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SALINITY MANAGEMENT BY USE OF LOW QUALITY WATER

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PREFACE

The work reported here exemplifies one of the major general research directions of the former Resources and Environment (REN) Area and also of the present Impacts of Human Activities on Environmental Systems (IMP) Project concerned with the analysis of conditions for stable "coexistence" of interacting socio-economic and environmental systems. Making this coexistence sustainable requires regulating the whole system by means of economic, social, and other mechanisms or policies, and the objective is to structure the analysis of those policies effectively using systems analytical methodologies and computerized systems of models. In this work, these general research issues were considered using a more specific example of salinity management in the Colorado River Basin, and a more specific research goal was to analyze regulatory policies capable of motivating water users in the basin towards using low quality water for electric energy production. The methodological framework of this study suggests a two-stage decompositional analytical procedure: a) generating rational scenarios of the desired "coexistence" and b) analysis of regulatory policies capable of making those scenarios realizable, taking into account behavioral aspects of the policy-makers involved. This paper outlines this framework, introduces a reader to the specifics of the Colorado salinity problem and describes the mathematical models developed for the scenario generation stage of the analysis, together with some computational results.

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Janusz Kindler
Leader
Impacts of Human Activities
on Environmental Systems

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1. INTRODUCTION

The Resources and Environment Area at IIASA has devoted considerable effort over several years to problems of regional management of water resources. This effort has covered a wide range of topics with particular emphasis on interaction of supply and demand functions. Since a separate group at IIASA worked specifically on water quality problems, the emphasis here has been on water *quantity* problems; however, quantity and quality obviously cannot be isolated. The demand function of a particular water user represents demand for water with an array of minimum requirements concerning particular water quality parameters.

One possible framework for regional water management is to formalize the quality management aspects explicitly as follows:

1. Emphasize regional management of water resources by allocation of water in a manner which matches water quality with user requirements. The implied objective here is to increase the useable water resource base by discouraging use of high quality water by sectors which could use/reuse lower quality water.
2. Accomplish objective 1 in a manner which considers regional economic efficiency. Note that objectives 1 and 2 may well be non-commensurate, and therefore exclusion of the regional economic

efficiency objective will doom any problem analysis to the already over-crowded realm of useless academic exercises.

3. Since regional economic efficiency is by no means synonymous with economic efficiency from the perspective of individual water using sectors, analyze policies for motivating acceptance of water allocation in accordance with objectives 1 and 2.

The emphasis of this initial IIASA salinity management study has been on the notion of encouraging zero discharge uses of low quality water, particularly water high in inorganic contaminants. The time and fiscal limitations of the study also constrained the scope of the research to approaches suitable for regions within semi-arid climates; however, a much more general discussion of management approaches and climatic regions is also included.

1.1. Salinity Management-Generic Difficulties

Along with agricultural and industrial development, water resource planners in many regions of the world are increasingly facing difficult management problems related to limiting to tolerable levels the dissolved conservative minerals (salts) in water resource systems. In this connection, one usually thinks of semi-arid regions where scarce water supplies result in most surface water being diverted from streams and used for a variety of purposes, all of which either add salts directly or at least concentrate salts by evaporation. In this setting, the inevitable result is downstream flows with undesirable levels of various salts (plus other contaminants). Both natural in-stream and mechanical treatment processes can successfully reduce most of such pollutants to allowable levels. The economics of desalination, however, continue to render salinity management by this direct means infeasible except for very highly valued uses. Since all desalination processes are very energy-intensive, recent increases in energy costs have destroyed cost reductions due to technological advances.

A few examples of semi-arid regions where salinity management has already become a high priority problem are: (1) the Colorado River in the Western USA, where the present value of total future damages from salinity are estimated at $2 billion; (2) the region around both the Aral and Caspian Seas in the Southern USSR, where the Aral Sea may soon be reduced to a salt marsh; and (3) the Murray River Basin in South Australia, which has a severe salinity problem in lower reaches due mostly to saline irrigation return flows in upper parts of the basin.

The problem of salinity management, however, is by no means limited to semi-arid regions. When salinity problems occur in humid regions, they are in some ways more difficult to manage than in more arid regions. A common approach in dry climates, for example, is to divert saline water into a zero-discharge evaporation pond to avoid its contaminating a river. In a humid climate, where annual rainfall exceeds evaporation, this is clearly not possible. Examples of major salinity problems in humid climates include: (1) the Vistula River Basin in Poland where highly saline water is drained from many coal mines; and (2) the Ohio River in the Eastern US, where effluent from industrial users of natural brines motivated the first major regional water quality management organization in the US.

There is a large body of literature on both the economic theory of, and actual experiences in, many countries attempting to manage water quality. While most management approaches to date have been limited to mandatory regulation of effluent limits, both economic theory and some experience with innovative techniques imply that for most situations, a better approach is some kind of *economic incentive* which makes it profitable for the water user either to minimize his effluent (perhaps to zero), or to maximize the quality of effluent.

This seems to work well for most industrial effluents where the liquid waste problem is a relatively minor fraction of the total cost of the product. Most salinity problems, however, are caused by either return flows from agriculture or mineral exploration and/or production. In the case of non-point effluents from agriculture, water treatment is simply not feasible. Whether in the form of penalties to the irrigator or subsidy for the cost of treatment, one very quickly finds that the problem solution cost is very large relative to the value of water in the production of most agricultural goods. The quantity of salt in return flows can be decreased marginally by improving irrigation efficiently via lining canals and through sprinkling rather than floor irrigation. However, the fact is that as long as irrigation continues, it will remain the major source of salinity in semi-arid regions.

The question then remains whether, in addition to any feasible on-farm actions to minimize salt in irrigation return flows, other management actions are possible. Since the value of water for irrigation is too low to solve the problem within the sub-system of an agricultural enterprise, is it possible to solve it within another sector such as industrial water use, where the value of water is very high relative to clean-up costs? Such a concept raises obvious "who pays" and "who benefits" types of equity questions as well as the more basic question: is there a net benefit to society from such an arrangement? If there is no such net benefit, a policy based entirely upon economic efficiency might be simply to require the irrigator to stop polluting. Since the only way agriculture may be able to do this is to stop production, the solution will take that form. This, of course, ignores other economic, social and political objectives such as rural development, unemployment, long-term agricultural stability, etc.

The approach used in addressing such questions during this study was to develop the necessary models to quantify the incremental costs (and benefits) of salinity management both from a regional and an individual water user perspective.

A complicating aspect of the salinity management problem is that it is not clear if a particular salinity management project should be pursued even when estimated costs exceed benefits. For example, policy introduced by an environmental regulating agency may result in allowable upper limits on salinity within a river basin without explicit benefit/cost justification. The implied rationale may range from public health factors to rural development policy. What is clear is that regardless of benefit/cost ratio cutoff criteria, it is important to be able to: (1) rank management projects according to relative economic efficiency; (2) understand the impact of such projects upon other water users in terms of costs, incremental salinity changes, and water volume availability; and (3) analyze the effectiveness of appropriate policies as the tools of the regional salinity management. These are the issues addressed by this study.

As previously suggested, man-made salinity problems are not caused solely by irrigation return flows in semi-arid regions. Mineral exploration processes such as oil test holes which penetrate saline artesian aquifers, and coal mines which produce highly saline and/or acid effluents are common sources. In the case of oil bore holes, it is often impossible to prevent saline flows once the aqui-clude is penetrated. In the case of coal mining, salinity management can be so expensive, particularly in humid climates where zero-discharge evaporation is not possible, that the cost is high relative to the value of coal, thereby causing the same kind of management difficulty as in the case of irrigation.

A principal topic of interest in this study is the motivation of industrial users to consume low quality water. Rather than addressing the question of penalizing a "bad", we will consider policies for motivating a "good", that is, motivating the users to implement technologies which help to improve salinity of the regional water resources system.

As will be seen from this report, we use a two-stage decomposition analytical approach. According to this approach, the first stage is the analysis of the salinity problem from the regional perspective, focusing on studying regional scenarios of the use of water resources; the second stage involves the analysis of motivation policies providing for the realization of regionally good scenarios. Although this report outlines the general approach and describes a relevant game-theoretic formulation of a salinity management problem, it is mainly concerned with the implementation of the first stage of this study--analysis of scenarios for regional salinity management.

The material in this report is organized as follows. In the subsequent section we discuss a broad scope of salinity management technological alternatives and classify them according to their applicability in different climates, their impacts on water quality, and their economic efficiency. Sections 3 and 4 are methodological. They outline a systems analytical framework that we follow in this study, and also a game-theoretic conceptualization of a regulatory policy. Section 5 serves as an introduction to salinity problems in the Colorado River Basin, that was used as a case region for the study. Section 6 describes the structure of the scenario generating module that was applied for the first stage analysis of the salinity management in that region. Preliminary results obtained using this module and their brief discussion are presented in Sect. 7. Further planned research for this study will be focused on the elaboration of a policy design module and we indicate a proposed initial approach to this in the Appendix to this report.

2. SALINITY MANAGEMENT ALTERNATIVES

Any project or policy which reduces diversion of relatively high quality water from a receiving stream, or which prevents more water of poorer quality from reaching the river, will result in a lower downstream salinity concentration. A wide range of activities can produce such a result. Examples of salinity management alternatives which have been discussed in the literature and/or are analyzed during this study are displayed in Table 1. The Table divides these alternatives into seven categories, indicates climates where each may be technically feasible, the nature of the impact on water quality and a very general indication of the economic efficiency. The economic indicator is necessarily very vague and not very useful at this level because the essence of any salinity problem is site-specific. Following is a brief description of salinity management alternatives which are indicated in Table 1.

Beneficial Use of LQW

This category includes most of the alternatives analyzed in more detail during this study and which therefore will be discussed in subsequent sections. They are all technically (though not necessarily economically) feasible in warm semi-arid climates where evaporation is substantially greater than precipitation even during infrequent wet years. Two of the alternatives (2 and 3) also may be useful in wetter and cold climates, since they do not require final disposal by evaporation and on-site storage of salt.

The zero-discharge evaporation pond concept is based on the premise that: (1) a pond lining is provided to prevent ground water contamination, and (2) adequate pond depth is provided for storage of salt precipitation for many years, after which the working pond will be replaced and the salt sealed under an impervious cover of non-erodible material. Such ponds are already being used extensively at electric generating plants in the Western US, where environmental regulations virtually prohibit return flows.

Strategies for Humid Climate

The second category includes alternatives especially suitable for humid climates but which are useable in other climates. The effectiveness of alternative 6 - temporary storage (less than 1 year) of saline water for release during high

Table 1. Classification of salinity management alternatives.

		Climatic Region Where Technically Feasible			Impact on River Quality			Increases total useable water volume	Economic Efficiency		Technically reasonable only with favorable site and/or hydrology
ALTERNATIVES	CATEGORIES	warm humid	warm semi-arid	cold	reduces salt loading	reduces salt conc. of river	adds fresh water		Added cost as fraction of product total cost	Cost of use relation to fresh water alt.	
1. Use of LQW for ind. cooling plus brine disposal in zero discharge pond	I. Beneficial use of LQW plus zero discharge disposal		x		x	x		x	<2%	high	
2. Use of LQW for mineral extraction and compaction of mine waste materials		x	x	x	x	x		x	very small	slightly larger	
3. Use of LQW for coal slurry or coal "Aqua Train"		x^1	x^1	x^1	x	x		x		small increase	
4. Use of LQW for solar non-convective ponds			x		x	x		x		much lower	x
5. Mineral recovery by evaporation			x		x	x					
6. Temporary storage for hi-flow release	II. Dilution alternatives	x	x	x		x					
7. Collection and conveyance to sea or large river		x	x	x	x	x					
8. Transfor. of fresh water from irrigation to off-stream energy production (with zero discharge)	III. Change in type of water use		x		x	x					x
9. Transfer of fresh water from irrigation to instream use			x		x	x	x				
10. Water right bank for transfers in salinity management mode (for example, transfer to irrigation of less saline soils)			x		x	x	x				
11. Canal lining	IV. Changes in irrigation technology		x		x	x		x			
12. Change from flood to sprinkler irrigation			x		x	x		x			
13. Import fresh water into region	V. Increase of useable fresh water supply	x	x	x		x	x	x			x
14. Weather modification			x	x		x	x	x			x
15. Evap. suppression on reservoirs			x			x	x	x			x
16. Phreatophyte control		x	x			x	x	x			
17. Desalination	VI. Direct removal of salt	x	x	x	x	x					
18. Effluent standards for brine producing industries	VII. Miscellaneous	x	x	x	x	x					
19. Deep well injection of LQW		x	x	x		x			small		
20. Evaporation ponds			x		x	x					

runoff periods - is directly proportional to the extent of high runoff volume (frequency times duration times flow rate). This approach is currently being used in Poland's Vistula River Basin to reduce salinity damages from very low quality flows from coal mines. In situations where the ratio of saline flow to local river flow volume is too high, alternative 7 may be explored. The economic feasibility of transporting the LQW to the sea or to a larger river is of course dependent upon the distances, types of terrain, and pumping costs involved. Pumping costs can be minimized by generating energy during descent, but pumps and turbines with impellers of special materials (corrosion/deposition resistant) will probably be required.

Change in Type of Use

Alternatives 8, 9 and 10 involve changes of water use in a manner which reduces salinity. Purchases of irrigation water by energy producers have been shown to produce salinity reduction benefits (Bagley, Willardsen, and Hughes, forthcoming) even when done without a salinity management objective. The reason for this is that energy producers are normally subjected to tough environmental controls (such as zero water discharge), while such control on irrigation return flows are simply neither economically feasible nor enforceable.

Alternative 9 involves a reduction of irrigation on land where return flows are particularly salty, and simply leaving this water in the river or tributary. The approach has the advantage of the previous energy transfer (avoiding salt loading of agricultural return flows) plus the additional advantage of increasing high quality dilution flow to the river. The obvious disadvantage is economic since the agricultural production foregone is not balanced by an increase in revenue-producing activity. However, when downstream reduction in salinity-related damages are important, this approach has been shown to be feasible (Narayanan et al., 1979).

Alternative 10 envisions the creation of a water right marketing authority--an agency empowered to act as a broker in the purchase of existing water rights from users which produce salinity problems (such as irrigators of highly saline soils) and to resell such water to users who would agree to manage their effluent in a salinity reduction mode. The water banking concept is currently being proposed for various reasons such as water conservation (Bagley et al., 1980), but also including salinity management (Howe and Orr, in Flack and Howe, 1974).

Improvements in Irrigation Technology

Various improvements in irrigation practice such as lining canals and conversion to sprinkler irrigation are being proposed and in some cases are already occurring due to salinity management policies (often federal subsidies). See, for example, USBR (1981a). The lining of canals is intended to reduce deep percolation through saline soils, while sprinkler irrigation is intended to reduce irrigation return flows relative to flood irrigation.

Increase of Useable Water Supply

One basic way to reduce salinity is to somehow increase the amount of high quality water (HQW) in a river. The most obvious method for doing this is to import HQW into the problem basin (alternative 13). This has the advantage of increasing the useable resource base (in the receiving region) as well as reducing salinity. That approach has been proposed for several regions of Southern USSR, including rivers terminating in both the Caspian and Aral Seas (Voropaev, 1978).

