Evaluate a first feasible solution satisfying the physical realities of the modeled system;
2. Determine the direction in which to adjust the previous estimate so that a closer approximation of the optimal is achieved;

3. Find the distance that can be moved without violating any of the problem constraints; and
4. Stop when the optimum is reached.

Urban Water System Model

A model of the quantity and quality aspects of an urban water network would incorporate three basic components. These are: (1) water sources (including recycled water); (2) the internal water uses; and (3) the wastewater treatment facilities. When these parts are integrated, a model such as the one illustrated schematically in Figure 1 can be derived. Each of the basic segments of the model is comprised of a complex set of physical, economic, social, and political subsystems. However, the detail in which a general urban model can examine these basic components cannot include a thorough examination and analysis of each respective subsystem without becoming completely entangled in their complexities. Therefore, each of the general parts of the system are examined in somewhat macroscopic detail relying upon future research or technological development to improve the models' interpretation regarding the behavior of these subsystems.

The scope of such a model as outlined here can either be one of investigating the policies best serving increases in supply, distribution, and treatment requirements, or modeling the system from a total demand viewpoint. Since the feasibility of developing short-life interim projects

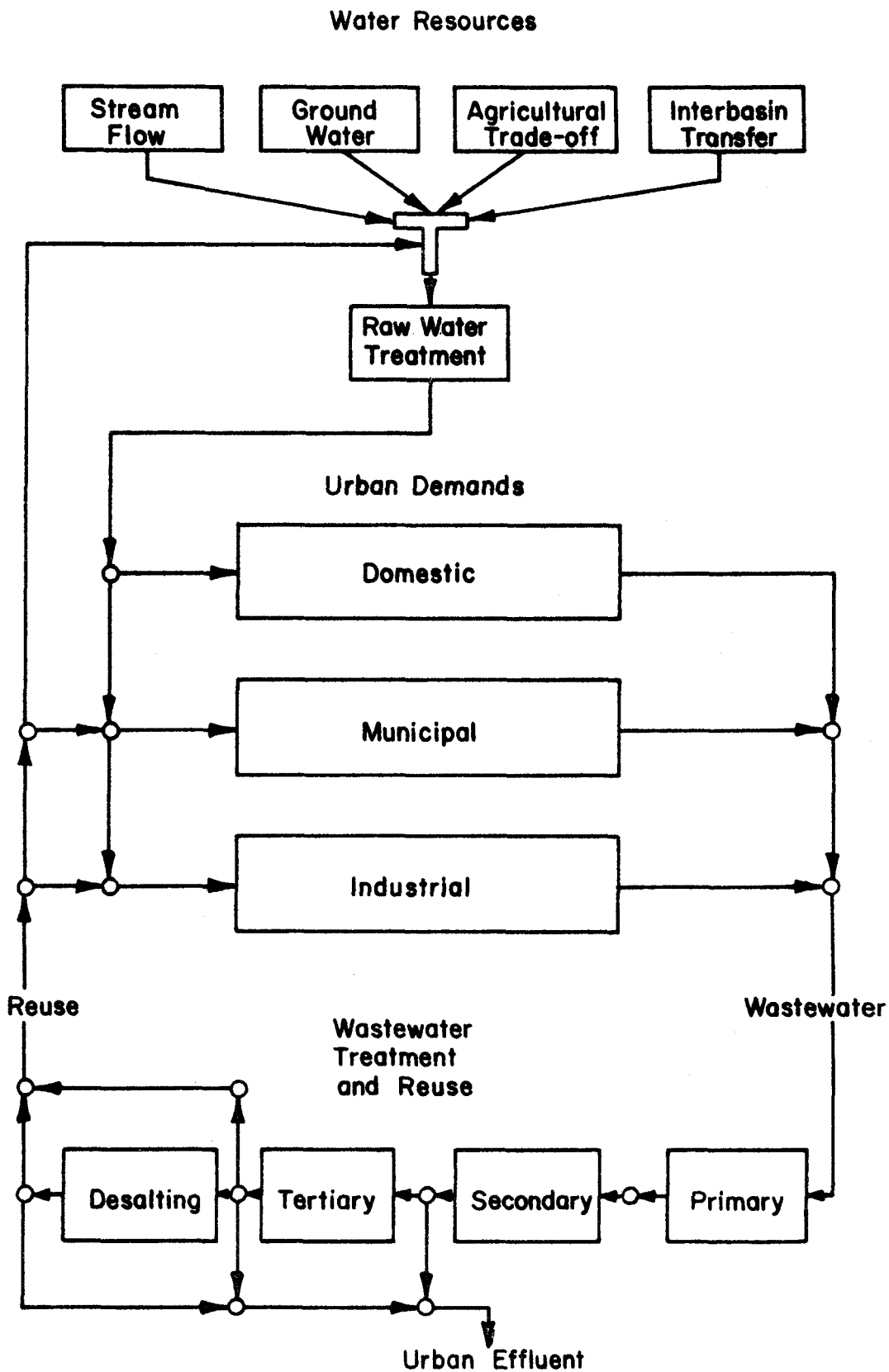


Figure 1. Urban water system model.

while the demands expand sufficiently to justify development of large scale and long-life projects has been demonstrated, it is the total demand context that will be investigated herein.

