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Development of a Water Quality Simulation Model Applicable to Great Salt Lake, Utah

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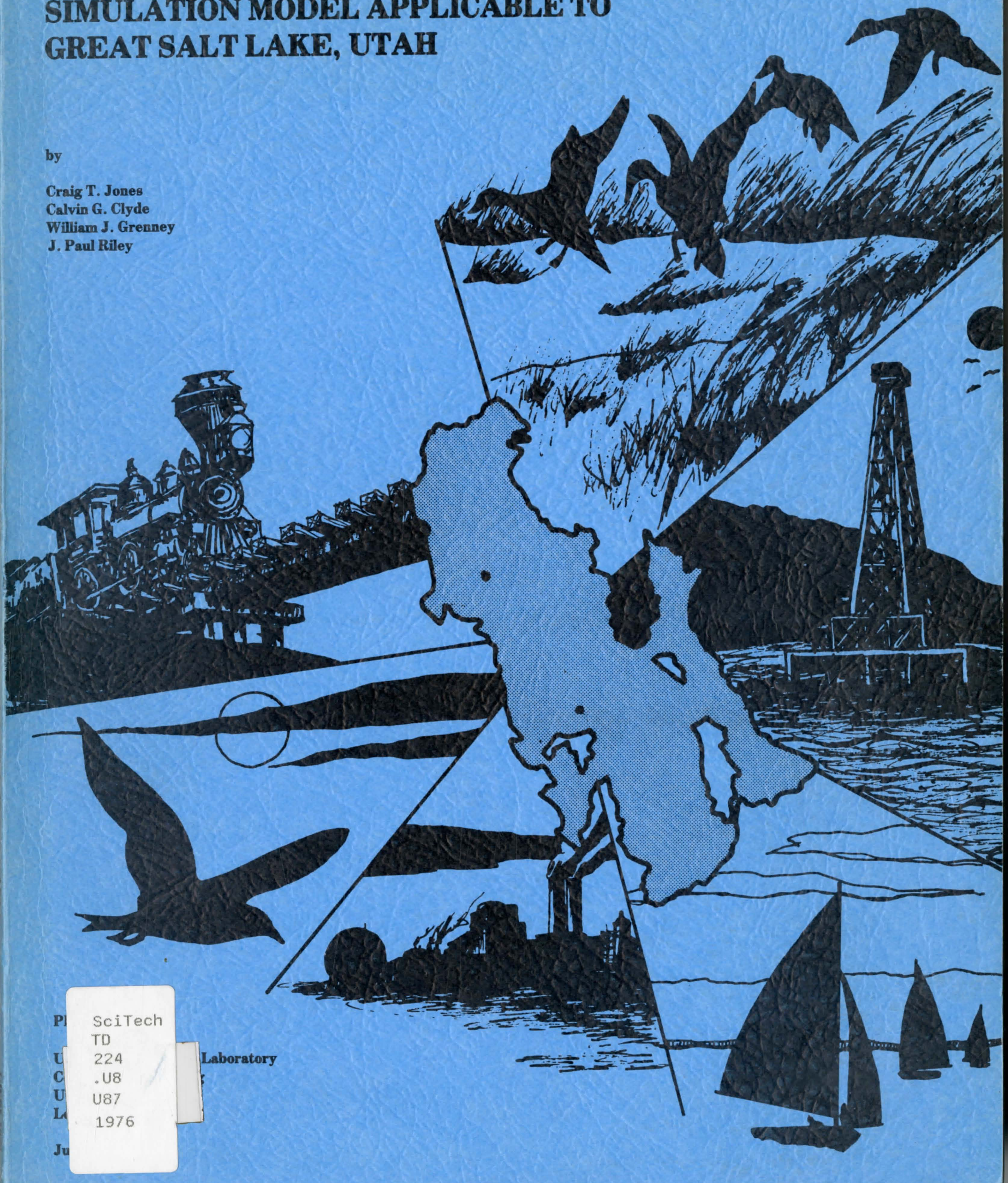

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ABSTRACT

The development of a model capable of predicting the long term (seasonal) distribution of water quality constituents within Great Salt Lake was undertaken as a portion of the ongoing Great Salt Lake project at Utah State University. The overall goal of the project is the development of a modeling framework to assist relevant decision making bodies in the comprehensive management of the Great Salt Lake system. Phase I of the project provided the overall structural framework for management of the Great Salt Lake system, identified data needs, and established priorities for the development of submodels for incorporation into the overall framework. Phase II of the project involves the process of developing submodels, and Phase III will be concerned with application of the framework of models to specific management problems.