Other approaches to increasing HWQ include weather modification, evaporation suppression and phreatophyte control. An interesting property of the two latter methods is that they in effect "create" water of perfect quality by reducing evaporation or transpiration. Both weather modification research and some operation programs designed to increase either snowpack or rainfall are well established ongoing programs in several regions of the world. The objective is normally to increase runoff, but the related salinity reduction benefit due to dilution is apparent.

Evaporation suppression efforts have largely been devoted to using either mono-layer films on large reservoirs or various membranes on small ponds (Cooley, 1974). The results of extensive research on mono-layer techniques in the US have been disappointing (Blackmer et al., 1970). Although more optimistic results were reported in Australia during the 1950's and 60's (Mansfield, 1962; Fitzgerald and Vines, 1963), no operational programs now exist. A more promising approach for some reservoirs appears to be thermal mixing to cool the reservoir surface (Hughes, Richardson and Franckiewicz, 1975), which should be able to produce evaporation reductions of 20 to 25 percent on deep reservoirs.

Phreatophyte control consists of reducing the amount of deep-rooted vegetation which consumes large quantities of groundwater, particularly along river flood plains in semi-arid regions. There are usually significant negative environmental impacts associated with eliminating such vegetation and therefore the outlook for reducing salinity by this method is marginal at best.

The potential for salinity reduction by any of the dilution-type approaches (including importation) is somewhat less than the associated increase in water volume. Simple calculations show, for example, that if an importation project adds water that is one-third of the previous concentration at some downstream point of interest (and if none of the new water is diverted above that point), the river flower flow would have to be increased by 100 percent in order to reduce river salinity by one-third or increased by 50 percent in order to achieve a 22 percent river salinity reduction.

Desalination

Direct methods of removing salt from water are usually feasible only for high valued uses such as municipal and industrial process water. There is a large body of literature on various desalination methods which will not be cited here. One unusual desalination project which is of interest since its product water will be used for irrigation is the proposed 49 MW, $190 million desalting plant near Yuma, Arizona (Van Schilfgarde, in Skogerboe, 1982). This solution to a problem of salt damage to agricultural soil was motivated by political considerations related to an international (US-Mexico) treaty, and could never be justified on a purely economic basis.

Miscellaneous

In situations where industrial activities produce effluents with substantial amounts of salt, the time-honored approach of effluent standards and/or the approach preferred by economists--effluent charges or marketable permits--are likely to be appropriate. One of the initial and largest regional water quality management efforts in the US was the Ohio River Valley Water Sanitation Compact (ORSANCO). One of the principal river contamination problems in this basin was related to mining of natural saturated salt brines and saline flows from coal mines. A regulatory effort for salinity management (chlorides) was implemented in which the principal alternative used was one discussed previously--temporary storage for discharge during high flow periods.

A large body of literature (produced principally by Resources for the Future) has been addressed to the economics of environmental policy, particularly to the concept of effluent charges. That literature was reviewed, but will not be discussed here, since the focus of much of this report will be the opposite of the effluent charge setting. As indicated in the introduction, a principal topic of interest here will be the motivation of industrial water users to consume LQW. Rather than addressing the question of penalizing a "bad", we will consider policies for motivating a "good."

A recent publication (Milliken and Lohman, 1981) on precisely that topic, which used the same river basin (Colorado) as this research for a case study, will be of considerable value in relation to the policy design portion of this research.

Two final methods of LQW disposal are long-term retention of salt, either below ground (injection into deep formations that are hydrologically isolated from better quality groundwater) or above ground by construction of zero discharge evaporation ponds.

An example of the former has been proposed by the US Bureau of Reclamation for disposal of an extremely saline water source in Paradox Valley, Colorado. The plan is to inject the brine into a permeable formation at a depth of 14,000 feet (USBR, 1982). The economics of such projects are highly site specific and require low energy demand for injection pumping and a suitable geologic formation.

The use of zero discharge evaporation ponds has already been discussed in connection with industrial cooling waste stream disposal; however, the evaporation pond is also a common solution for disposal of naturally occurring (or man-made) surface flows of LQW. The cost of this approach is highly dependent upon large areas of very low-cost land with relatively flat topography which allows inexpensive low perimeter dikes. A small but constant flow of water requires a surprisingly large evaporation surface. For example, a flow of only 1 liter per second at a site with 1 meter of net annual evaporation (total evaporation minus precipitation) requires a pond area of 32,000 m^2 (8 acres).

3. SYSTEMS ANALYTICAL BASIS OF THE STUDY

Problems of salinity management fall into a more general category of regional environmental management problems. Their principal feature is that apart from analyzing relevant environmental systems and process, an explicit consideration is required of economic, social and other incentives, regulation mechanisms, etc. which play a decisive role in the evolution of environmental systems. Here we briefly outline both the basic general features of this type of problem, and also a systems analytic conceptual and methodological basis that provides a framework for structuring the analysis of these problems and for developing appropriate analytical procedures and systems of mathematical models.

Environmental and socio-economic subsystems

We consider a regional system under study as consisting of two major parts: the environmental subsystem (ES) and the socio-economic (SE) subsystem (Figure 1).

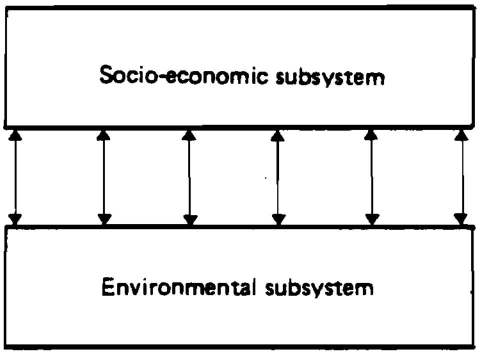

Figure 1. Major subsystems of a regional system.

Both subsystems are in interaction with each other; the analysis of this interaction, aiming at the determination of the means and the limits of regulating it to some extent, is the general goal of the study.

Environmental subsystem

Generally, the models of the environmental subsystem include the description of all natural aspects and processes like water resources, soil, air, and others. But in a more specific study such as the one considered in this paper, it suffices to include in the models of the ES the description of only those parts and processes that pertain to the goals of the analysis. As an example, for the salinity management study it suffices to include in the ES only a description of the natural surface (and possibly ground) water resources in terms of quantity and salt concentration.

Socio-economic subsystem

Typically, the SE subsystem is of a complex hierarchical structure and consists of interdependent elements (producers-users of the environmental resources, various legislative agencies, governmental commissions, etc.), each possessing its own goals and possibilities for action to influence the evolution of the whole system.

The lower level elements (users of the resources) of this subsystem are those directly interacting with the environment (by exploiting natural resources, discharging waste products, etc.), but these interactions are of a local character since each of these elements considers at the most his own local environment and even then only in cases when there is a direct feedback from that local environment to his goals. These interactions depend upon the production technologies (or the resources use technologies) implemented by the users, which are chosen according to their goals. In the context of salinity management various types of such technologies for various producers are outlined in Section 2 of this paper. The point is that in most real systems these local interactions are focused on local goals, are not coordinated with each other, and do not satisfy regional objectives.

On the other hand, the upper level elements of the SE subsystem (governmental agencies, etc.), which have goals more closely reflecting the regional perspectives, do not directly control the interactions of the SE subsystem with the environment, but have some (more or less limited, depending on the particular system) possibilities for influencing (regulating or motivating) the behavior of the lower level elements of the system. (A concept of a regulatory policy used in this study is discussed in Section 4 of the report). The problem is to determine those policies which can induce (or motivate) those interactions of the lower elements with the ES (and therefore the interactions of the SE subsystem with the ES) that are rational from the regional perspective.

The feasibility and applicability of various regulatory policies depend on the institutional and social structure of the particular SE subsystem considered and therefore an understanding of this structure and of the goals and possibilities of its interacting elements is required.

Model Structure of the SE System

No mathematical formulation can encompass all the aspects of a real regional SE subsystem, and the goal of a mathematically based analysis is not to determine final solutions to a real problem under study, but rather to elaborate supplementary tools which can be used together with other analytical approaches to obtain insights which can be of help to policy-makers. Any model structure chosen for the analysis must be fairly simple and yet include essential characteristic features of the real system in question. As a first approximation in this study we use a simplified two-level structure of the SE subsystem of the form shown in Figure 2. The upper level element of this structure (regulating body or, in our case, a salinity management agency) represents the regional perspective and has at its disposal policies capable of motivating to some extent rational interactions of the lower level elements (producers-users) with the environmental subsystem. This structure allows for a reasonably simple and clear mathematical formulation within the framework of the hierarchical game

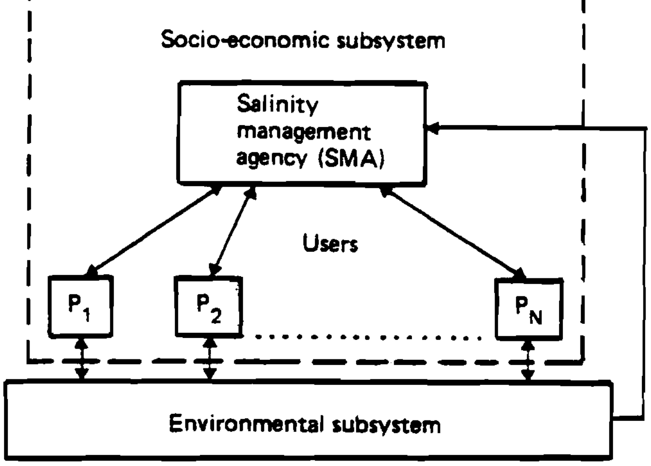

Figure 2. Model structure of a regional system.

theory. This formulation helps to conceptualize and understand the nature of regulatory policies and processes in systems of this type and also to indicate the lines of the analysis. An example of this type of formulation for the salinity management study is discussed in Section 4 of this paper. On the basis of the results obtained using this simplified structure, further research dealing with more comprehensive institutional models can be facilitated.

Decomposition analytical approach

More often than not substantial difficulties arise when the abovementioned game-theoretic formulation is directly used for the analysis, and simplified practially implementable approaches are needed. In this study we use an approach based on the approximate decomposition of the problem. This approach makes it possible to analyze qualitatively various types of regulatory policies, and is also suitable for the implementation of interactive means of analysis.

The *first stage* of the analysis using this approach is directed towards generating scenarios of the development of the regional system under study. At this stage the analysis aims at the evaluation of the marginal possibilities of the regional development in terms of the regional indicators of effectiveness; no interests of the lower level elements are considered explicitly and the analysis results in generating in some sense an ideal scenario of salinity management (or, more generally, the scenario of rational ES-SE interactions). This scenario is described in terms of the essential parameters of the socio-economic and/or of the environmental structure of the system.

At the *second stage* of the analysis, the scenario just obtained serves as a "target" scenario; the analysis at this stage is concerned with the search for those region-specific feasible regulatory policies that can provide for the development of the whole system along the lines specified by the scenario.

Since the first stage of the analysis is performed without explicitly considering the feasible regulatory policies, the scenario obtained at the first stage may be practically unattainable, or, in other words, no one of the feasible policies may provide for the realization of this scenario. In such cases, the analysis has to come back to the first stage and search for another "less ideal" scenario that is attainable using some of the feasible regulatory policies. Moreover, feasible policies may differ from each other in their "degree of feasibility" (for example, two policies may differ from each other by the public reaction to their implementation). Recognizing these (social, political, etc.) factors, environmentally and/or economically less effective scenarios may have to be considered that may be achieved using regulatory policies which are more attractive to the interest groups involved.

These and many other aspects of the system under analysis that have not been explicitly included in the formulation of the mathematical models necessitate performing the analysis interactively; therefore, interactive analytical methodologies and procedures should be elaborated and included in the computer software supporting the analysis.

Schematically, this decomposition analytical procedure is illustrated in Figure 3. The basic part of the scenario generating module is a regional model

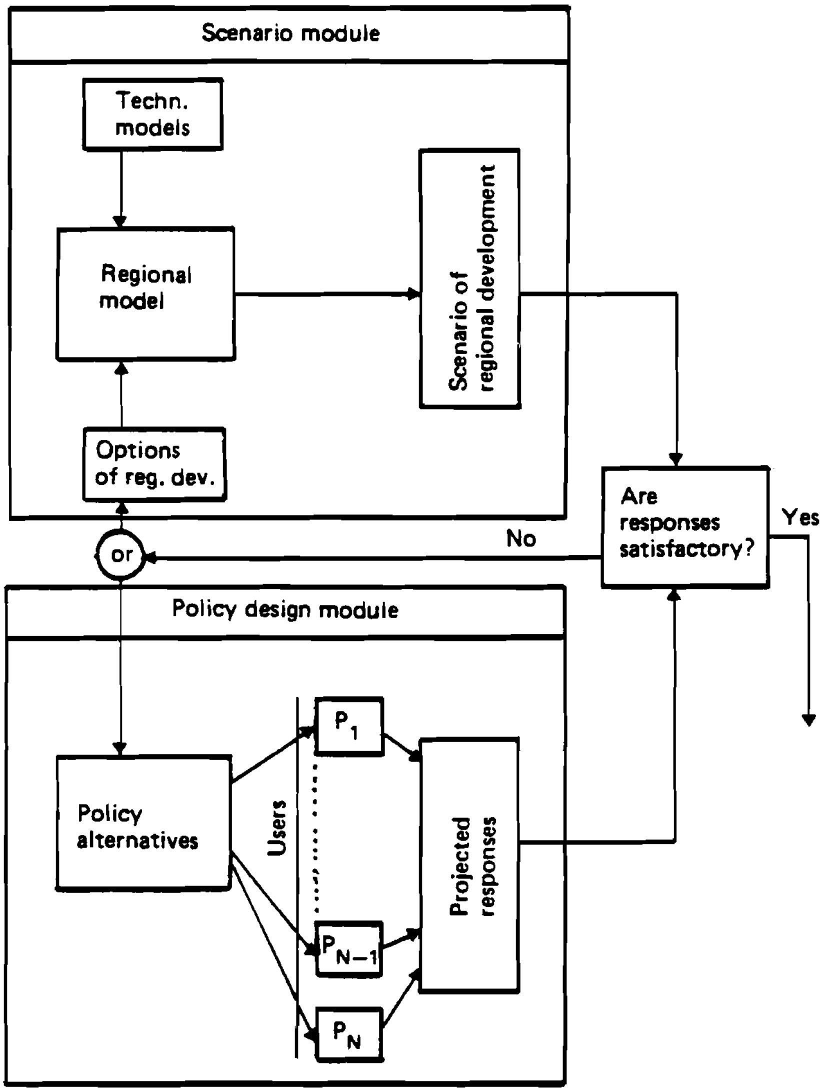

Figure 3. Schematic of decomposition approach.

which includes an aggregated description of the technological, hydrologic, and economic aspects of the regional system in question. The technological models indicated in Figure 3 are used for obtaining functional relationships between water, energy and money inputs and outputs which drive the regional model. Options of regional development ("Options of reg. dev." in Figure 3) include setting up various limits on salinity reduction in a river system, limits on the agricultural production, values of the installed capacities of power plants, etc. By varying these options, various scenarios of regional salinity management are generated. The "policy design" module is used to verify whether the scenarios obtained can be attained using appropriate classes of regulatory policies. The game- theoretic conceptualization of a regulatory policy for regional salinity management is discussed in the subsequent section of this report.