Briefly reviewing each of the three major parts of the model, it is noted that among the prospective sources of water are interbasin diversions, recycling, in-basin acquisition of other rights, appropriated stream flow, and groundwater developments. These respective sources are individually characterized by their utility in the urban system.

Urban water uses are generally grouped as domestic, municipal, or industrial demands. The domestic water serves such uses as the myriad of household uses. Municipal supplies include fire protection, park irrigations, and certain recreational uses to mention a few. The water consumption in the industrial sector for the purpose of this study is limited to the demands upon the urban system and does not include the water which may be reused within the plant.

Wastewater treatment for either meeting the stream quality standards or for recycling is the most complex aspect of the urban water system. In this effort, it has been broken down into a primary, secondary, tertiary, and desalting treatment and reclamation system.

The model was operated by assuming that costs of the water supplies are linear, thus making the decisions in the

model primarily functions of the effluent standards imposed upon the wastewater. Therefore, the relative feasibility of recycling water becomes the basic variable in the model. For example, if demands are met with recycled water, less water comes into the system via interbasin transfers, etc. To a large extent, the effluent standards control the feasibility of recycling.

Coordinating Agricultural-Urban Water Quality Management

The modeling of water quality management alternatives in a drainage area in order to insure continued use of the resource elsewhere, is different than strictly urban modeling. This type of condition exists in the Utah Lake area, thereby necessitating the development of an agricultural model to go with portions of the urban model. Water quality management programs must consider which combinations of agricultural and urban treatments are most efficient when both uses exist in the drainage basin that supplies another larger urban area--Salt Lake City in this case.

The urban wastewater treatment segment of this model is equivalent to the model derived for the Denver analysis. The conceptual integration of the urban model with the agricultural model is shown in Figure 2. Such a model assumes that diversions to the sectors are independent in nature and thus does not allow for the subsequent use of effluents by another use. This type of operation is