This study provides, as part of the second phase of the Great Salt Lake project, a model capable of predicting the long term distribution of quality constituents within the lake. This capability is a necessary component of the modeling framework since it will allow the investigation of the effects which alternative water quality management plans will have on the distribution of water quality constituents within the lake.

The water quality model of the lake is based on the application of the advection-diffusion equation to the three-dimensional transport of a quality constituent. The modeling technique is formulated by discretizing the system as a network of nodes interconnected by channels in both the horizontal and vertical directions. This representation of the system allowed the horizontal transport to be treated mathematically as one-dimensional. The resulting modeling technique is applicable to any lake, estuary, or bay in which the concentration gradients must be described in all three coordinate directions.

In applying the model to Great Salt Lake a two-layered vertical network was employed due to the physical characteristics of the system. The model was further simplified by describing vertical transport by diffusion alone. Using observed total dissolved solids concentrations, a method was developed during the study for establishing the vertical diffusion coefficient as a function of depth.

A unique feature of this water quality modeling technique is that it allows the seasonal distribution of a quality constituent to be studied without the necessity of developing a hydrodynamic model of the system. The advective transport is designed to be input to the model based on observed long term circulation patterns. In the case of Great Salt Lake, circulation patterns are not yet well known. However, approximate patterns have been established from some observations to date, and those were used to provide preliminary tests of the validity and response characteristics of the model. These tests have demonstrated that the model will be a practical and useful tool for monitoring the distribution of quality constituents within the lake.

ACKNOWLEDGMENTS

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Many people assisted with the acquisition of needed data, and provided constructive comments and suggestions throughout the course of the study. Special thanks are extended to Mr. Ted Arnow and his staff of the U.S. Geological and Mineralogical Survey in Salt Lake City, and to several members of the staff of the Utah Geological and Mineral Survey. These people were very helpful throughout the study and provided useful data on concepts which contributed to the success of the research. Gratitude also is expressed to Dr. Ronlald V. Canfield, Dr. Gary Z. Watters, and Mr. Jim Mulder for their careful and constructive review of the manuscript. Their comments added significantly to the content of the report.

In conclusion, the authors wish to recognize the degree to which the Utah Center for Water Resources Research and the Office of Water Research and Technology in Washington, D.C., have contributed to the success of this project. Over the years these offices have provided a large portion of the funding support which contributed to the development of the computer modeling techniques and procedures which were applied in this study. In a very real sense, the project represents the application of research results to the solution of practical problems of the real world.

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CHAPTER I

INTRODUCTION

Because of the wide range of effects water quality has on the uses of water and related resources, it is assuming an increasingly more important role in water resources planning. This study was undertaken with the objective of producing a water quality distribution model of Great Salt Lake as part of an ongoing Utah Water Research Laboratory project involving the lake. The major objective of the Great Salt Lake project is to develop a framework of computer models which will aid in the proper management of the resources of the entire lake system including the lake and its drainage area. This study provides a water quality model of Great Salt Lake necessary for that framework of models.

A time varying computer model of the water quality component of the lake was developed. The technique was modified to simulate the long term (seasonal) response by holding the lake constant at a specific surface elevation throughout the simulation period and by using lake current patterns, inflows, and outflows averaged over a season of interest.

The finite difference modeling technique was structured to represent the system as a network of nodes, interconnected by channels. This schematization allowed the two-dimensional horizontal transport to be treated using a flexible non-rectangular grid. The resulting modeling technique is general in nature and is applicable to the simulation of the distribution of both inorganic and organic water quality constituents.

The research presented in this report is unique in that the modeling technique allows the distribution of a quality constituent to be described in all three dimensions. Thus, the modeling technique is applicable to systems in which the spatial variation of quality constituents in each coordinate direction is too large for the system to be represented mathematically as a one- or two-dimensional system. This will allow the technique to be adapted to lakes and estuaries in which vertical density stratification is an important characteristic of the physical system.

In a system such as Great Salt Lake, the hydrodynamics of flow are quite complex due principally to the vertical density stratification. At present, no numerical models are available which adequately describe the flow in such a system. Models which describe the hydrodynamics of flow in less complex systems indicate that, even when a hydrodynamic modeling technique applicable to Great Salt Lake becomes available, it will be costly to operate and will require an extensive data base for verification.