4. GAME-THEORETIC CONCEPTUALIZATION OF REGULATORY POLICIES IN SALINITY MANAGEMENT

4.1. Introduction

As has been discussed one of the effective means of reducing the salinity level in a river consists in introducing those water use technologies that reduce the amount of salt entering the main stream of the river. Such technologies, which have been described in Sect. II of this paper, include, for example, sprinkler irrigation in agriculture, and also cooling technologies for power plants which allow the use of highly saline water. However, the use of these technologies requires additional capital investments which are often not economically justified from the viewpoint of the water users since the advantages of these innovations may benefit the other (usually downstream) users. On the other hand, the implementation of the new technologies may be effective for the development of the basin as a whole.

Obviously, a detailed analysis of the problem would require the consideration of multiple factors like the interrelations of the federal government with the river basin states, the roles played by various commissions regulating the activities of private enterprises and many others. In this section, however, we aim at illustrating the application of the general hierarchical analytical approach and therefore simplify the institutional structure of the region by considering only two basic interest levels (see Fig. 2): a salinity management agency, (SMA), (the upper level), and the producers (lower level) using water resources of the upper part of the basin and thus affecting the salinity of downstream water. Each of the producers has his own goals and his possibilities which are generally different from each other and also from those of the government.

The subsequent discussion will appear to attribute powers to the SMA that probably no single agency will ever possess. The reason for this apparent naivety is that the term SMA as used here is not a single agency but rather a surrogate for all government agencies at federal, regional or state level which either: (1) have an interest in salinity management or: (2) have regulatory powers which can influence the effectiveness of those agencies with salinity management objectives. In the U.S., examples of the first group entities would be in the Colorado River basin the seven state salinity forum, the US Bureau of Reclamation (USBR) and the Environmental Protection Agency (EPA). Examples of the second type are utility rate regulating commissions (both state and federal), and Upper Basin state governments and their water right agencies. Since these entities do not have the same objectives, the single SMA concept is an obvious first approximation which nevertheless can be a useful starting point for further research in this direction using more comprehensive institutional models and analytical procedures.

4.2. Goals and possibilities of the regional producers

Each of the major water users in the region is characterized by his technological, institutional and other characteristics, which should be considered to a smaller of greater extent in the formulation of relevant mathematical models. In this section, however, we use a somewhat general aggregated description to outline more clearly the logic of our analytical approach.

We assume that there are N water users in the region considered. Each of them can implement various production technologies with different requirements for water resources quantity and quality. For k-th producer (user) we denote by X^k the technological matrix describing his possible technologies. As an example, for an agricultural producer an element x_{ij} of the matrix X^k may have the meaning of the area of land allocated for growing i-th type of crop using j-th technologies of irrigation, soil treatment, use of fertilizers, etc. For an energy producer, x_{ij} may have the meaning of the amount of electricity produced using water from i-th source (of particular salinity) and j-th cooling technology (ordinary cooling tower, binary cooling tower, nonconvective ponds, etc.).

Denote by $W^k(X^k)$ vector of the amounts of water withdrawn by the k-th producer from various sources in the region, and by $S^k(X^k)$ the corresponding total amount of salt removed from the river by this producer. We should note here that $S^k(X^k)$ may have a negative value when the technologies X^k used by the producer cause the introduction of additional amounts of salt into the river.

Clearly, the amounts of water and salt removed from the river basin by the producers are constrained by physical, institutional and other constraints that depend upon the existing structure of the water rights, various water regulation legislations, etc. We write the system of this type of constraints in the following form:

$$\varphi^k(W^k, S^k) \le 0. \tag{1}$$

An activity of the k-th producer lies in the choice of a technological matrix X^k that is feasible with respect to the constraints of type (1).

The rationality of the producer's behavior depends upon the structure of his preferences on the set of his feasible technological matrices. The case when a producer evaluates the rationality of his behavior using multiple indicators is very typical to many real problems, but here for simplicity we assume that any producer uses only one aggregated indicator -- his net benefit -- that includes the revenue obtained by selling his products on the market, capital investments, management costs, etc. Then the rational behavior (choices of technological matrices) of a producer is that which gives the maximal value of that indicator (maximal net benefit).

An important feature of the regional system considered here is that the benefit of a producer depends not only upon his choice of a technological matrix, but also upon the mechanisms or policies applied by the SMA for regulating the activities of the producers in the region. To account for this we denote the net benefit function of the k-th producer by $B^k(X^k, u^k)$ with u^k being a vector of parameters controlled by the SMA. Which parameters of the producers' benefit functions can be controlled by the SMA and can therefore be included as components of the vector u^k depends upon the economic structure of the region, upon its institutional configuration, upon the existing practice of the relations between the government and the producers in the region, and also upon other region-specific factors.

As an example, the following parameters may, in principle, be considered as possible components of the vector u^k:

1. maximum prices per unit production by a monopoly (such as electricity prices set by a utility regulating commission);
2. sizes of the subsidies for the introduction of progressive technologies;
3. sizes of credits (and the interest rates);
4. taxes on the profits of the producers;
5. maximal amounts of water withdrawn from various sources;
6. prices per unit amounts of water from various sources;
7. value of the fair return rate on the capital.

We should note, of course, that the parameters indicated here serve only as an illustration, and a thorough analysis is needed to justify the effectiveness and the feasibility of the use of these parameters in each particular case.

The interaction between the SMA and the producers may be modeled as follows. The SMA either sets the values of the control parameters, or communicates to the producers its functional rules for fixing these values depending, for example, on the technologies implemented by the producers, on the amount of salt removed from the river, on the amounts of water withdrawn from the river, etc. *These functional rules are what we refer to as* **regulation or motivation policies.** Their feasible structures also depend upon institutional, political and other aspects of the regional system, and should be considered in advance and possibly modified, in the course of the analysis.

All these feasible rules constitute ***the set of feasible regulation (motivation) policies*** at the disposal of the SMA. We shall use the notation:

$$\tilde{u}^k = u^k(X^k),$$

for a policy of the SMA's influence on the activity of the k-th producer, and U^k for the corresponding set of all feasible policies.

It is worthwhile noticing here that despite the feasibility of all policies from the set U^k, the SMA may prefer one type of policies to another; for example, taking into account public opinion and other factors that are exogenous with respect to the mathematical formulation considered. For this reason, the rational choice of policies should always be made on the basis of a trade-off between the economic, environmental, and other effectiveness of policies, and their degree of "popularity".

The SMA's influence on a producer's activity can be affected not only through the goal (benefit) function B^k, but also through the constraints under which the producer chooses his rational behavior. For example, the SMA may have the authority to set upper limits on water withdrawals from various sources, set standards for waste products discharges into the river, etc. To account for the possibility of such actions, we also introduce control parameters into the constraints vector-function (1), and write the constraints in the form:

$$\varphi^k(W^k, S^k, \tilde{u}^k) \leq 0 \qquad (2)$$

Using the above notation, the activity of the k-th producer with regard to any policy set up by the SMA may be described as the tendency to choose a technological matrix X^k maximizing the value of the benefit function $B^k(X^k, \tilde{u}^k)$ subject to the constraints (2). In other words, for a fixed policy $\tilde{u}^k$, the rational behavior of the k-th producer (choice of matrix X^k) can be obtained as a solution to the following problem:

$$\begin{gathered} B^k(X^k, \tilde{u}^k) \to \max_{X^k} \\ \varphi^k(W^k, S^k, \tilde{u}^k) \le 0 \end{gathered} \tag{3}$$

with B^k, φ^k, $W^k(X^k)$, $S^k(X^k)$, $\tilde{u}^k$ being functions which are either explicitly formulated or are implicitly contained in the mathematical models used for the analysis.

4.3. Goals and possibilities of the SMA

In the context of the salinity management problem considered here, we assume that the SMA evaluates the effectiveness of the regional development in terms of the following indicators:

1 P - total (regional) net benefit of all the producers in the region plus the downstream benefits due to the improvements of the water salinity;

2 Q - total SMA expenditures on the implementation of the motivation policies (including possible subsidies, lower interest rates on credits, etc.);

3 C - reduction of the salinity of water at a specific point of interest.

If we denote the downstream benefits from the salinity reduction by $R(X^1, \ldots, X^N)$, then the total regional benefit function can be written in the form:

$$P = \sum_{k=1}^{N} B^k(X^k, \tilde{u}^k) + R(X^1, \ldots, X^N). \tag{4}$$

Using the above indicators we can describe the objectives of the SMA as obtaining possible greater values of the functions P and C, and possible lower values of Q. Therefore, in the case when the preferences of the SMA are based on multiple indicators, the analysis of the problem requires the application of both game-theoretic reasoning and techniques for multiobjective decision-making. However, to simplify our formulation, we shall first assume that the SMA has set the lowest admissible level C^* of the downstream salinity reduction and thus considers all salinity reductions satisfying the inequality:

$$C(X^1, \ldots, X^N) \geq C^*,$$

as equally satisfactory. Secondly, we shall combine all the costs Q with the net benefit function P and assume that the goal of the SMA is to obtain the greater possible total benefit $(P-Q)$.

Under these assumptions, we obtain the goal function of the SMA in the form:

$$\tilde{P}(X^1, \ldots, X^N; \tilde{u}^1, \ldots, \tilde{u}^N) = \sum_{k=1}^{N} B^k(X^k, \tilde{u}^k) + R(X^1, \ldots, X^N) - Q(\tilde{u}^1, \ldots \tilde{u}^N) \tag{5}$$

and also that the rational behavior of the SMA consists in maximizing this function by choosing feasible policies $\tilde{u}^k \in U^k$, $k=1,\ldots,N$ under the additional constraint:

$$C(X^1, \ldots, X^N) \geq C^*. \tag{6}$$

4.4. Rational behavior of the SMA (principles of choosing the motivation policies)

The next stage of our analysis is to obtain a mathematical formulation for the problem of rational choice of motivation policies outlined in the preceding sections. Here we use a framework provided by the hierarchical game theory based on the modified max-min principle (see Germeyer, 1976) and it is our aim here to demonstrate its application to our problem.

Let us assume that the SMA has set up some feasible motivation policies $\tilde{u}^k \in U^k$, $k=1,\ldots,N$, and has informed the producers about them. Denote by $\Omega^k(\tilde{u}^k)$ the set of all solutions to problem (3) describing all possible responses of the k-th producer to the policy u^k. In other words, the set $\Omega^k(\tilde{u}^k)$ consists of all technological matrices X^k, which provide for the maximal (or satisfactory) benefit of the k-th producer subject to the corresponding constraints for the given policy of the SMA.

Since this analysis is performed prior to the actual implementation of policies and that, therefore, the SMA is not in a position to know the particular response of the k-th producer to the policy $\tilde{u}^k$, it should naturally consider all matrices from the set $\Omega^k(\tilde{u}^k)$ as equally probable reactions of this producer. Then the adequate evaluation of any feasible policies $\tilde{u}^k$, $k=1,\ldots,N$ from the point of view of the SMA is the following value (guaranteed value):

$$\tilde{P}(\tilde{u}^k, \ldots, \tilde{u}^N) = \min_{\substack{X^k \in \Omega^k(\tilde{u}^k) \\ k=1,\ldots,N}} \left[\sum_{k=1}^{N} B^k(X^k, \tilde{u}^k) - Q(u^1, \ldots, \tilde{u}^N) + R(X^1, \ldots, X^N)\right].$$

On the basis of this evaluation, the SMA considers as rational those policies which give the maximal guaranteed value or, in other words, which maximize the function $\tilde{P}(\tilde{u}^1, \ldots, \tilde{u}^N)$. Therefore, the problem of the rational choice of motivation policies can be formulated as the problem of determining policies $\tilde{u}_o^1, \ldots, \tilde{u}_o^N$, which give the following value of the goal function of the SMA:

$$\tilde{P}(\tilde{u}_o^1, \ldots, \tilde{u}_o^N) = \max_{\substack{\tilde{u}^k \in U^k \\ k=1,\ldots,N}} \min_{\substack{X^k \in \Omega^k(\tilde{u}^k) \\ k=1,\ldots,N}} P(X^1, \ldots, X^N; \tilde{u}^1, \ldots, \tilde{u}^N), \qquad (7)$$

and also provides for the satisfaction of the salinity constraint (6).

It is important to note here that according to this formulation the rational choice of policies is based on the information possessed by the SMA with regard to the behavior of the producers. In Eq. (7), this information has the form of the sets $\Omega^k(\tilde{u}^k)$ of possible responses of the producers to various motivation policies. These sets can be obtained by the SMA (or rather by the analysts performing the analysis for the SMA) either explicitly, for example, by consulting experts, or using a model of the producers' behavior of the type (3). In both cases, the "wider" these sets are, the greater the uncertainty is with regard to the behavior of the producers, and the "lower" the guaranteed total SMA's "benefit" or the guaranteed effectiveness of the policies $\tilde{u}_0^1, \ldots, \tilde{u}_0^N$ is.

The practical implementation of this type of formulation of the problem requires simultaneous consideration of problem (7) and also of all problems of the type (3). The associated mathematical and computational difficulties depend greatly upon the form of the functions involved. Some examples of obtaining solutions to economic problems of this type can be found in Vatel and Ereshko, 1977.

In this study we use a simplified approach based on the decomposition of the analysis into two major stages. This approach, that has been outlined in the previous section and illustrated by the diagram in Figure 3, is applied to the problem of salinity management in the Colorado river basin chosen as the case region for this study.

In the subsequent Section 5 we introduce some issues specific to this region. Then, in Sect. 6 we describe the models implemented for the scenario generating module that, according to our approach, is used to perform the first stage of the analysis. This module includes facilities for its interactive use and some preliminary results obtained for the Colorado basin are discussed in Sect. 7 of this report. These and other results obtained using the scenario generating module are intended for their use at the next stage of the study concerned with the analysis of the roles of various classes of motivation policies in the regional salinity management. We briefly outline an approach to this second stage analysis that we plan to implement in the future in the Appendix to this report.

5. THE COLORADO RIVER SALINITY PROBLEM

5.1. Background

During the past 50 years, the Colorado River has evolved from a watercourse characterized by alternating periods of raging floods and extreme low flows to one of the world's most regulated major rivers. An indication of the degree of regulation is the fact that the major reservoirs have a combined storage of 65 million acre-feet (80 billion m^3, which is more than four times the average annual flow of 15 million acre-feet (18.5 billion m^3) (Skogerboe, 1982).

This river is the major source of water for the four upper basin states of Wyoming, Colorado, Utah and New Mexico (in which 83 percent of the water is produced) as well as the lower basin states of California, Nevada and Arizona. This 2300 km long river (see Figure 4) begins in a pristine mountain environment more than 4000 meters in elevation, from which it descends through a high plateau and eventually a low desert, creating such scenic spectacles as the Grand Canyon during its journey.