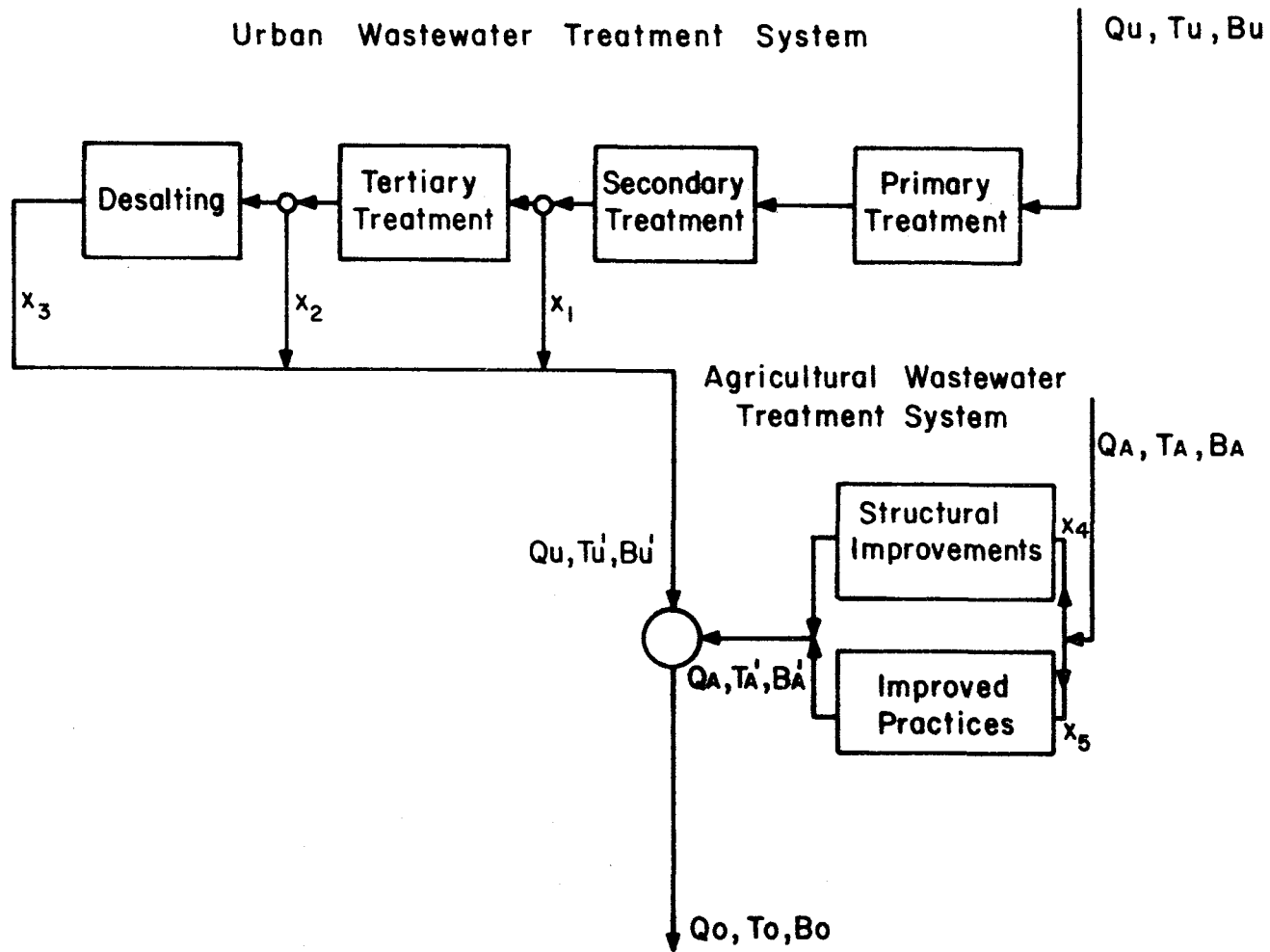


Figure 2. Utah Lake district model.

prevalent in the Utah Lake study area, but can be modified easily to represent the more general situation.

The agricultural segment of the model is divided into two treatments for reducing TDS concentration (the most important parameter in agricultural wastewater) in the return flows: (1) improving the water use practices in the districts; and (2) rehabilitating the structural elements of the system.

Briefly, the agricultural model is based upon concepts of dynamic programming. The Utah Lake area, due to physical characteristics, necessitated dividing the basin into four districts. A specific dynamic programming model was developed for each district and then a coordinated solution was obtained using the multi-level optimization philosophy.

Basin-wide Water Quality Management

In order to satisfy the water quality requirements of the uses below the Utah Lake drainage area, the flows in the Jordan River would necessarily be subjected to a maximum concentration of total dissolved solids (TDS). To meet such a constraint optimally would require the distribution of water quality standards throughout the basin on each individual segment of the water use system. In addition to the alternatives of coordinating agricultural and urban water pollution control in the urbanizing regions surrounding Utah Lake, two other important measures are

being considered; namely, lake diking and desalting. The task of this model was therefore to determine the optimal basin-wide strategy for amending the outflows from the Utah Lake drainage area sufficiently to allow for more effective utilization of such flows downstream. When the three alternatives are integrated into a management level model, such as that shown schematically in Figure 3, questions concerning important water quality management decisions can be resolved.

Denver Analysis and Results

The application of the urban model to the Denver area and the subsequent results are summarized briefly in this section. The analysis integrated the management level characteristics of water supply, distribution, and wastewater treatment present in Denver. Current sources of water for Denver come from interbasin transfers and direct diversions from the South Platte River. In the future, however, the alternative of recycling the unused portions of the interbasin transfers and acquisition of agricultural water rights deserve careful attention. Linear costs amounting to 1¢/1000 gal for South Platte supplies and 10¢/1000 gal for the interbasin transfers from the Colorado River Basin were determined from planning reports and other similar studies. Then, these costs were compared with the costs of recycled water to determine the optimal combination of supplies which meet the urban demands.