A basic feature of the modeling technique described in the report is that the technique can be used either independently of, or in conjunction with, a hydrodynamic model. Circulation patterns and velocities can be input to the model based on observed data. The advantages of this approach are:

1. The model is not dependent on the development of a hydrodynamic model to describe flow patterns but may be used in conjunction with one if such a model is developed at a later time.

2. The model provides information on the distribution of water quality constituents based on observed transport processes.

3. The modeling technique gives enough detail to provide most of the information required for management decisions.

4. The modeling technique allows the identification of areas where data gathering or data refinement is required.

The water quality model can be used to investigate the behavior of the water quality aspects of Great Salt Lake in two different modes. Independent of other problems, the water quality model can be used to investigate the response of Great Salt Lake, at a fixed elevation, to the input of various levels of water quality constituents from different sources and to possible modifications of the physical lake system. When the water quality model is used in this manner, it is a valuable management tool which can provide insight into the proper management of the water quality aspects of the lake by predicting the fate of pollutants which reach the lake. This approach was used in this study to demonstrate the applicability of the model to the simulation of the distribution of water quality constituents within Great Salt Lake.

The water quality model is also applicable, when linked with a hydrologic model of the lake, to investigations of changes in the hydrology and water quality components of the lake in response to input alterations or modifications to the physical lake system. The water quality model is not designed to be independent of a lake hydrology model when combined in the framework of computer models under subsequent phases of the Great Salt Lake project. Over the periods for which the water quality model will be applied, the hydrologic model will provide information to the water quality model relating to the lake stage and the exchange of brine through the railroad causeway which divides the lake. The United States Geological Survey has developed a hydrologic model of the lake which will be available for use during later stages of the Great Salt Lake project.

The water quality modeling technique developed during this study can accommodate both conservative and non-conservative constituents, including the interactions which may occur between non-conservative constituents.[1] This capability of evaluating the consequences of inputting various levels of water quality constituents to the lake is a highly valuable function of the water quality model. The model is able to represent the distribution of a single constituent or to account for interactions between constituents including interactions within the ecosystem. Once appropriate data become available, the water quality model can be used to study the effects on the water quality system which will result from altering the present level of water quality constituents entering to the lake. Altering the present level of quality constituent inflow or the location of the inflow may produce changes in the distribution of water quality constituents within the lake which could adversely effect some uses of the lake. Since the interactions which occur in the ecosystem are a major component of the water quality system increasing or decreasing the level of input of certain constituents to the lake such as nutrients or toxic chemicals could significantly alter the present ecosystem and change the water quality characteristics of the lake.

The water quality model can be used, with certain limitations, to investigate the consequences of changes to the physical lake system on the distribution of water quality constituents. Since the flows in the water quality model are determined from observed circulation patterns, the use of the model in this manner is restricted by the extent to which the lake circulation patterns are predictable following the change. In many situations, such as pumping brine to maintain a specific maximum surface elevation in the lake, the effect on the circulation pattern would be local if the withdrawal were small in comparison to the advective transport and the model should provide realistic results. However, major alterations to the physical lake system, such as diking part of the lake, may significantly alter the circulation patterns. In such cases, the model could be used to investigate possible consequences the modification may produce by assuming circulation patterns which might result and testing for adverse effects on the distribution of quality constituents. The investigation of alterations to the physical lake system could, of course, be aided by the separate development of a hydraulic model of the lake. Such a model would provide information to the water quality model concerning the circulation patterns which would result from proposed alterations. Such information would be used in the water quality model to determine the effect the proposed alteration would have on the distribution of quality constituents.

The water quality model was applied to the south arm of Great Salt Lake to illustrate the type of water quality distribution questions which can be investigated with the model and to test the sensitivity of the model to variations of the model parameters. The south arm of the lake was chosen because the principal uses of the lake are associated with this arm and future data gathering efforts will probably focus on this arm. At the outset of this study it was realized the data presently available for Great Salt Lake were limited. Data gathering by state and federal agencies concerning the transport processes within the lake are in the preliminary stages. Data concerning the distribution of water quality constituents within the lake and the non-transport processes which effect the concentration levels of quality constituents are inadequate. However, by developing the model at this time it was possible to gain valuable insight into various sensitivities regarding the Great Salt Lake system. This process aided the assessment of relating data needs and

[1] The concentration of a constituent within a system is a function of the processes which transport the constituent through the system and any processes within the system which generate or degrade the constituent. The concentration of a non-conservative constituent is dependent on both the transport processes and the internal processes, while the concentration of a conservative constituent is dependent on only the transport processes.

importance. The ability of the model to realistically simulate the distribution of quality constituents within the south arm of the lake was demonstrated by approximating unknown parameters from those data which are presently available.