The river produces the lowest outflow per unit area of any river in the US (60 acre-feet per square mile). It serves 15 million people including drinking water for about 10 million people in Los Angeles (an export from the basin); however, irrigation is by far the largest use of water. Given these conditions of extensive development in a semi-arid climate, one might expect a classical situation for salinity problems. Add to this setting the fact that much of the river flows through shale formations that are notorious salt producers; then consider the fact that the high plateau of the basin is a rich storehouse for all sorts of fossil fuels, development of which is currently producing a rapidly growing major new use for water. One indication of the growing attention being directed to the salinity problem is that in a recent volume of the international journal "Water Supply and Management" which was totally devoted to water and energy

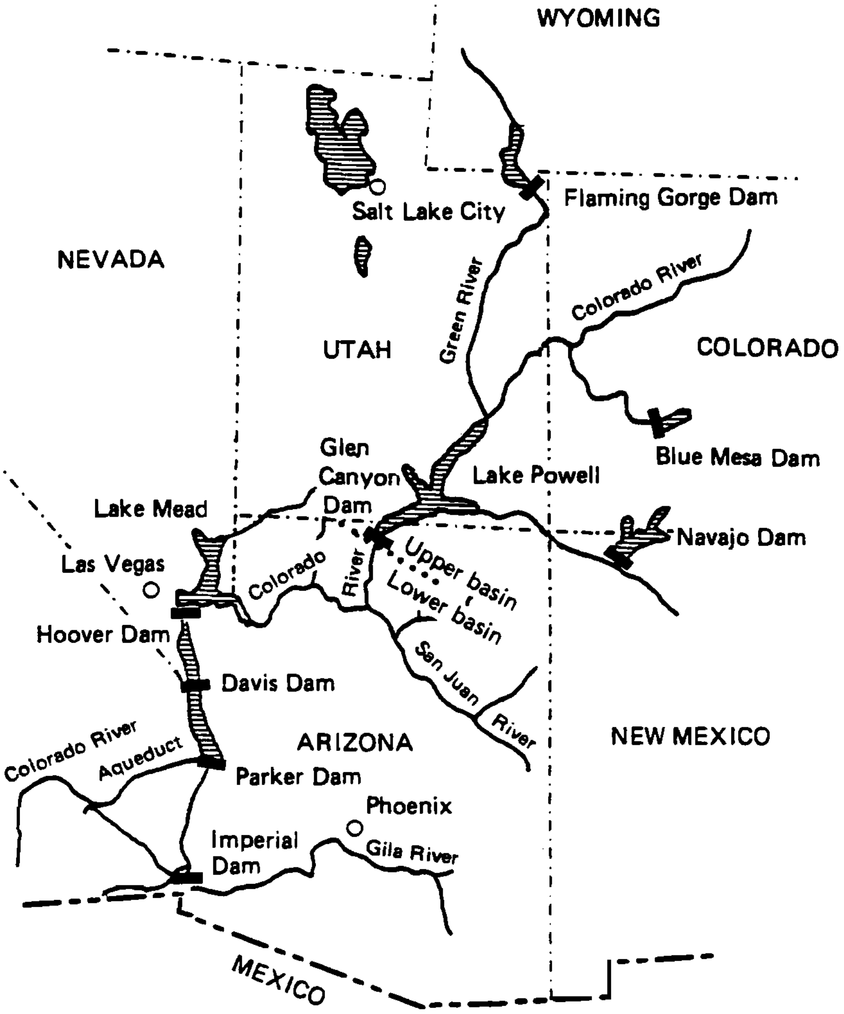

Figure 4. Colorado River major impoundments.

development in this basin, virtually all of the papers discuss salinity, and in seven of the twelve papers, salinity is the principal subject (Skogerboe, editor, 1982). The current sources of salinity have been quantified (Lawrence and Saunders, 1981) as follows:

Natural diffuse sources:	39%
Natural point sources:	8%
Irrigated agriculture:	37%
Municipal and *industrial*:	1%
Exports out of the basin:	3%
Evaporation and *phreatophytes*:	12%
Total:	100%

Considerable research effort has been devoted to the subject of salinity-related damages in general and to damages within the Colorado Basin in particular. One such major study (Anderson and Kleinman, 1978), or its summary version (Kleinman and Brown, 1980), is now widely quoted (with annual inflation corrections) as a basis for quantifying such damages. The current estimate is $370,000 per year per mg/l of increase in salinity at Imperial Dam.

Much of the political interest in salinity control is generated by the fact that a significant amount of damage now occurs to irrigated agriculture in the very productive Imperial Valley region of the lower basin. Agricultural damages vary with particular ions and crops, but in general, they become apparent in the 600 to 700 mg/l range, and water at Imperial Dam now contains more than 800 mg/l. The economic analysis cited previously found that most of the direct damages occur not to agriculture, but to municipal water users (in the form of more rapid replacement of hot water heaters and other plumbing components), principally in Los Angeles.

Another political aspect of the problem is that the river is international– it ends in Mexico, and the lowest water quality is in the Mexican reach. The only flows which now reach Mexico are those required by a treaty agreement. The original treaty did not mention quality, but after extensive damages occurred due to highly saline return flows from a project just inside the US border, an agreement was reached in 1973 that required the US to deliver water to Mexico at no more than 115±30 mg/l greater salinity than that at Imperial Dam. Details of the Mexican salinity problem are given by Holburt and also by van Schilfgarde in Skogerboe, editor (1982).

Efforts by water resource leaders in the seven basin states to organize a collective salinity management policy resulted in 1960 in forming a conference. At the seventh session of this group (in 1972) the states agreed to adopt a policy of attempting to not exceed current salinity levels, but delaying adoption of numeric criteria for salinity while the Upper Basin states continued to develop their share of the water and recognizing that salinity levels may rise until effective control measures are developed. However, federal environmental legislation in 1972 forced a stronger policy. The very different vested interest and objectives of the upper and lower basin states are described by Lawrence and Saunders (1981) as follows:

> *Passage of Public Law 92-500, however, forced action on the part of the conferees which they believed to be premature. It was apparent that the EPA would not settle for anything less than numerical standards by October 15, 1975, and that if the states did not come up with an acceptable proposal, the EPA would in all likelihood publish standards themselves. On November 9, 1973, the seven Colorado River Basin states formed the Colorado River Basin Salinity Control Forum with members appointed by the governers of the respective states, to address the issues of: (1) establishing numeric criteria for salinity in the Colorado River Basin; and (2) developing a plan of implementation which would insure that those criteria were met.*

Accomplishment of Initial Objectives.–At first glance, it seemed that the forum was faced with an impossible task. Since the EPA seemed to be firmly committed to standards of salinity concentration at then existing levels, not only could no salts be added to the river system, but no dilution water could be removed. The Forum could easily have been polarized, since the lower basin had an economic stake in maintaining present salinity levels, while the upper basin had a minimal salinity problem, but wanted to remain free to develop remaining unused compact allocations. . .

Over time, it became apparent that maintaining present salinity levels while allowing further water development could be accomplished by a two-pronged approach: (1) minimizing salt pickup from future developments, and (2) reducing, wherever practical, present salt inflow to the system from natural and man-induced sources. The first action could be accomplished by imposing additional design criteria for proposed irrigation projects, and presented relatively little problem. The second action, which potentially could result in much larger reductions of salinity, would require a substantial outlay of funds. . . . The Forum began to generate support for federal salinity control legislation, and on June 24, 1974, the Colorado River Basin Salinity Control Act (Public Law 93-320) was passed.

Title I of the Salinity Control Act authorized measures which would ensure that water deliveries to Mexico would meet the quality requirements of Minute 242. Title II dealt with salinity control projects above Imperial Dam; it authorized construction of the Grand Valley, Paradox, Crystal Geyser, and Las Vegas Wash Units, and investigation of twelve other projects. The costs of each unit were to be financed 75% by the federal government, and 25% from the states through the Upper Colorado River Basin Fund and the Lower Colorado River Basin development Fund.

In June 1975, the Forum completed the draft "Water Quality Standards for Salinity Including Numeric Criteria and Plan of Implementation for Salinity Control."

A special group was formed within the Bureau of Reclamations and assigned to the Colorado River Quality Improvement Program. This group is continuing with various salinity management activities.

One of the very complex aspects of regional salinity management is the extent to which almost any management activity impacts other parts of the system. For example, removal of salt by use of LQW for cooling or for a non-convective pond system seems to be a desirable approach; however, regardless of the water quality, LQW is currently treated under water law like any other unit of water volume. The Colorado River water has been completely allocated (probably over-allocated) among each basin state for many years, and each state's water law system and water right agency has in turn formalized the legal share of each tributary belonging to individual users or groups of users. If therefore, a large amount of LWQ in Utah is evaporated specifically to reduce salinity in California, an interesting question arises as to which state's allocation such a diversion will be charged.

Another example is that while it is possible to reduce salinity by allocating water to special energy-related activities, an equal effect both in terms of downstream salinity and water flows might be achieved by taking some irrigated land out of production or by changing irrigation technology on certain salt-producing soils. Questions then arise as to relative economic, social, and political impacts of each alternative. In a basin of this size there are thousands of such tradeoffs to be analyzed.

6. SCENARIO MODULE

The scenario generating module for the Colorado basin described in this section (also see Figure 3) includes an expanded version of a regional model developed previously at the Utah Water Research Laboratory (UWRL) (Narayanan, Padungchai and Bishop, 1979) and a model describing a technology based on the use of non-convective ponds (NCP). This last model, which is described in Hughes and Orlovsky (1982) and outlined in this section, was used to obtain an aggregated data related to the implementation of this technology for the subsequent use of these data in the regional model.

The original LP model allocated water in a manner which maximized net benefits to the energy (both primary fossil fuel mining activities and energy conversion processes) and agricultural sectors. The UWRL model included both water and salt balance constraints and therefore could also quantify the impacts upon salinity of alternative water allocations. This generalized model had been applied (Narayanan, et. al., 1979) to the Upper Colorado River Basin. In addition to conventional energy-agricultural water uses, the application also included several potential salinity management projects such as canal lining, sprinkler irrigation, evaporation ponds and desalination plants which had been proposed by the US Bureau of Reclamation in the Upper Colorado Basin.

The model did not, however, take into account the possibility of using low quality water for cooling of power plants, nor the non-convective pond technology for disposal of brine. The UWRL model has therefore been modified and expanded during this study in collaboration with Rangesan Narayanan in order to add these capabilities. A simplified schematic of the revised model is shown in Figure 5.

The original UWRL model is described in detail in Narayanan et al., (1979). The description that follows will detail only the changes to that model. The

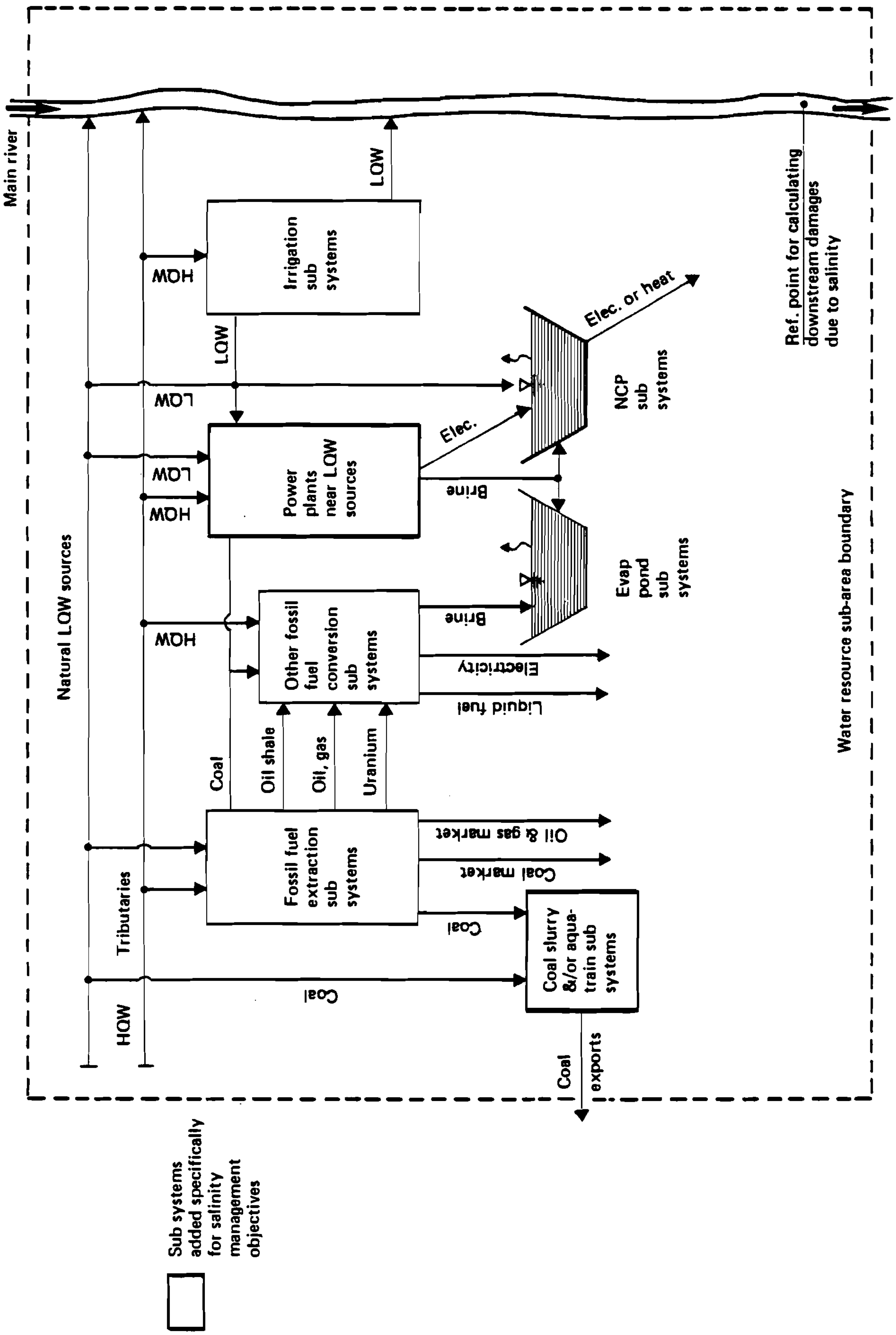

Figure 5. Regional allocation model scope.

original model will, however, be described in a very summary fashion.

6.1. Original Model Description

Objective function

The UWRL model maximizes the following objective function:

$$Z = \pi_A + \pi_E - TC_{SM}, \tag{8}$$

where the π_i represent the net return from agriculture and energy, and TC_{SM} is total annual cost of salinity management activities. Each π_i is defined as annualized total revenue (TR) minus total cost (TC).

Constraints

The UWRL model included the following types of constraints:

Land: Irrigated land is classified between cropland and pasture and the sum of land used for each of several crops which are suited to each water resource sub-area (WRSA) are limited to the quantity of crop or pasture land designated for that WRSA.

Crop rotation: Crop rotation constraints for proper crop diversification and soil quality are included as ratios of particular types of crops.

Energy output: The quantities of each raw material directly sold on the market plus the sum of each raw material (coal, oil, gas, oil shale, tar sands, uranium) flows to all conversion processes in the WRSA must equal the total extracted (which in turn is constrained to an upper limit).

Conversion process efficiency: Final products are limited by efficiency of conversion processes.