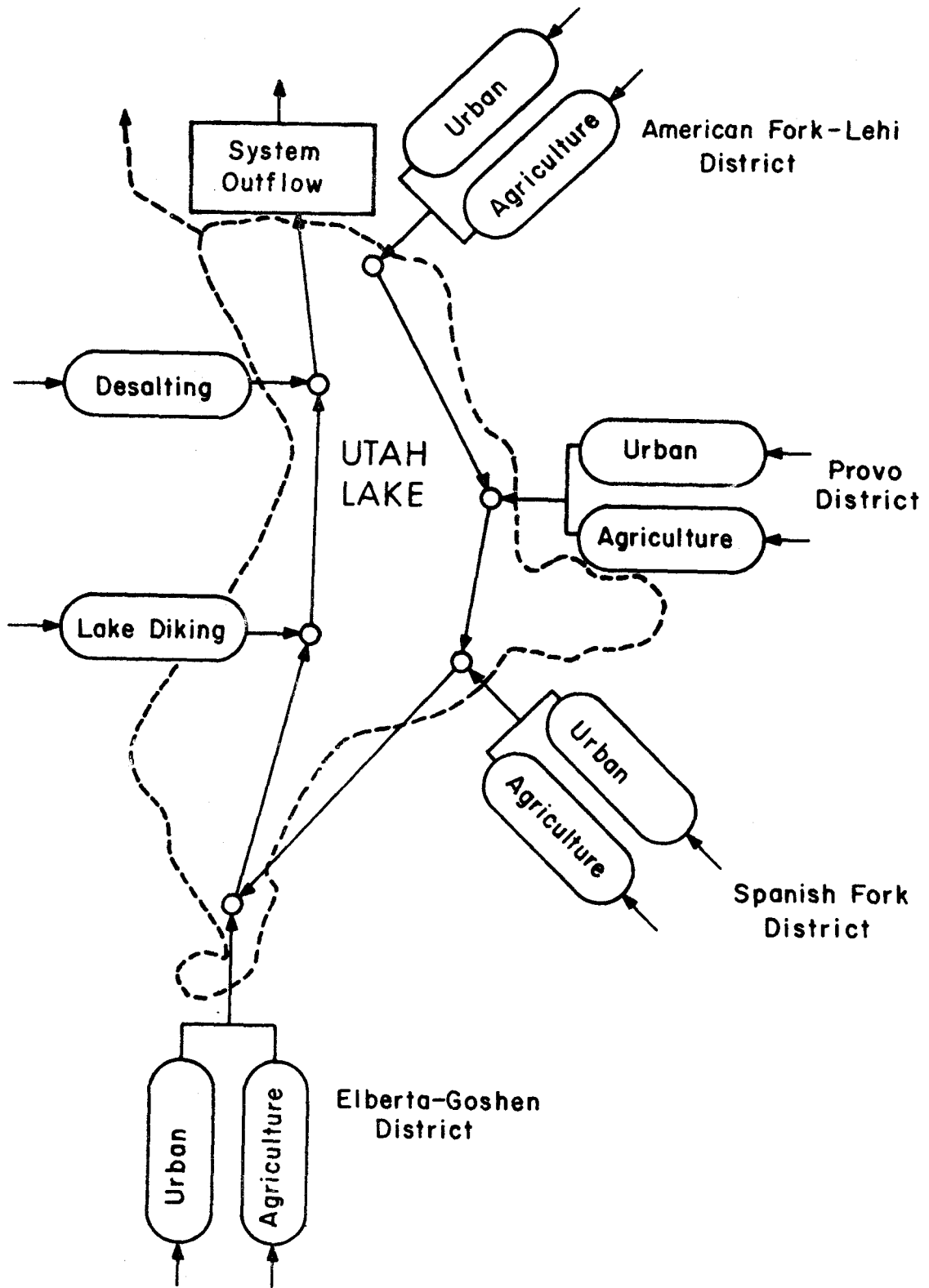


Figure 3. Utah Lake drainage area water quality management model.

In order to test the strategies involved with distributing water to the urban demands, three distribution alternatives were defined. The first alternative represented the case in which recycling would take place through existing raw water treatment facilities. Second, recycling to individual municipal and industrial demands was allowed, but restricted to an aggregate TDS concentration of 300 mg/l, the value for the domestic supplies. And finally, an alternative was outlined in which recycling was allowed directly to the municipal and industrial demands but at the relaxed TDS standards of 800 mg/l and 500 mg/l, respectively. These three alternatives were delineated to evaluate the effects of public attitudes and the costs of modifying the distribution system to allow for efficient allocation of water within the urban area.

The most important aspect of this modeling effort is the coordination of the wastewater treatment system with the water supply and distribution system through the vehicle of reuse. Various water quality standards were shown to substantially affect the costs of the recycled flows, and thus to significantly influence the broad water management strategies.

Optimal water management strategies were generated for a wide range of model inputs for each distribution alternative. From these results, three primary policies evolved which were compared to determine both the characteristics of the system and the effects of institutional

factors involved with its operation. Initially, the costs associated with reclaiming and recycling wastewater were prohibitive and this supply alternative was not used. However, as the water quality standards on the urban effluents became more stringent, the economies of scale in the wastewater treatment facilities reduced the unit costs of the recycled water until it was feasible to use poor quality recycling. As the effluent standards forced implementation of more refined methods for pollutant removal, the costs of recycling eventually became feasible at any quality in the range of values examined, and it therefore became a part of the water supply and distribution policy.

Total system costs, as well as water supply costs, were determined for each distribution alternative over a range of effluent quality standards. These costs were then compared to determine the effects of various constraints and modes of operation. Since these results were generated for present conditions, the procedures were repeated for expected 1990 and 2010 conditions, and presented as multipliers of present costs to illustrate the effects of the model parameters in the future.

The major conclusions drawn from this work can be organized into three topics. First, the characteristics of optimal water management policies in Denver can be examined to better understand the basic nature of the strategies. Second, the array of institutional factors

involved in administering water resources in the urban setting indicate the policies which can be implemented. And third, the conditions which can be expected in the future suggest the direction which should be taken to achieve effective water management.

System Characteristics

Because of the linear cost assumptions for both stream flows and interbasin transfers, the strategies in the urban water system model as it is applied to Denver are primarily ones indicating the trade-off between recycling and importations. The factors which affect the economic feasibility of reuse (effluent water quality standards) therefore act as prime variables in the integrated urban system. The annual water supply costs indicate that as BOD and TDS constraints on the urban effluents are reduced to 5 mg/l and 500 mg/l, respectively, the implementation of recycling to individual urban demands will annually save the users between \$3 and \$5 million, a savings of about 10-20%. This savings, amounting to about 4-6¢/1000 gal, is somewhat misleading, however, as the total system costs (water supply plus wastewater treatment) actually increase by \$4 - \$5 million annually. Consequently, as water quality standards are imposed to force wastewater treatment to remove more and more of the pollutants, the money which must be spent will be substantial. In addition, if coordination of water supply and wastewater

treatment is not facilitated, the total system costs can be expected to increase about \$7 million annually.