Data which were available on the distribution of total dissolved soids within the south arm were used to establish the value of the vertical diffusion coefficient as a function of depth. Besides using the vertical diffusion coefficient to describe vertical transport in the water quality model, the vertical transport was included in a separate water and salinity balance model of the lake.

The water and salinity balance model was formulated by assuming the north arm of the lake to be a completely mixed unit and dividing the south arm of the lake into layers along the vertical axis. In the south arm this resulted in a one-dimensional vertical transport model. The model was used to simulate the water and salinity balance within the lake over monthly time steps which allowed the future trend of brine within both arms of the lake to be investigated. The addition of vertical transport to the hydrologic model provided the refinement of the water and salinity balance model which was necessary to properly simulate the salinity balance in the south arm. The hydrologic model developed by the United States Geological Survey is based on a more sophisticated water balance of the lake than the water balance used in this study. Incorporating the vertical transport into the USGS model would result in a model with both a refined water and salinity balance of the lake.

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CHAPTER II

BACKGROUND

In general, the development of Great Salt Lake has proceeded as a series of uncoordinated activities without an overall management plan. However, in recent years public concern has increased that the resources of Great Salt Lake and its surrounding basin be properly managed in order to achieve maximum public benefit from these resources. A myriad of potential uses exist for these resources, and the manner in which the resources are eventually allocated and used will have a long term impact on the economic and social development of the entire State of Utah. The question of how the resources of Great Salt Lake can be utilized to best meet the needs of the citizens of Utah is a real one, and the answer requires a well integrated and cooperative approach by all groups and agencies concerned with the resources of the entire lake system.

The Great Salt Lake Project

In early 1973 a study was initiated at Utah State University with the goal of formulating an integrated approach to the management of the entire Great Salt Lake system. The basic consideration of the study was the development of a framework of computer models with the capability of analyzing and predicting the consequence of various development or management alternatives. Such a framework of models would aid the decision-making process by providing a means to develop a management strategy for allocating the resources of the region so as to provide for the optimal enhancement of environmental quality, economic development, and the social well being within the region.

The overall objective of the Great Salt Lake project can be broken into subobjectives as follows:

1. To examine societal, environmental, economic, and other activities relating to the Great Salt Lake system, such as oil well-drilling, extraction of minerals from the lake, and the construction of physical structures in the lake.

2. To examine the positive and negative impacts (societal, environmental, and economic) of various commercial and economic activities, such as land use (including urbanization) and structural developments within the tributary basins to the lake.

3. To examine the positive and negative impacts (societal, environmental, economic, and others) of various exogenous (from outside the region) inputs and constraints, such as:

a. Federal decisions which affect environmental quality, appropriation of funds, and changing use priorities.

b. Economic development outside the region.

c. Advances and changes in science and technology, such as improvements in mineral extraction processes and shifts in demands upon particular resources.

4. To develop a comprehensive planning framework for the development of the Great Salt Lake and its immediate environment. This framework will provide productive assessments of alternatives helpful in the decision-making process.

At the time the project was initiated, it was divided into three separate phases as outlined in Figure 2.1. Phase I was involved with defining the problem and the scope of activities for the subsequent model development phase (Phase II) and the model operation and application phase (Phase III). Depending upon the ultimate stage of model development, various aspects of Phases II and III could be continued for an extended period of time with considerable overlapping.

Summary of Phase I

The completion of Phase I resulted in a report (Riley et al., 1975) which basically outlines a management framework for the Great Salt Lake