Water requirements and availability: Agricultural water diversions and return flows are calculated as estimated consumption per unit of land per crop in each WRSA. Water use for energy is estimated per unit of output for each output and because of environmental regulations, no return flows are expected.

Water availabilities: Average annual flows into each downstream WRSA are calculated as inflows minus diversion, plus return flows, plus local tributary flows.

Institutional restrictions: In the upper Colorado, application net diversion in each upper basin state is limited to the legal entitlement (a particular fraction of the total flow).

Water quality: Salt balance equations use estimated salinity concentrations of both diversions and agricultural return flows in each WRSA to calculate salt flows to downstream subregions.

Salinity projects: Sprinkler irrigation reduces salt loading (relative to flood irrigation) by decreasing return flow. Canal lining reduces salt by reducing deep percolation. Conversion to sprinkling is allowed by repeating all irrigation activity variables and constraints for the sprinkling mode. Canal lining is modeled by estimated maximum lengths and salinity impact per unit of length for linings in each WRSA. Other special evaporation pond and desalting projects at major LQW locations are allowed as estimated by the USBR.

Downstream salinity changes: Since the model calculates both water and salt flows at the exit of each WRSA it is possible to constrain the downstream salinity to any particular level and observe the configuration of agriculture, energy, and salinity management projects necessary to achieve that salinity while maintaining economic efficiency. This is a very important capability which allows analysis of a wide range of management strategies and not only their impact on total regional economic efficiency but also their impact on agricultural or energy activities in individual sub-regions.

6.2. Modifications for LQW Use in Cooling and Non-Convective Ponds

The modifications to the original UWRL model are those necessary to add the capability of modeling use of LQW for industrial cooling and brine disposal by non-convective solar ponds rather than conventional evaporation ponds. These changes require new variables, new constraints, and new terms added to existing constraints and to the objective.

The new salinity management alternatives to be considered will be defined in terms of 5 alternative technologies or configurations at any location where an opportunity exists for use of LQW for industrial cooling. For simplicity's sake, the notation will refer to cooling of fossil fuel power plants only, but the model would easily generalize to any industrial cooling application. The 5 alternatives are defined in Table 2.

Table 2. Alternative Technologies.

ALT	Power Plant Water Source	NCP Water Source	Special Cooling Tower (High Salinity): Fossil Plant	Special Cooling Tower (High Salinity): N.C. Plant	Brine Disposal Method
1	HQ	-	No	-	Evap. Pond
2	HQ	LQ	No[1]	Yes	N.C. Pond
3	LQ	LQ	Yes	Yes	N.C. Pond
4	LQ	-	Yes	-	Evap. Pond
5	No Power Plant	LQ	-	Yes	N.C. Pond

[1] This plant has a conventional tower for 94% of the cooling load and a high salinity tower which handles the remaining cooling load and concentrates the brine to 120,000 mgl.

The original model includes power plant activity variables in terms of MWH of electricity produced. The particular power plants where the salinity management alternatives are to be considered will therefore also use this dimension, as will the NCP projects. The required new constraints are the following:

Capacity of Special Power Plants

The total capacity of the K-th potential power plant in WRSA is assumed not to exceed a planned upper limit B^s_k. Therefore:

$$\sum_{i=1}^{4} PP^s_{ki} \leq B^s_k \qquad (each\ s \text{ and } k) \tag{9}$$

where PP^s_{ki} is the production of electricity using the i-th technological alternative (Table 2). This theoretically allows a combination of alternatives at a single plant; however, it was hoped that in general a single alternative would be selected. It does not make sense, for example, to have a combination of alternative 5 and any other alternatives at a single location; however, a combination of alternatives 2 and 3 implies simply a mixture of high and low quality makeup water for the cooling tower (which may well be the best solution). Therefore, a discrete 0,1 algorithm was not selected, but rather an LP formulation. If an inconsistent combination does occur at a particular site it could easily be eliminated by forcing either alternative to zero in a subsequent solution.

Capacity of non-convective ponds

Alternatives 2 and 3 require non-convective ponds which are sized properly for utilizing the brine from power plant blowdown. Therefore, the activity level (in MWH) of the k-th NC pond in WRSA's using alternative 2 (NC^s_{k2} must be functionally related to that of power plant PP^s_{ki}. Therefore, we add the following constraints:

$$NC^s_{ki} \leq \alpha^s_{ki} PP^s_{ki} \qquad (i=2,3), \tag{10}$$

where α^s_{ki} is the ratio of maximum NC pond to power plant output (calculated by the NCP sub-model—to be discussed later).

Also, an upper limit β^s_{k5} on production of the NCP in alternative 5 must be given:

$$NC^s_{k5} \leq \beta^s_{k5}. \tag{11}$$

Diversion of water for power plants

It is necessary to calculate total water diverted for power plants ($WPPT^s$), and also for NC ponds ($WNCT^s$), in each WRSA in order to subtract these quantities from water flows leaving each WRSA. Therefore, we add

$$\sum_{i=1}^{4} \beta_{ki}^{s} \cdot PP_{ki}^{s} = WPPT^{s} \tag{12}$$

and also

$$\sum_{i=2,3,5} \delta_{ki}^{s} \cdot NC_{ki}^{s} = WNCT^{s} \tag{13}$$

where the β and α constraints are water use per unit of electricity produced by the power plants and NC ponds respectively. These totals are then subtracted from the water balance rows (including points at each state boundary) in the original model.

Water balance for low quality water

In addition to total water balance constraints, it is also necessary to limit total diversion of LQW to its availability as follows:

$$\sum_{i=3}^{4} \beta_{ki}^{s} \cdot PP_{ki}^{s} + \sum_{i=2}^{3} \delta_{ki}^{s} \cdot NC_{k2}^{s} + W_{k} \cdot SS_{k}^{s} \leq LQWC_{k}^{s} \tag{14}$$

where the SS_k^s are other (existing) salinity management variables such as evaporation ponds, desalination plants, or coal slurry lines using LQW (in terms of tons of salt removed); W_k^s are quantities of water per ton of salt; and the $LQWC_k^s$ are quantities of LQW available.

Salt balance constraints

Salt diversions by special power plants and by NC ponds are calculated as:

$$\sum_{i=1}^{4} \lambda_{ki}^{s} \cdot PP_{ki}^{s} + \sum_{i=2,3,5} \mu_{ki}^{s} \cdot NC_{ki}^{s} \tag{15}$$

where λ_{ki}^s and μ_{ki}^s are the salt diverted per unit of output of the power plants and NC ponds respectively. These terms are added to existing salt balance constraints.

Coal supply

In order to account for coal supplied to special power plants it is necessary to add the following terms to equations which calculate coal use per unit of electricity produced:

$$\sum_{i=1}^{4} PP_{ki}^{s} \tag{16}$$

6.3. Power Plant Water/Salt Flow Functions

The regional model requires as input data, water and salt demands, and waste streams as functions of plant capacity and technology. The technologies modeled are defined in Table 2. Alternative 1 represents the status quo--conventional cooling towers using high quality water and a zero discharge evaporation pond for brine disposal. Alternatives 3 and 4 require a high salinity cooling tower capable of concentrating cooling water to 120,000 mg/l before blowdown. Alternative 2 requires a combination of both types of cooling tower or at least a brine concentrator for the waste stream. Therefore, three types of technologies are required.

Alternative 1—conventional technology

The phrase "conventional technology" is very ambiguous, since modern cooling tower systems vary greatly in their design and particularly in their ratio of water demand (tower makeup water) to waste stream (blowdown). The principal variation is related to the extent to which brine is concentrated. In the context of total water budget, the problem is complicated by the fact that cooling is not the only water demand. Boiler process water losses are significant (roughly 5 percent of cooling demand); if air scrubbers are required, another water demand is added (same order of magnitude as boiler makeup) and ash handling may be either by water or air. Figure 6 shows a typical water cycle through such a plant. The width of the flow arrows suggests relative magnitudes.

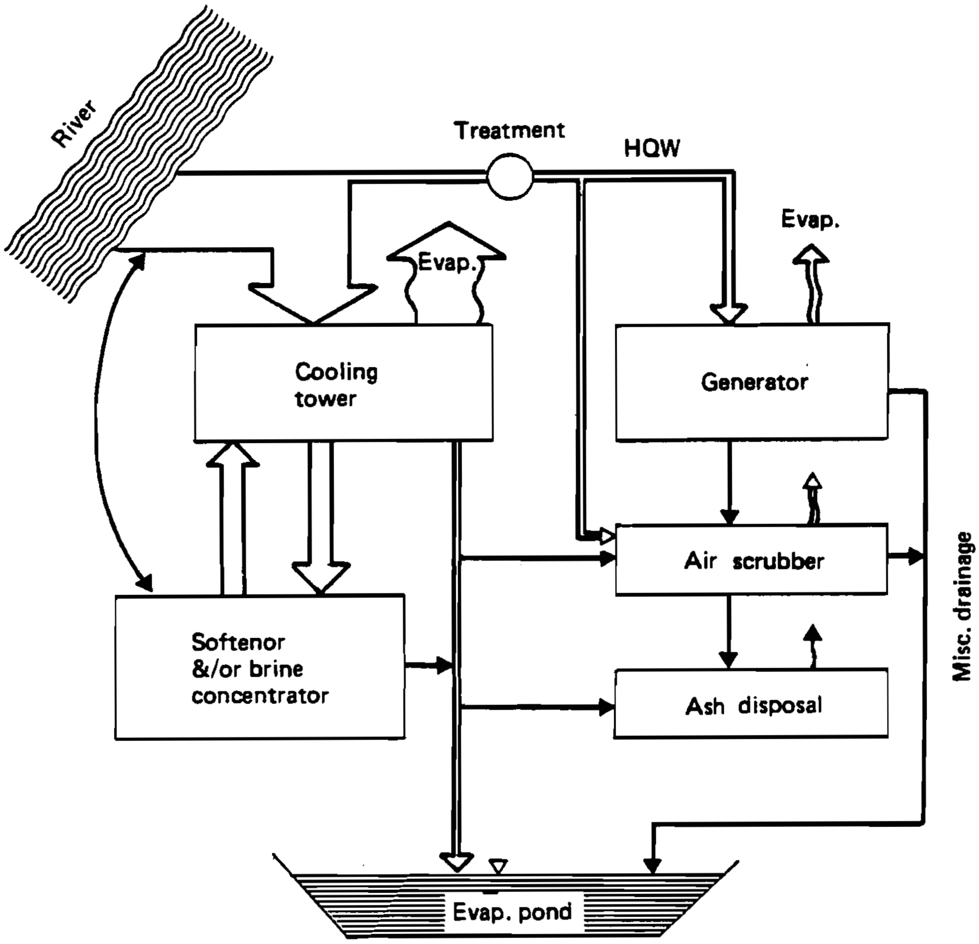

Figure 6. Power plant water flows.

The focus of this study was on changes in water flows due to various cooling tower technologies. It was possible to ignore flows other than the cooling cycle (since they are independent of type of cooling). This means, for example, that disposal pond areas discussed here will tend to be slightly smaller than total areas required because they do not include waste streams from such components as the generator building and the air scrubber.

Recent experience in the US suggests that in an environment where water is scarce and where strict environmental regulations on effluents exist, it is most economical to use extensive treatment of cooling water and perhaps some desalination in order to both conserve water and to reduce the size of disposal ponds. Israelsen et al., (1980) describe and quantify the water and salt budgets of two such technology mixes—cold process softening of both tower makeup and sidestream (Israelsen's option 2); and use of a brine concentrator plus side stream softening (their option 3).

Conventional cooling (our alternative 1) will be defined here as follows: a high quality source (not over 300 mg/l tds) will be softened to allow concentration of blowdown to 10,000 mg/l. This will be accomplished by keeping the total of Mg^{++} Ca^{++}, and S_iO_2 concentrations below 400 mg/l. This will likely require softening of the tower makeup source in addition to the sidestream softening shown in Figure 6. The quantities of makeup and blowdown are estimated (after Israelsen et al., 1980) as follows:

$$\begin{aligned} Makeup &= 16+(1.63)SCmu && (acre-feet\,/\,MW\,/\,yr) \\ or &= 19.7+(2.0)SCmu && (10^3 m^3/\,MW\,/\,yr) \\ Blowdown &= (1.6)SCmu && (acre-feet\,/\,MW\,/\,yr) \\ or &= (1.97)SCmu && (10^3 m^3/\,MW\,/\,yr) \end{aligned}$$

where $SCmu$ is in metric tons/m^3 or (mg/l times 10^{-6}). These functions are shown in Figure 7.

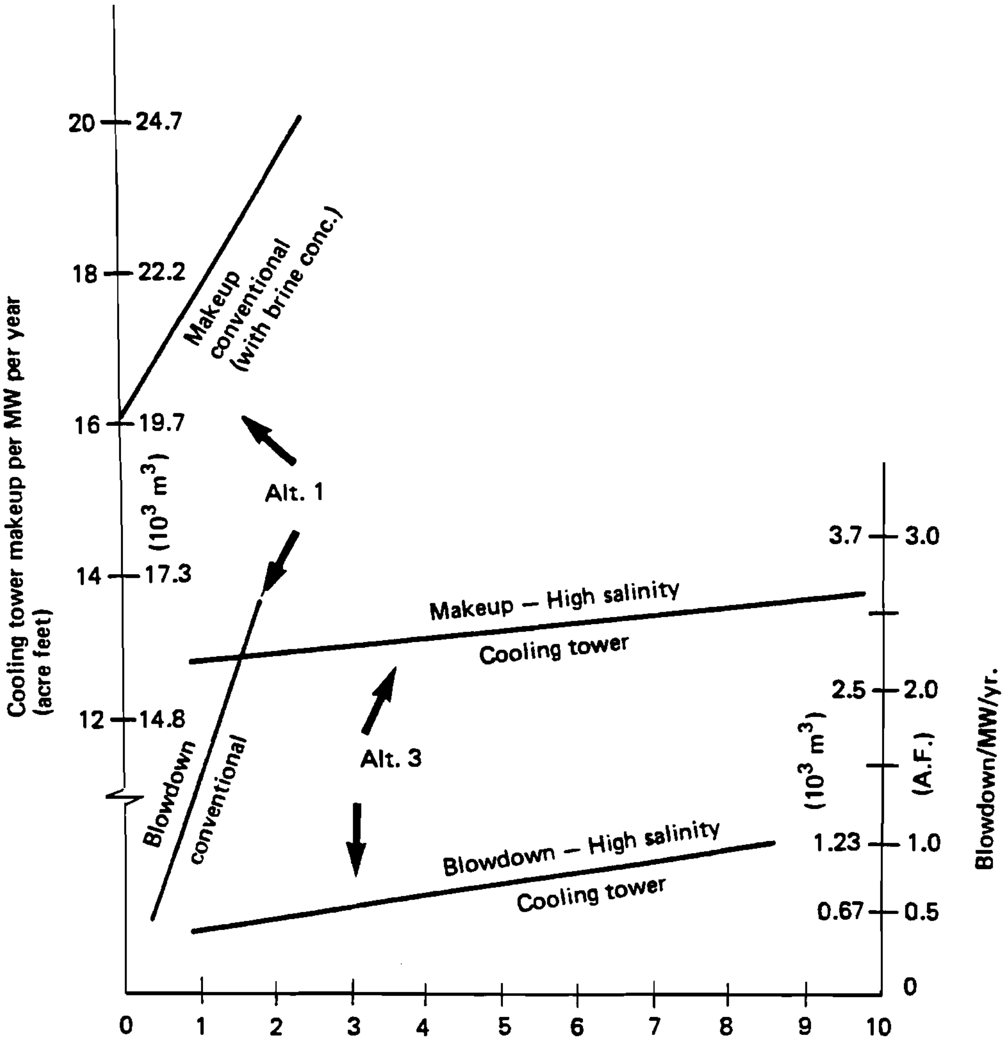

Figure 7. Power plant water supply and waste quantities.