There are certain characteristics of the urban water system which must be considered as part of any policy towards recycling. For example, if reuse is introduced as a source of water, it will be characterized by TDS concentrations more than twice the same levels in interbasin transfers or streamflows. The net result will be that overall water quality to the urban demands will be deteriorated to the permissible limits. These effects are certainly to be reflected in the outflows from the urban area. An assumption was made that these effects would be proportional, and the results indicated that TDS concentrations could be expected to increase in the outflows between 50 and 250 mg/l depending on the respective distribution alternative. However, the nature of these increases was not examined and may be of interest in further studies, since downstream interests would resist degradation in their water supplies.

Evaluation of Institutional Factors

The complex economic, legal, political, and social structures formulated to accomplish equitable allocation of water resources need periodic evaluation to insure that improvements are being made which result in more effective water use.

Public attitudes towards water management alternatives are undoubtedly the most important factors affecting future policies and must therefore be evaluated. Occasionally, public decisions are made which are detrimental to themselves under long range considerations. As a result, it is important that these decisions be made with full knowledge of the alternatives. One of the principal decisions to be made concerns the question of recycling. If the system conditions change to the point where recycling is indicated, the savings realized by recycling will be substantial as noted previously. However, the methods employed to accomplish recycling are also of importance. For example, if recycling is undertaken in accordance with the first alternative rather than the last, it will cost about \$2 million more annually. These effects amount to about 5-10% of total water system costs in most cases, but have far more important implications.

Water is becoming a scarce resource not only because the supply is diminished through increased depletions, but also because the quality is being degraded to the extent that the more sensitive uses are unable to use these flows. A need therefore exists to consider setting priorities based on the sensitivity of various water uses to water quality. In the urban environment, this can be accomplished by supplying industrial and municipal demands with poorer quality water, while using the best water for domestic uses. Such a policy will reduce rates if implemented,

especially to the municipal and industrial users, which may realize as much as a 5-10¢/1000 gal reduction.

Another institutional factor considered was the value of agricultural water to the urban user. Transfers have not been widely attempted to date, but may be necessary in the future. By allowing higher levels of reuse than are currently permissible, an indication of this value is gained. The results of this study indicate that this water is worth about 60-70\$/ac-ft to the urban system, but only 40-50\$/ac-ft to the water supply agencies. This source of water exhibits decreasing marginal value with scale, so large transfers are not desirable. It should be noted, however, that these values do not suggest unlimited transfer from agricultural to urban use, but rather the price the urban user can pay to acquire such rights.

Finally, the costs of constructing and then operating and maintaining the facilities inherent in urban water systems are very substantial expenditures in the budgets of metropolitan areas. These systems generally exhibit some economy of scale, which suggests that water management be consolidated to the extent possible. In addition, close coordination should be maintained between the individual sectors of the system to realize the benefits of recycling.

Future Policies

Although the events of the future remain unknown, plans must nevertheless be formulated to insure the ability of the urban system to satisfy its water demands. Denver

has rapidly expanded in recent years and this growth is expected to continue in the future. As a result, the question of future water supply and sewerage are important.

Federal water pollution control policies are certain to require greater pollutant removal efficiencies in the future, so recycling must be considered as the prime water source for the future. Results of this study were projected into expected conditions for the years 1990 and 2010 and suggest little change in the strategies outlined for the immediate future. However, new advances in technology and the probability of population control in metropolitan areas cannot be included in such predictions. Thus, a need exists to repeatedly review the situation.

Utah Lake Analysis and Results

The Utah Lake drainage area is the headwaters of the Jordan River system encompassing the Salt Lake City metropolitan area, where most of Utah's municipal and industrial water demands are located. Owing to the sensitivity of these demands to water quality, implementation of effective water management policies is essential for continued expansion. The high mountainous regions of the Utah Lake drainage area, along with interbasin transfers from the adjoining Colorado River Basin, produce large quantities of good quality water for needs in the immediate area, as well as the Salt Lake City metropolitan area. However, the urban and agricultural water uses in the Utah Valley area,

along with the evaporative depletion of Utah Lake degrades the quality of the area outflows so as to be unsuitable for urban water supplies. Thus, in order to protect downstream users while continued development occurs in the Utah Lake drainage area, and to in fact improve the qualities of the outflows for the more sensitive urban uses in the Salt Lake City area, water quality controls will be imposed in the Utah Lake region. Of critical importance is the strategies with which such controls are implemented. In addition, the effect of institutional constraints must be reconciled with optimal policies in order to best achieve the goals of the water quality control measures. This study was initiated to resolve some of these significant questions. To do so, an extensive hydrologic and water quality inventory was conducted to define the flow systems in the area. Then, these results were incorporated into water quality management models whereby optimal policies could be evaluated.

Hydrologic Analysis

Previous to this study, a number of detailed evaluations regarding water flow systems in various segments of the Utah Lake drainage area were conducted. The results of these studies were collected and analyzed. Then, a comprehensive budgeting procedure was undertaken to coordinate the segmental results of these previous studies into a complete quantification of the water flow network for the

drainage area. Once this effort had been accomplished, water quality parameters consisting mainly of total dissolved solids (TDS) and biochemical oxygen demand (BOD) were added to the flows.