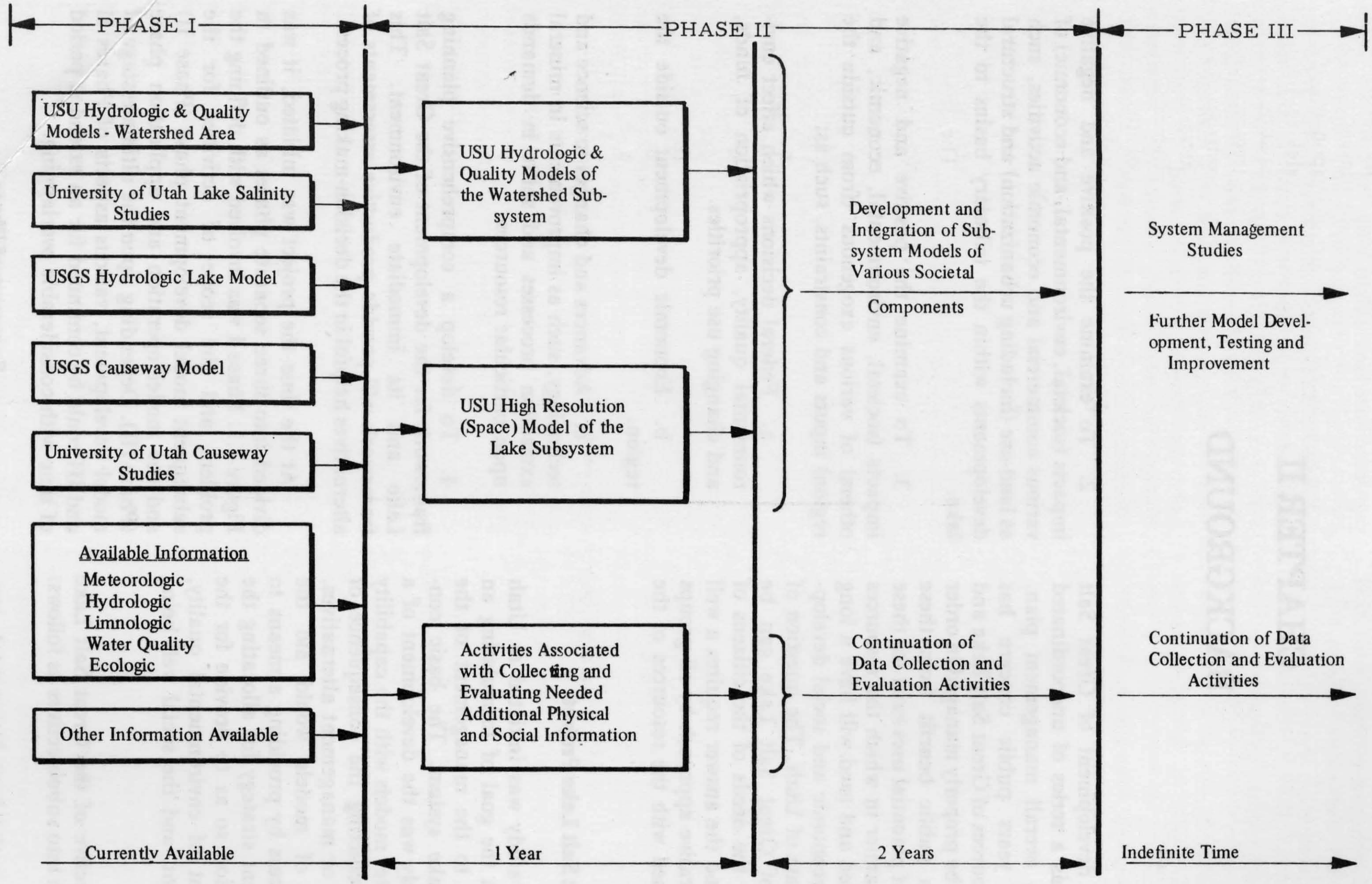


Figure 2.1. Schedule of phases in the project to develop a management model of the Great Salt Lake water resource system (Riley et al., 1975).

system. The specific accomplishments of Phase I can be summarized as follows:

1. The identification and evaluation of the previous studies, data, and other information pertaining to the lake system.

2. The identification of the following:

a. The major present or potential societal uses associated with the lake system.

b. Means by which the physical system might be modified to implement these societal uses within the environmental constraints.

c. Potential problems or impacts which might occur as a result of the modifications suggested under 2(b) above.

3. The identification of a procedure for estimating the relative magnitudes of the impacts identified under 2(c) above.

4. The identification of general information needs, model structure, and steps for the model development processes of Phase II.

An important objective of Phase I was the development of a procedure to define the management problems and objectives involving the Great Salt Lake system. Without this essential step, a meaningful and effective management strategy obviously could not be formulated and implemented.

A system is managed in order to accommodate specific goals and objectives which are identified with particular social uses. For the Great Salt Lake system the major social uses are:

1. Recreation and tourism.
2. Mineral extraction.
3. Transportation.
4. Brine shrimp harvesting.
5. Oil drilling.
6. Fresh water supply.