Alternative 3–Use of LQW for Cooling plus NCP

Since alternative 2 requires a mixture of technologies 1 and 3, its discussion will be delayed. Alternative 3 uses LQW as the tower makeup. In the application to be described later, these concentrations vary from 2,700 to 5,000 mg/l. These already poor quality sources will be concentrated to 120,000 mg/l before blowdown.

In order to operate a cooling tower at such high salinities, a secondary loop is required in which a thin plastic membrane separates the saline water which is being evaporated from hot high quality water which is a closed loop from the condenser heat exchanger. The membrane therefore becomes a secondary heat exchanger. Such a tower has been successfully tested in the US (EPRI, 1981), and will be referred to as the binary cooling tower (bct). Israelsen et al. (1980) give water budgets for the bct as follows (also shown in Figure 7):

$$\begin{aligned} Makeup &= 12.75+(0.095)SCmu & &(acre-feet\,/\,MW\,/\,yr) \\ or &= 15.7+(.117)SCmu & &(10^3 m^3/\,MW\,/\,yr) \\ Blowdown &= .25+(.093)SCmu & &(acre-feet\,/\,MW\,/\,yr) \\ or &= .31+(.115)SCmu & &(10^3 m^3/\,MW\,/\,yr) \end{aligned}$$

Disposal of brine is in a non-convective pond, which will be discussed later.

Alternative 2–HQW for Cooling Plus NCP

The binary cooling tower (bct) system described previously was originally designed for use as a brine concentrator which, as a side benefit, also handled a small part of the cooling load--rather than the total cooling load as required by Alternative 2. The principle is that the blowdown from a conventional tower becomes the makeup supply for the bct portion of the cooling tower. The conventional tower blowdown at say 5,000 mg/l is further concentrated to about 120,000 mg/l (which also involves additional softening). The water and salt flows assumed here for alternative 2 could likely also be produced by adding a desalination-type brine concentrator to the alternative 1 system, although the conventional tower would need to be slightly larger.

Alternative 2 is assumed to consist of a HQW source for a conventional tower which carries 15/16 of the cooling load plus a bct unit which carries 1/15 of the load and which produces an effluent at 120,000 mg/l tds (Sanderson et al., unpublished). Disposal is via an NCP system.

Alternatives 4 and 5

Technology 4 is the same as 3 except that brine disposal is by a normal evaporation pond, rather than an NCP.

Technology 5 does not involve a fossil-fueled power plant at all--it is simply an NCP system for disposal of LQW.

6.4. Non-Convective Pond Model

The basic idea of a salt gradient solar pond is to float a thin layer of fresh water over a few meters depth of highly saline brine. If the salinity gradient of the layer between these two qualities of water is sufficiently steep, the brine temperature can approach $100C^{o}$ without mixing convectively with the lighter, although colder surface layer. Since the cooling effect of evaporation is confined to the surface layer, the brine can become both a solar collector and an effective heat storage reservoir.

This concept has produced a considerable body of literature (see, for example, JPL, 1982, and Tabor and Weinberger, undated). Most of the literature is addressed to the idea of finding an ideal site where either a source of highly saline brine (near saturation) already exists such as at inland seas, or where salt in solid form can be easily mined to produce such brine. This research, however, addresses the notion of using the waste stream from an electric generating plant as the source of brine plus a less saline but still low quality source for freshening the upper layer of the NCP. In this setting, the volume and salinity of both sources of water and the timing of expansion of such a system (as more brine is produced) become very important. A separate optimization model for this rather difficult non-linear systems problem was developed during this study and is described in a separate publication (Hughes and Orlovsky, 1982). A brief summary of that model follows:

The NCP pond system is shown in Figure 8. The brine production pond (pond 2) is required to concentrate (to about 260,000 mg/l) the 120,000 mg/l power plant effluent from the NCP surface layer. The working pond (pond 3) requires the heavy brine both for initial filling of each pond increment and for replacing salt lost to the upper layer by diffusion. The upper layer is maintained at about 50,000 mg/l by flushing blowdown back to pond 2 and replacing blowdown plus evaporation from the LQW source (2,000 to 5,000 mg/l). Pond 1 (missing from the figure) may be needed to regulate the supply of LQW.

Another water demand is related to cooling of te NCP energy conversion system if the final energy form is to be electricity rather than heat. This process creates another waste stream which is also used to produce brine.

The problem which is solved by using this model is the following:

Given: (1) the water and salt quantities available at a particular site; (2) the evaporation, precipitations, radiation, and other physical characteristics of the site; and (3) the costs of constructing and operating the pond and energy conversion system and the estimated revenue from the sale of energy—what is the best size and timing of construction for each cell of ponds 2 and 3?

Both the generalized model and its application at seven sites in the Colorado River upper basin are described by Hughes and Orlovsky (1982). The results will be summarized in the subsequent section of this report.

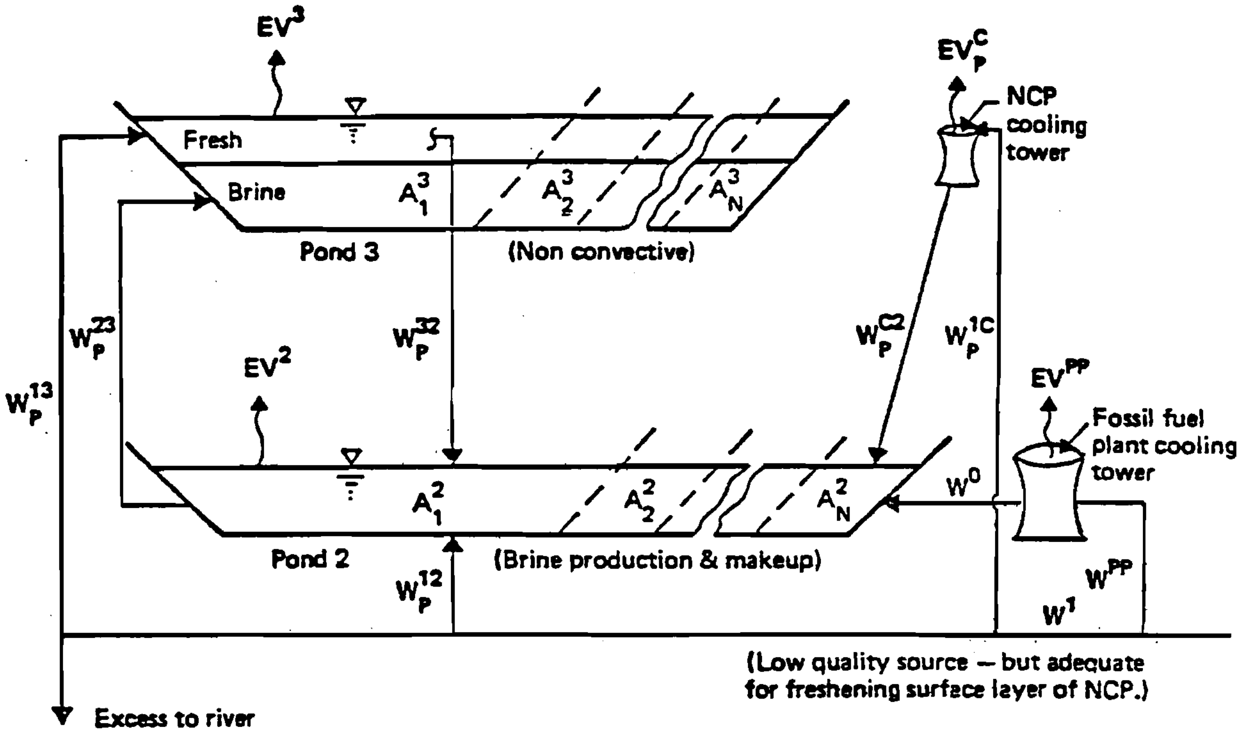

Figure 8. NCP schematic including thermal/electric conversion water demand.

7. APPLICATION OF THE SCENARIO MODULE TO THE COLORADO RIVER

7.1. LQW Use Alternatives at Individual Sites

The scenario module was applied to the Upper Basin of the Colorado River in a mode that included most of the potential salinity management projects which are being considered by the Colorado River Water Quality Improvement Program (CRWQIP) of the US Bureau of Reclamation (USBR). These include conversion from flood to sprinkler irrigation, lining of canals, plus several site-specific alternatives including use of LQW for cooling by electric generating plants at 7 individual sites which have been identified by the USBR as being within 100 miles (160 km) of a significant source of LQW (see Figure 9). Any of the 5 alternative technologies defined in Table 2 could be selected at each of these sites. USBR studies to date have included the concept of using LQW for cooling at these sites with brine disposal in conventional ponds, and have also considered the possibility of NCP systems at other sites (such as the terminus of very large coal slurry pipelines). This study, however, analyzes the coupling of power plant waste streams to NCP systems at individual plant sites.

Physical Input Data

The quantities of water and salt available at each of these sites and the water demands and waste streams associated with each of the cooling technologies are given in Table 3.

The NCP model was used to determine the pond areas, water demands, and energy capacities of ponds shown in Table 4. The time for reaching equilibrium (when all available LQW is needed for NCP pond freshening plus cooling) varies greatly; therefore, an arbitrary planning peeriod of 30 years was used for all sites to calculate the quantities shown in this table.

The NCP model output also provides information on quantities of salt removable from the river at each site due to each technology. These quantities are shown in Table 5.

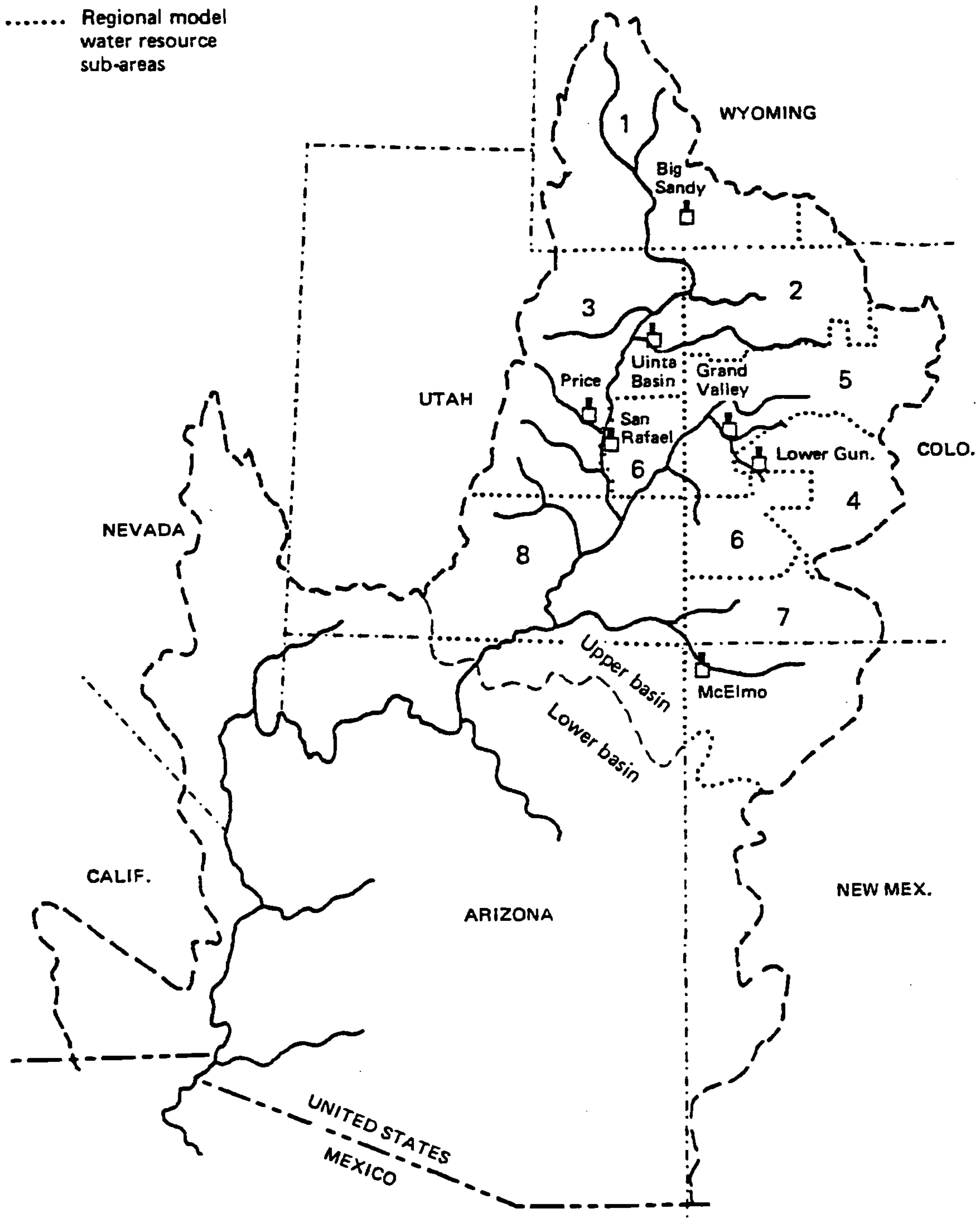

Figure 9. Subwatersheds and potential power plants close to sources of low quality water.

Table 3. Fossil fuel power plant water demands and waste streams (water and salt dimensions are 10^3M^3 and mg/l respectively).

				Alt. No. 1		Alt. No. 2		Alt. No. 3 & 4		LQW Remaining for NCP Freshening	
Site	Total Available LQW	Salt Conc.	Power Plant MWe	HQW Makeup	8000 mgl Blowdown	HQW Makeup	120,000 mgl Blowdown	LQW Makeup	120,000 mgl Blowdown	Alt. 2 & 5	Alt. 3
Big Sandy	17,900	5,000	350	7,130	173	5,520	120	5,725	302	17,900	12,170
Uintah Basin	16,780	4,500	800	11,930	395	12,610	274	13,030	661	16,780	3,750
Price River	10,490	4,000	500	10,180	246	7,880	172	8,100	383	10,490	2,380
San Rafael	8,390	3,600	400	8,140	197	6,300	137	6,470	296	8,390	1,925
Grand Valley	33,560	3,300	800	11,930	395	12,610	274	12,960	497	33,560	20,600
Lower Gun.	21,220	2,900	800	11,930	395	12,610	274	12,830	494	21,220	8,400
McElmo Creek	25,670	2,700	1,600	32,580	790	25,230	550	25,670	990	25,670	0[1]

[1] Assumed that HQW is available for this purpose at $25/$10^3M^3$--this site only; other sites were modeled as being limited by quantity of LQW available.