The hydrologic budgeting analysis was extended from the 1960 historical condition to 1980, 2000, 2020 projected conditions. In addition, the expected improvements in water use efficiencies and the development of the Bureau of Reclamation's Central Utah Project were incorporated into the models. These results indicate substantial urbanization occurring in the Utah Valley area surrounding Utah Lake. This region (Utah Valley) was divided into four principal districts (American Fork-Lehi, Provo, Spanish Fork, and Elberta-Goshen) in which the policies for water quality management were evaluated.

As a final determination, an exhaustive operation study on Utah Lake was undertaken to examine the alternative salinity control measures of evaporation reduction by diking or implementation of regional desalination to improve the water quality in the Utah Lake effluents.

Modeling Water Quality Management Policies

A four level water quality management model was formulated which was used to select the optimal water quality control measures for achieving a specified water quality standard on the area outflows. TDS was selected as the quality parameter in the model since salinity is the most

pressing basin-wide problem. However, the growing demand for recreational water uses was included in the modeling by considering BOD removal in urban effluents. The first level of the model considers optimal strategies for reducing salinity in urban and agricultural return flows. The urban treatment process involves desalting a portion of the effluents in order to achieve a desired level of TDS in the urban outflows. The agricultural salinity control measures are structural rehabilitation and improving irrigation practices to minimize the quantities of water entering the groundwater basin where salts are picked up from contact with the soils and groundwater aquifers.

In the second level of the model, optimization of combined urban and agricultural water quality management policies is accomplished. This procedure is repeated on each district of Utah Valley in order to reflect individual differences between the agricultural-urban mix in each district. Then, the next level coordinates and optimizes water quality controls among the districts. These results are significant in that they illustrate the effects of local urbanization and the influence of one area's water quality control on others'.

Finally, the model optimizes water quality control on a basin-wide scale by evaluating the best combination of control in the Utah Valley, including lake diking and regional desalination.

Each of these four levels of optimization produce interesting and important results relating to the best strategies for controlling water quality deterioration in regions where urbanization is occurring.

District Water Quality Management

At the district level, water quality management involves the optimal coordination of agricultural and urban treatments. Since BOD is generally not associated with agricultural return flows, district policies are independent of this parameter because the costs are fixed by the BOD standard on the district outflows.

Agricultural salinity control costs exhibit increasing marginal costs with scale since it can be assumed that the more detrimental salinity effects in the area can be treated first. Consequently, initial investments in the agricultural sector are more "cost-effective" than are later expenditures. This is a most significant characteristic because it indicates that agricultural pollution controls should be limited to the areas where substantial results can be achieved. Although this conclusion must be limited to the conditions in the Utah Lake drainage area, it is nevertheless important to note that this basic characteristic may be found in other areas as well.

The removal of salts from urban effluents is principally accomplished by desalting, which is characterized by decreasing marginal costs with scale. Thus, the larger

desalting facilities exhibit greater cost-effectiveness. In addition, since salts can be removed in excess of the urban contribution, a great deal more water quality management flexibility is associated with desalination.

The optimal coordination of agricultural and urban water quality control policies is dependent on the characteristics of the respective cost functions. In addition, the relative magnitudes of the two uses also determines the nature of such optimal policies. However, the basic structures of these strategies are the same. Initial salinity control measures are largely agricultural in nature because of the low expenditures necessary to accomplish significant TDS reductions. As the removal requirements are increased, the marginal costs of the agricultural alternatives surpass those for the urban sector and an abrupt change occurs in which primary emphasis is directed towards desalination. Eventually, both measures are incorporated to achieve water quality standards.

Regional Water Quality Management

After the individual districts have been optimized for any specified effluent standard, the next question is the optimal allocation of pollution control responsibilities among the districts. Solutions to this problem give important direction for setting water quality standards in order to equitably charge polluters. Also, these solutions

clearly illustrate the effects of urbanization upon water management strategies.

The results of optimizing strategies for water quality control among the districts closely follow these results indicated in the previous paragraphs. As the water quality standards on aggregate Utah Valley return flows become increasingly stringent, initial salinity control centers in the agricultural districts; however, the controls gradually shift to treatments of urban district effluents. Consequently, the effect of urbanization is to increasingly stress urban water pollution where cost advantages can be gained by the inherent economies of scale associated with urban wastewater treatment.

These results have implicitly assumed regionalization of urban wastewater treatment facilities. Important institutional constraints need to be resolved so that consolidation can be achieved. Agricultural water quality control on the other hand is assumed to be as disaggregated as possible in order to invest in controls with the maximum cost-effectiveness. As a result, institutional constraints are only minor in nature for the levels of agricultural salinity control which are suggested by this study.

Basin-wide Water Quality Management

In order to satisfy potential demands on the outflows of the Utah Lake drainage area, standards on the flows in the Jordan River would be required. Then, the Utah

Lake area could devise and implement a least cost strategy for meeting the goal. Three basic alternatives would be involved. First, controls could be imposed on the aggregate return flows from Utah Valley. These controls would then be distributed according to the optimal policies generated previously. Since the effect of Utah Lake is to double the TDS concentration of the inflows to the lake because of large evaporation losses, reduction in the evaporative losses by diking segments of the lake would also be considered. Finally, the economies of scale noted previously regarding desalination suggests that desalting some flows and then mixing these with the total outflows would be a realistic water quality management tool.

Optimization of these three alternatives were not surprising in retrospect. Initial controls involved the alternative of lake diking but rapidly shifted to desalination. This typical policy, indicated at all levels of the Utah Lake study, suggests the need for renewed emphasis on physically removing salts rather than attempting to prevent their inclusion in the water resources of Utah Valley.

SECTION III

INSTITUTIONAL FACTORS AFFECTING OPTIMAL WATER MANAGEMENT STRATEGIES

Water management in arid urbanizing areas is approaching a critical stage as traditional sources of water are no longer readily available and deteriorating water quality is reducing the utility of existing supplies. Many of these areas are facing decisions which are radical departures from the traditional role of water resource planning. At this point, it is difficult to clearly conceive the specific nature of these decisions since previous experience is currently deficient. However, because future policies will be implemented to achieve the purposes of water resource development and use under more restrictive constraints, planning must assume a posture of broader perspectives and increased sensitivity. This study has evaluated some of the important alternatives for the Denver, Colorado and Utah Lake drainage areas. From these analyses, specific directions to the planning process have been given and methods for evaluating additional problems have been outlined.

The purposes and scope of this investigation directed that the modeling be macroscopic in nature. Such a format was conducive to regional evaluations rather than the more detailed local determinations. In this manner, important institutional factors affecting the implementation

of more effective water management policies were evaluated. In this section, a brief and general discussion is presented regarding several of the more important institutional factors which affect numerous urbanizing areas in the West.

Modeling Philosophy

The modeling efforts under this study concentrated on water management decision-making in order to provide meaningful insights into the technical, economic, social, and political ramifications of the available alternatives. Continued efforts along this vein will be necessary. In particular, future modeling efforts can be made more fruitful by involving the decision makers, themselves.

Two basic modeling alternatives present themselves. First, the objectives of the modeling can be achieved by the construction of single highly sophisticated models. And second, the integration of several limited purpose models into a sophisticated scheme for solving the problems can be employed. The advantages of the latter are monumental, and have convinced the authors of its desirability. Several of these advantages include:

- (1) Added flexibility and increased generality can be generated when sub-models are limited to the evaluation of a single variable. In addition, the evaluation of the interdependence among such sub-models by a multilevel coordination, for

example, is often more efficient than attempting to program the interrelationships.

- (2) The involvement of the policy makers is significantly enhanced since they can identify with the specific sub-model describing the function of most interest to them and yet avoiding the detail of overall model operations.
- (3) More detail can be incorporated in the limited purpose sub-models than in larger all-inclusive models because of the increased involvement of the policy maker. Consequently, this philosophy can potentially duplicate the physical and social realities to a higher degree.
- (4) Models can be easily adapted to other conditions since restructuring sub-models is more readily facilitated.

Even though these modeling concepts are rational and valid within the assumed constraints, and the complications are minimized, the use of such models may yet remain beyond the expertise or priority for a given planning agency. Many administrators and planners simply do not have the time to devote to such broad-scale analyses. They are more involved with specific project planning or day-to-day brush fire activities. However, with more concern being expressed by the public for broad-scale evaluations of alternatives, these conditions may change, thus permitting more comprehensive evaluations of this nature.

Nevertheless, the decision-makers using the results of modeling efforts should understand the conditions under which they are generated. The results of modeling provide additional information for decision-making with respect to water management, but the results do not make the decision.

Reallocation of Water Resources

Although coordinated efforts at the local, regional, and national levels for effective water management have been repeatedly suggested, only a few realistic attempts have been made to achieve this objective. Yet, as water resources become increasingly scarce, this theme must be reiterated.

One of the severe constraints in implementing more efficient water management programs are the legal structures surrounding water rights. Original division of water resources in the West occurred when irrigated agriculture was the predominant water use. As the more recent urban growth occurred, water supplies were obtained from agricultural right acquisition and transfer, groundwater development, interbasin transfers, and junior in-basin stream flow rights. Thus, a status quo for early water users has resulted, while a somewhat frantic search by later developers has been undertaken. Both circumstances are inefficient from a regional or national viewpoint because the options for resource conservation are reduced significantly.

At the present time, effective mechanisms are lacking by which a reallocation of water can take place in light of the changing priorities placed on water. A commonly encountered example where exchanges would be of benefit is a transfer of water from agricultural to urban use. Many original agricultural decrees were based on about 4 ac-ft/ac; but as time passed, significant portions of initial acreage was converted to roads, ditches, homes, stock yards, etc. without a corresponding reduction in the diversion rights. In other cases, not all of the lands were developed for which a water right had been obtained. Consequently, areas can be found in which the actual water duty may be as high as 12 ac-ft/ac, or higher. If the legal interpretation of water rights allowed a rental, purchase, or lease of this excess water, or if the beneficial use concept were more strictly applied, a much more effective use would be made of the available water resources.