Table 4. Pond areas, LQW water requirements, and electric generating capacity of ponds after 30 years.

	Inches of Evap. Minus Precip.		Pond Areas ($10^3 M^2$)							NCP Water Requirements (LQW in addition to Fossil Plant Blowdown) ($10^3 M^3$)				Generating cap. of NCP (10^4 MWH/Yr)	
			Alt. 1	Alt. 2		Alt. 3		Alt. 4	Alt. 5	Alt. 2		Alt. 3			
Site	Evap. & Brine Pond	NCP	Evap. Pond	Brine Prod. Pond	NCP	Brine Pond	NCP	Evap. Pond	NCP	Freshening	Cooling	Freshening	Cooling	Alt. 2	Alt. 3
Big Sandy	5.6	6.4	1,214	0	0	0	0	3,700	0	0	0	0	0	0	0
Uintah Basin	17.0	18.2	915	3,063	2,163	3,594	1,945	1,600	0	1,775	911	1,505	772	5.83	5.24
Price River	17.2	18.4	567	1,954	1,376	2,663	1,540	990	0	1,142	582	1,274	650	3.7	4.17
San Rafael	17.4	18.6	445	1,497	1,014	2,049	1,276	776	0	847	440	1,027	533	2.73	3.44
Grand Valley	16.8	18.0	931	3,061	2,156	5,254	4,144	1,625	0	1,724	898	3,358	1,726	5.82	11.11
Lower Gunnison	16.8	18.0	931	2,755	2,067	4,968	3,914	1,625	0	1,638	858	3,172	1,637	5.58	10.51
McElmo Creek	46.1	49.4	672	1,907	4,434	3,433	7,982	1,1173	0	7,486	2,229	13,416	4,398	13.13	23.9

Table 5. Salt diversion at fossil power plant plus NCP sites. (Quantities are US tons--multiply by .9072 to get metric tons).

	Alt. 1	Alt. 2			Alt. 3			Alt. 4
Site	P.P.	P.P.	NCP	Total	P.P.	NCP	Total	P.P.
Big Sandy	2,356	0	0	0	0	0	0	31,552
Uintah Basin	3,942	4,170	16,438	20,600	64,627	13,935	78,560	64,627
Price River	3,366	2,607	9,378	11,980	35,740	10,482	46,220	35,740
San Rafael	2,690	2,085	6,301	8,390	25,655	7,637	33,290	25,655
Grand Valley	3,942	4,170	11,767	15,940	47,124	22,817	69,940	47,124
Lower Gun.	3,942	4,170	9,844	14,010	30,160	18,966	49,130	30,160
McElmo Creek	10,770	8,344	35,644	43,990	76,377	30,875	107,250	76,377
Totals	27,110			114,910			340,170	244,085

Cost Coefficients

The model does not explicitly calculate total revenue and subtract costs; rather, it simply multiplies the total quantity of any product by the estimated net profit (or loss) per unit. In the case of electricity, net profit in the original model varied over sub-regions but averaged $13/MWH (1975 dollars). This profit dominated all agricultural production in terms of competing for water allocation and therefore, no purpose would have been served by the laborious task of updating all agricultural and energy costs and revenues (500 variables) to 1982 levels (and perhaps obtaining the same net difference in many cases). What was important in the model revision process was to obtain adequate current estimates of the net return to energy production activities since the objective of the new portion of the model is to compare economic efficiency of various cooling tower and brine disposal technologies. This was also not an easy task, since the unit costs of both evaporation and solar salt gradient ponds (NCP) cited by various sources vary by several hundred percent. Also, the wholesale value of electricity varies greatly depending upon whether it is peak or base load.

It appears that electricity produced by NCP systems would be best used in a peaking mode, because of (1) very low start-up costs, and (2) the much higher production in summer (the peak electricity demand season in parts of the Colorado Basin). Therefore, a higher value of NCP electricity may be justified. The model was run with two values of gross revenue from electricity--$57/MWH, which is considered to be consistent with the $13 net revenue estimate for conventional power plants, and $95/MWH. The latter figure was used by the USBR in a related study of NCP systems (USBR unpublished report, 1981b).

Pond costs (either conventional or NCP) are difficult to estimate without a detailed site analysis of each site (which was beyond the scope of this study). The principal cost component is usually the lining. The purpose of the lining is to prevent contamination of groundwater and/or prevent brine from seeping toward the river. At sites where groundwater is already highly saline, no lining may be required. Where highly impervious soils are available near the site, a compacted clay lining may be used rather than the much more costly rubber or plastic membrane lining. A recent UWRL publication (Israelsen et al., 1980) estimates the cost of ponds with a membrane lining at $8-10 per m^2 The model runs reported here used costs varying from $2.7 to $10 per m^2. Since individual site conditions are not yet known, the same costs were used at all sites for any particular run.

7.2. Results

Descriptions of Model Runs

The regional model was run several times with a range (pessimistic to optimistic) of pond unit costs and price of electricity from the NCP systems and with various other changes in model constraints. These input data constraints and a brief summary of the results are shown in Table 6.

An important parameter that was varied is the constraint on change in salinity at Lee's Ferry (a measuring station near the exit to the upper basin). Environmental regulations have been interpreted as requiring no increase in lower Colorado Basin salinity above 1972 levels. Therefore, an important capability of this model is that of either (1) fixing the salt concentration at the upper basin outlet at that (or some other) level and observing the salinity management activities and the changes in agricultural and energy related water use which best achieve that water quality (in terms of economic efficiency); or (2) allowing the salinity to vary and observing resulting changes in water quality and economic efficiency.

Other special constraints which were included in some model runs were the elimination of downstream benefits due to salinity reduction and also forcing particular management activities in or out of a solution.

The model consists of 8 sub-watersheds, 5 of which contain one or more of the sites where use of LQW for cooling and for NCP sub-systems were considered (Figure 9). The type of information included in Table 6 (plus a great deal more detailed information) could therefore be presented for each sub-basin. It is not the intent of this report, however, to propose detailed site-specific recommendations. Rather, the intent is to demonstrate the model capabilities in a qualitative manner and to compare alternative types of salinity management activites and their approximate range of impact on the system given the assumptions on costs and efficiencies. For that purpose, the regional summary information contained in Table 6 is adequate.

Table 6. Summary of Regional Model Application Results.

RUN SPECIFICATIONS ——→						SOLUTIONS ——→											
	Cost Data Indicator[1]		Salinity at Lee's Ferry % Change From 1972			Alternative Technology Selected in Optimal Solution							(AF)[3]	(AF)			
					Misc.	Power Plant Site							Total	Total	Lee's	Net Benefit	Cost &
Run No.	Pond Costs	Price of Electricity	Fixed At	Solution Level	Special Constraints	BS	UB	PR	SR	GV	LG	Mc	LQW Used	AG Diversions	Ferry (10^6AF)	Minus a Large Constant[2]	Revenue Ranges
1	Hi	Lo	free	+.157	none	1	1	1	1	1	2	3	48,527	4,814,796	10.065	24.04	most pessimistic
2	Hi	Lo	0	0	none	1	1	1	1	1	2	3	48,527	4,794,769	10.072	24.03	
3	Hi	Lo	0	0	coal slurry lines deleted	1	1	1	1	1	2	3	29,768	4,794,769	10.147	0.11	
9	Hi	Lo	-5.0	-5.0	none	1	1	1	1	1	2	3	48,527	4,171,999	10.274	23.44	
10	Hi	Lo	free	-1.92	all alt.=3 except BS	1	3	3	3	3	3	3	93,269	4,814,769	10.065	0	
4	Hi	Hi	0	0	none	1	1	1	2	2	2	3	55,782	4,815,345	10.059	39.78	moderate
5	Hi	Hi	free	-.175	none	1	1	1	2	2	2	3	55,782	4,814,796	10.059	39.83	
14	Hi	Hi	free	+17.7	no downstream benefits	1	2	1	2	2	2	3	55,782	4,510,446	8.991	52.85	
15	Hi	Hi	0	0	no downstream benefits	1	1	1	2	2	2	3	55,782	4,815,345	10.059	39.78	
16	Hi	Hi	-2.0	-2.0	none	1	2	1	2	2	2	3	55,782	4,591,936	10.139	39.64	
18	Hi	Hi	-2.0	-2.0	no downstream benefits	1	2	1	2	2	2	3	55,782	4,591,936	10.134	35.35	
6	Lo	Lo	0	0	none	1	1	1	2	1&2	2	3	52,406	4,915,345	10.063	27.33	
7	Lo	Lo	free	-.018	none	1	1	1	2	2	2	3	52,805	4,814,796	10.062	27.34	
20	Lo	Lo	-2.0	-2.0	none	1	1	1	2	2	2	3	52,804	4,572,724	10.149	27,14	
8	Lo	Hi	free	-1.21	none	1	2	2	2	2	2	3	51,375	4,814,796	10.062	46.80	most optimistic
11	Lo	Hi	free	-.863	all alt.=3 except 2	1	2	3	3	3	3	3	58,764	4,814,796	10.065	39.06	
12	Lo	Hi	-2.0	-2.0	none	1	2	2	2	2	2	3	54,702	4,585,318	10.145	46.61	
19	Lo	Hi	free	+.14	SR=3 (fixed)	1	2	2	3	2	2	3	49,956	4,814,795	10.072	42.10	

[1] Lo pond cost = \$2.7/M^2 for brine makeup and \$7.0/M^2 for NCP; hi pond cost = \$4.8 and \$10/M^2; Lo price of electricity = \$57/MWH; Hi price of electricity = \$95/MWH.

[2] Run 10 objective function = 5797.82197 (10^6) was subtracted to improve scale.

[3] AF multiplied by 1.234 = $10^3 M^3$.

Comparison of Energy-Related Alternatives

(1) The solution summary suggests that with any cost and low revenue assumptions, use of LQW for power plant cooling (alternative 3) is economical only at the McElmo Site, where the LQW source is least saline (2700 mg/l). Other uses of alternative 3 shown in the table (runs 10, 11, and 19) were not selected by the optimization routine but were forced in order to answer "what if" questions.

(2) Under most pessimistic cost and revenue assumptions, the use of NCP systems (alternatives 2 and 3) for brine disposal is justified only at two sites. If the cost assumptions had been made even more pessimistic (costs higher and revenue lower), the same selection of power plant technologies (mostly conventional cooling and disposal) would remain until at some point alternative 1 would be selected even at Lower Gunnison and McElmo.

(3) Although not shown in the table, all coal slurry alternatives (using LQW) entered every solution at maximum levels. The large decrease in LQW use by problem 3 relative to 2, the much larger decrease in water use by agriculture (necessary to maintain salinity at the reference level), and the large drop in net benefits suggest the magnitude of the beneficial role very large coal slurry lines could play in salinity management.

(4) The apparent dominance of alternative 2 at most sites when moderate as well as optimistic cost and revenue assumptions are made suggest that use of HQW plus NCP systems should have important salinity management benefits.

(5) Salinity reduction is highly correlated with reduction in irrigation diversions. When salinity reductions are forced on the model, it responds by reducing agricultural diversions rather than increasing

use of LQW by power plants.

(6) If use of LQW by power plants other than at McElmo is forced on the model, a very significant decrease in total net benefit occurs. This fact together with (5) implies that use of alternative 3 is not desirable *unless objectives other than economic efficiency are important.*

(7) The fact that economic criteria do not favor use of LQW for power plants does not mean that power plants should not play an important role in salinity management (even if non-economic objectives are ignored). The importance of use of HQW for cooling but with blowdown supplying brine for NCP systems is clearly demonstrated by the solution summary. The NCP system is totally infeasible at sites without a supply of highly concentrated brine. The power plant can be conceptualized as a brine concentrator which is necessary for any use of NCP's at these sites. This is a crucial difference between the sites modeled here and those at dry lakes where brine already exists (such as the Danby and Sevier sites being modeled by the USBR).

(8) The left-to-right pattern of increasing use of LQW, particularly by NCP systems in the table is not accidental. The power plant sites are listed in general order of downstream river movement as well as decreasing latitude. Therefore, the high elevation of Big Sandy site has the lowest radiation and highest precipitation (a very bad NCP site), while McElmo has very high temperatures and low rainfall (with expected results favoring use of an NCP system).

Multi-Objective Conceptualization

Figure 10 shows the modeled variation of regional net benefits (to agricultural plus energy) with downstream salinity for various cost-revenue assumptions. For most functions, there is only a very small variation in benefits (a slight

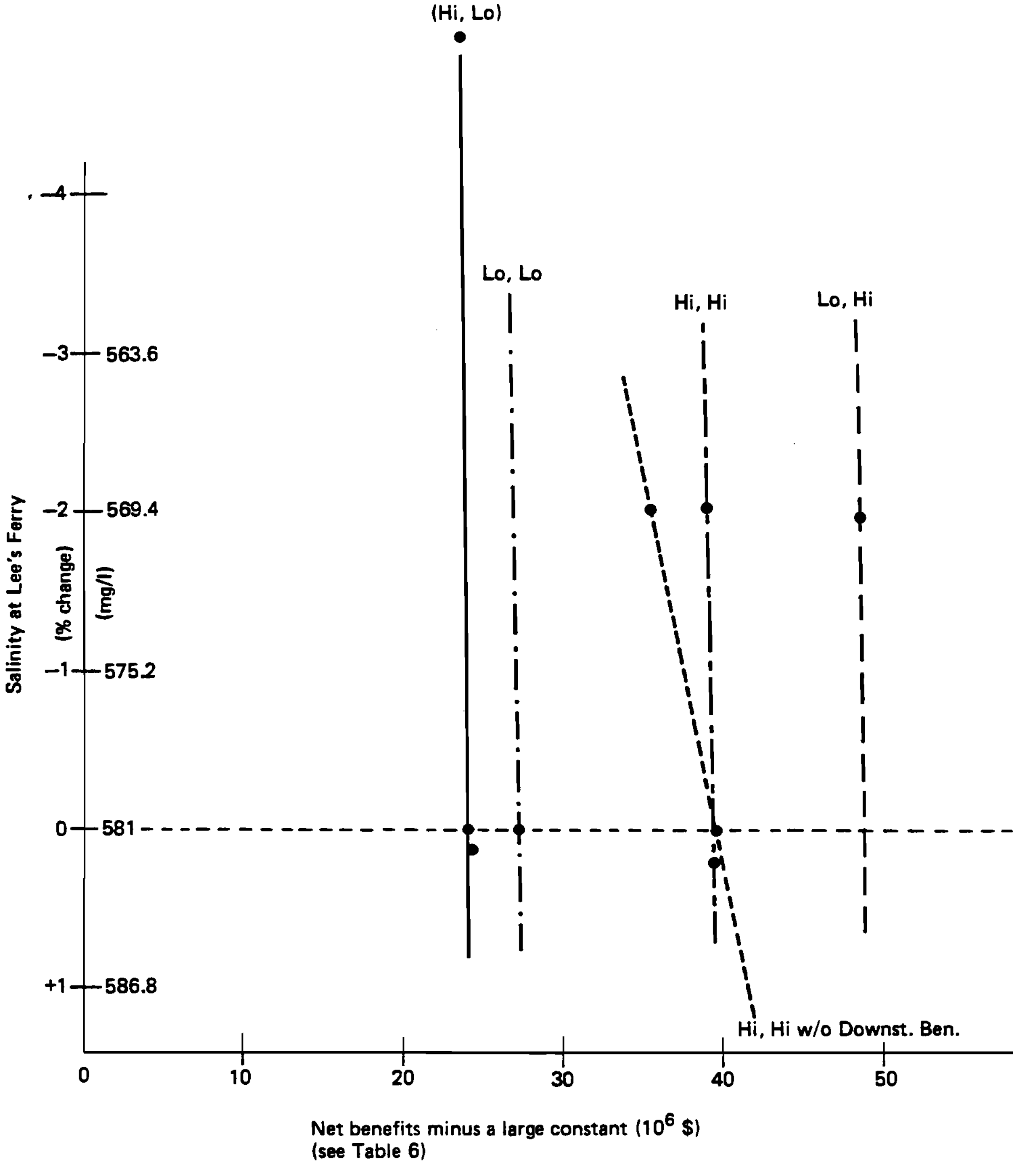

Figure 10. Relation between net benefits and downstream salinity for various cost assumptions.

slope to the left as salinity is reduced). The apparent reason is that downstream benefits are included in the net benefits. Salinity improvement entails costs but these are almost balanced by the downstream damages prevented. However, when downstream benefits are deleted from the model, the function slope increases as shown by the dashed "Hi Hi" cost assumption.