As the federal government becomes more active in water quality management, it is likely that states will be forced to make sure that water is used in the most efficient manner possible. By now developing such procedures, all interests within a state would have a stronger voice in implementing equitable reallocation procedures. If a state waits for federal action, a rapidly developed plan to meet a federal deadline may be less than adequate, or not in the state's best interest.

Combined Management of Water Resources

As water quality standards increase (no pollutant discharge by 1985), the effort devoted to wastewater treatment will become quite large. After devoting a large effort to cleaning wastewater to meet the standards, the small additional treatment necessary to make the water acceptable as an urban water source will enhance the feasibility of recycling. As this occurs, the separation of water supply functions from water distribution and wastewater treatment functions will, in all probability, introduce inefficiencies in the system.

As recycling becomes more feasible, the ways and means of combining supply, distribution and treatment entities (and the form of the combined institution) must be considered by urban areas. The fact that recycling will probably be an evolutionary process will require that the institutions themselves be sufficiently flexible to evolve the necessary mechanisms for achieving the various types and forms of recycling.

Relating this consolidation of supply, distribution, and wastewater treatment to the current situation in urban areas, it is noted that very rarely are all the agencies in supply, for example, consolidated. Or, in many metropolitan areas, numerous sanitary districts are in existence which are responsible for wastewater collection and treatment. This implies that the consolidation of supply,

distribution and treatment may come after consolidation within each segment of the system. Thus, the consolidation process must occur within each segment (horizontal integration), as well as among the segments (vertical integration). Due to the traditional problems associated with agency consolidation, urban areas must be prepared to begin this process as soon as possible if they expect to efficiently handle the larger problems that are on the horizon.

This study has not undertaken investigations of organizational arrangements for achieving efficient urban water management. Rather, this study has indicated the cost savings associated with achieving coordination of the water supply, distribution, and treatment functions. Thus, there exists a need to study the mechanisms by which the necessary coordination might be achieved.

Public Attitudes and Water Management

Public attitudes are becoming more and more important as a factor in the acquisition of water by a municipality. This is especially true with respect to recycling and the environmental impact of constructing additional collection systems (dams, canals, etc.). Since it is the public which must eventually support the water projects via bond approval, taxes, water rates, etc., it is crucial that they fully understand the conditions and alternatives for satisfying future water demands. This will require more contact

with the public by water engineers, planners, and administrators to insure future funding of projects.

This study has shown the future importance of recycling as an urban water source. The acceptance of recycling in the present distribution system, or the use of a dual distribution system, or the complete rejection of recycling is a public decision, which should be based upon adequate and accurate information for each situation.

Water Quality Standards

Water quality criteria and standards are set by decision-makers at three primary levels of control: (1) federal; (2) regional, and (3) local. National policies, such as indicated by recent legislation, define the objectives of water quality management, but give only cursory information as to the best regional and local courses of action. Consequently, once the national philosophy has been solidified, regional planners should coordinate their activities (state-by-state probably) in order to achieve this national goal. Such decisions set the standards on specific water uses in each area. Next, each area can optimize their water use system accordingly. Then, the procedure can act in reverse to improve regional and national strategies.

The impact of water quality standards on optimal water management strategies is becoming one of the more important variables in regional water resource planning. For

example, the recent federal legislation requiring a "no pollutant discharge" by 1985 will require radical departures from current water management philosophies. One of these major effects will be the increased use of recycled wastewater as a source of supplemental water. However, for recycled water to be economically competitive with other sources, the concentration of certain pollutants such as TDS will be significantly higher than in existing raw water resources. In order to protect the variety of water uses from damages due to these increased pollutant concentrations, the system must be capable of optimally mixing the various flows. As a result, future water management decisions will be significantly influenced by the policies adopted to manage water quality. This also implies that the setting of water quality standards should only be made after a thorough regional analysis.

In river basins where conditions of urbanization are occurring, the urban-agricultural pollution control plans encompass two basic alternatives. First, the sources of pollution may be removed from the hydrologic system by improving the structural elements of the water use system, including the implementation of more efficient water use practices. This type of water quality management is primarily used for diffuse sources such as agricultural return flows. The second alternative is to physically and chemically remove pollutants after having passed through the system. This scheme, of course, is the approach taken

in urban wastewater treatment. Both of these measures can be extended to special water management alternatives such as phreatophyte control, evaporation suppression, and regional desalination.

Given the interrelationships between water quality standards and other aspects of water management, it is clear that the criteria for setting quality standards should be based on information derived from optimizing the total water use system. This would imply, for example, that effluent standards on urban effluents be formulated in conjunction with optimal policies for water supply and distribution within the metropolitan setting. In addition, the standards set on specific urban effluents should be based on an analysis of both urban and agricultural inputs to the system within the river basin.