That particular function can be considered to quantify the tradeoff between the two objectives of economic efficiency and environmental quality if all downstream salinity damages are included as environmental impacts. In that case, elimination of downstream benefits from the model objective function is required in order not to duplicate the surrogate for environmental quality (salinity damages). The figure could therefore be revised by repeating all model runs without downstream benefits and re-labelling the axes environmental quality and economic efficiency. In one sense, this would be stretching the normal definition of environment quality, since most of the negative effects of salinity are really economic (damages to agricultural and municipal plumbing components). However, the salinity of this water in the lower basin is also approaching levels where public health effects could be of concern; therefore, an environmental quality objective has some logic and in this sense, keeping economic damages prevented in the model's single objective function may best represent reality.

Another multi-objective conceptualization is demonstrated by Figure 11. Each state government within this region (as well as federal government) places great importance on such objectives as rural development and stability of agricultural production. If we accept diversions of water for agriculture as an index of agricultural production (the model defines them as directly proportional) then we can consider Figure 11 as demonstrating trade-offs between agriculture and environmental quality (salinity). The figure suggests that an average of 1

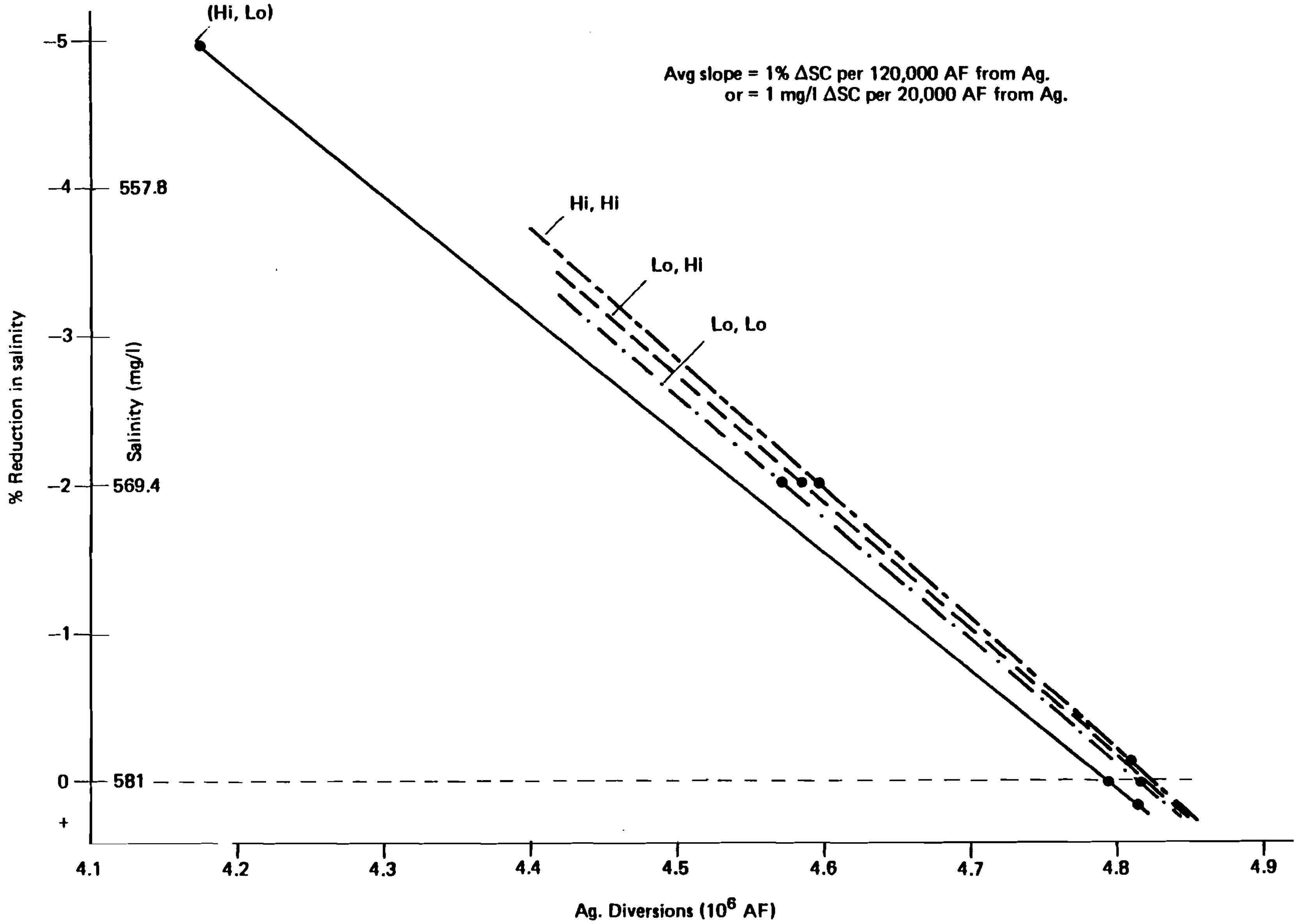

Figure 11. Variation of river salinity with ag. diversions.

percent reduction in salinity requires 120,000 acre-feet less water allocated to irrigation (20,000 AF per mg/l). This, of course, varies significantly among subbasins and a rational salinity management policy might be to encourage reduction in irrigation only in areas where return flows are most saline.

7.3. Conclusions from Application of Scenario Module

Conclusions related to policy design for salinity management cannot in general be made until the policy analysis module has been applied and analyzed. However, there are several important points which emerged from analysis of scenarios obtained using the regional model, as follows:

1. The order of magnitude of salt quantities which could be removed by applying the various management technologies at each of the seven proposed power plant sites which are within 100 miles of low quality water sources are as follows:

Technology	Tons of Salt	Fraction of Lee's Ferry Load
1. Status Quo (no use of LQW)	27,000	0.4%
2. HQW for cooling but add NCP	115,000	1.7
3. LQW for cooling plus NCP	384,000	5.6
4. LQW for cooling but no NCP	244,000	3.6

Technology 4 is totally infeasible economically. Therefore potentially realistic power plant related salinity reduction alternatives reduce to technologies 2 or 3.

2. From the viewpoint of *purely economic considerations*(that is, costs vs. economic benefits) technology 3 (use of low quality water for power plant cooling) is not justified at most sites. However, its use may be justified by other social objectives such as agricultural based rural development and stability or

environmental objectives.

3. Use of technology 2 (use of high quality water for cooling but with additional effluent concentration for supplying NCP brine) appears to be justified at most sites on a purely economic basis, and even in cases when downstream salinity reduction benefits are not considered.

4. Even though use of LQW for cooling is not cost effective, power plants can play an important role in salinity management if they are coupled to nonconvective solar ponds (as in technology 2). NCP's which are otherwise totally infeasible can become economically attractive when coupled to fossil fuel power plants which concentrate their effluent sufficiently.

5. Motivation of private (or public) power producers to adopt technology 2 should be possible with very little incentive (financial or other--such as expedited site approval) since the only requirement is a high level of brine concentration. Use of brine concentrators or other technologies such as binary cooling towers (which accomplish the same function) are already increasing for reasons unrelated to salinity such as decreasing the size of zero discharge evaporation ponds.

6. The amount of salt potentially removable at seven sites by technology 2 as given in conclusion 1 (115,000 tons) is greatly understated if one assumes that the high quality water acquired for cooling would be purchased from the agricultural sector (which usually is the case in this basin). For example, if the irrigation water involved was previously diverted at a quality of 300 mg/l and 50% was returned at 3,000 mg/l, the transfer to energy use would remove an additional 124,000 tons of salt making the total 239,000 tons.

7.4. Relation of Model Results to Salinity Management Policy Design

The foregoing discussion of the regional model application gives rather specific details on water and salt flow change related to assumed NCP efficiencies and cost coefficients, both for the total region and at individual power plant sites. The writers do not pretend that salinity management policy in the basin should now proceed based upon these numbers. Our modesty is dictated by the following reasons:

1. Engineering analysis of NCP system designs including much more detailed investigations of energy producion efficiencies, loading patterns, costs and revenues at each site are obviously needed.
2. Even in the happy but highly unlikely event that the model results represent the real system perfectly--they still represent only necessary but not sufficient information for policy design. So far, we have said little about the extent to which individual water using entities (farmers, corporations, irrigation districts, etc.) might be willing to change their water use patterns in order to move toward the regional model solution(s). We have said even less about what kind of policy designs and what levels of economic incentives might be required to motivate such changes. These are objectives for the second stage of this study.

What we have demonstrated is: (1) the kind of information the model is capable of producing, and (2) the approximate range of variation in power plant technologies which make economic sense (from the regional perspective) given our cost, discount, efficiency, etc., assumptions.

We are now in a position to undertake the second stage of the study concerned with the analysis of salinity management policies, using the economic and hydrologic understanding of the system obtained from the scenario module.

However, policy analysis requires models with several new dimensions. It involves knowledge of the objectives and possibilities of achieving them of the principal actors in the water use and policy universe which is to be defined. These include various levels of government, their agencies and the water users themselves. We plan to start using very simple representation of these issues with the hope to develop the approach further basing on qualitative results obtained using this simplistic version.

APPENDIX: OUTLINE OF A SIMPLE ANALYTICAL APPROACH TO THE SECOND STAGE OF THE STUDY

As has been discussed in Sect. 3 of this report, the first stage of the analysis results in obtaining a regional scenario that can be used as a target scenario at the second stage. According to the formulation of the problem in Sect. 4, we can understand a scenario as a tuple of technological matrices denoted by $(X_0^1, \ldots, X_0^N)$. This scenario is obtained using the scenario module of the type outlined in Sect. 5 of this report and describes the rational from the regional perspective allocation of the regional water resources among the producers and also in a certain sense degrees of their participation in the improvement of the quality of water resources in the region. After having determined this scenario we come to the second stage of our analysis.

To illustrate a possible approach to the second stage we consider it using as an example a simple model of one of the energy producers. We assume that the k-th producer considered can use water from two sources: one with high quality water, and the other with low quality (saline) water. Denote by W_1^k and W_2^k water withdrawals from the respective sources allocated to this producer according to the scenario obtained at the first stage of the analysis. In other words, withdrawing these amounts of water from the sources is considered rational from the regional perspective. Then the problem of the SMA with respect to this producer may be formulated as that of determining policies effectively motivating this producer towards withdrawing amounts of water from the respective sources possibly close to W_1^k and W_2^k.

We denote by w_i^k, $i=1,2$ actual amounts of water withdrawn by k-th producer from these sources, and by $E_i^k(w_i^k)$ the corresponding amounts of electricity produced (using the technologies compatible with the salinities of water from the sources considered). Let us also introduce the following notation:

K_i^k - capital investments for i-th technology;

S_2^k - subsidy (provided by the SMA) for the implementation of the technology using the low quality water;

p_E - market price per unit electricity produced;

p_i^k - charge per unit amount of water withdrawn from the source i, $i=1,2$.

r_i^k -interest rate, $i=1,2$.

Using this notation, the net benefit function of the k-th producer can, for example, be written as follows:

$$\begin{gathered}F^k(w_1^k) = p_E[E_1^k(w_1^k)+E_2^k(w_2^k)]-r_1^k K_1^k(w_1^k)- \\ -r_2^k[K_2^k(w_2^k)-S_2^k]-p_1^k w_1^k-p_2^k w_2^k\end{gathered} \tag{1}$$

With the values of all the parameters in this function fixed, the behavior of the k-th producer consists of achieving the greater possible net benefit F^k by appropriately choosing the amounts of water w_1^k and w_2^k satisfying all physical as well as institutional constraints specific to the region considered.

The SMA regulation lies in choosing the values of these parameters (or some of them) in such a way as to motivate the producer to use the amounts of water from the source 2 (with low quality water) not smaller than W_2^k and from the source 1 not greater than W_1^k. As has been discussed earlier in Section 4 of this report, the SMA can inform the producers about its functional rules of fixing the values of these parameters depending upon the actual amounts of water withdrawn from the sources. In this case, the net benefit function of the k-th producer takes the form:

$$\begin{gathered}F^k(w_1^k,w_2^k) = p_E[E_1^k(w_1^k)+E_2^k(w_2^k)]-r_1^k K_1^k(w_1^k)- \\ -r_2^k(w_2^k)[K_2^k(w_2^k)-S_2^k(w_2^k)]-p_1^k(w_2^k)w_1^k-p_2^k(w_2^k)w_2^k\end{gathered} \tag{2}$$

The SMA expenditures associated with the implementation of these policies can be written in the form:

$$Q = \sum_{k=1}^{N} (r_1^k - r_2^k(w_2^k))K_2^k(w_2^k) + r_2^k(w_2^k)S_2^k(w_2^k) +$$

$$+ p_1^k(w_2^k)w_1^k + p_2^k(w_2^k)w_2^k$$

The goal of the SMA is to make these expenditures the lowest possible, and also to make the vector $w_2 = (w_2^1, \ldots, w_2^N)$ not smaller (by elements) than the vector (scenario) $W_2 = (W_2^1, \ldots, W_2^N)$ and the vector $w_1 = (w_1^1, \ldots, w_1^N)$ not greater than the vector (scenario) $W_1 = (W_1^1, \ldots, W_1^N)$, where w_1 and w_2 are "responses" of the producers to the policies $r_2^k(w_2^k)$, $S_2^k(w_2^k)$, $p_i^k(w_2^k)$, $k = 1, 2, \ldots, N$, $i = 1, 2$.

An implementation of this analytical scheme can be based on fixing appropriate parametric families of these policies and then determining values of the parameters which provide for the responses of the producers closer possible to the values specified by the scenario. The computational difficulties, although not exceptional, call for the application of interactive analytical procedures. The elaboration of appropriate interactive models and procedures for this type of analysis is the subject of further research for this study.

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