These major social uses were used in preparing a chart (Table 2.1) which illustrates how problems associated with possible uses of the resources of the system can be identified. Table 2.1 lists some of the desirable system characteristics for each use and the methods or system modifications by which these characteristics might be achieved. Table 2.1 further identifies problem areas which might result from modifying the system and the social use area these modifications affect.

Table 2.2 contains a matrix which is used to assign relative magnitude and importance to each of the areas of impact listed in the fourth column of Table 2.1. The information which ensues from Table 2.2 aids the development of a management model by defining critical areas of potential impacts. In this way, insight is increased concerning the kinds of problems which the management model should be designed to solve.

The long range goal of developing a comprehensive management model of the lake system requires a model which is sufficiently broad in scope to consider the entire lake system, and which also has adequate resolution in terms of both time and space dimensions to realistically represent the system. The development of a comprehensive model of a system such as the Great Salt Lake system is a difficult and lengthy process. For this reason, the problem is being approached by decomposing the total system into a number of subsystems and considering the subsystems as being organized in terms of hierarchies or levels, as shown by Figure 2.2. This procedure permits the separate identification and subsequent development of models for the various components of the total system. In this process, model resolutions might be varied from one component subsystem to another, depending upon the requirements of the overall model and the available knowledge of each particular subsystem. The hierarchical-multilevel structure shown by Figure 2.2 is achieved through the combination of the models of the several subsystems which become submodels in the hierarchical structure.

Two layers are recognized in the hierarchical structure (Haimes and Macko, 1973) namely, an information layer (first layer) and a prediction and optimizing layer (second layer). The first layer submodels are used to represent the various physical aspects of the system. The second layer is composed of two levels: societal and economic goals and considerations (first level); and political and decision-making considerations (second level). The first level of the second layer in the hierarchy consists of submodels which consider the societal and economic goals of the six earlier named social uses of the lake system. Each of the social uses must be quantitatively analyzed with respect to its benefits and utilities, cost to the public and environment, and its impact on hydrological, limnological, and ecological aspects of the lake and its basin.

Table 2.1. Identification of problems associated with possible uses of Great Salt Lake (Riley et al., 1975).

Possible Uses	Desirable System Characteristic Related to Uses	Some Methods of Achieving Desirable System Characteristics	Some Possible Problem Areas Influenced by Implementation of Methods (Impact Areas)	Some Social Use Areas Affected by Problems
Recreation and Tourism	Stable Water Level	Dike Construction in the Great Salt Lake	Alterafion of Circulation Patterns	Mineral Extraction Industry Recreation
			Physical Barrier to Free Access to Entire Lake	Recreation Water Transportation
			Maintenance of Dikes	Recreation and Tourism
			Alteration of the Biological Habitat	Wildlife Bring Shrimp Harvesting Recreation
		Construction of Tributary Storage Reservoirs	Flooding of Developed Lands	Recreaction Agriculture Industry Transportation
			Alteration of Biological Habitat	Wildlife Recreation
		Transbasin Diversions	Interrupted Deliveries During Low Flow Periods	Recreation
		Weather Modification	Alteration of Biological Habitat	Wildlife Recreation
			Control Procedures not Sufficiently Well Established	Agriculture Recreation
	Fresh Water Bodies for Water Based Activities (Skiing, Boating, Swimming, Fishing)	Dike Construction in the Great Salt Lake	(Same as those Listed Under Stable Water Level)	
		Construction of Tributary Storage Reservoirs	(Same as those Listed Under Stable Water Level)	
	Easy Access	Road Construction	Maintenance Problems	Recreaction
			Obtaining Right-of-Ways	Agriculture Wildlife
		Dike Construction in GSL for Road Bed	(Same as Those Listed Under Stable Water Level)	
		Development of Parks, Resorts, Beaches, and Associated Features	Adverse Ecological Effects	Wildlife Recreation
			Aesthetics (Visual)	Recreation
			Use Regulation	Recreation
			Interference with Other Possible Uses	Recreation Industry Agriculture

Table 2.1. Continued.

Possible Uses	Desirable System Characteristic Related to Uses	Some Methods of Achieving Desirable System Characteristics	Some Possible Problem Areas Influenced by Implementation of Methods (Impact Areas)	Some Social Use Areas Affected by Problems
Recreation and Tourism (cont.)		Boat Launching, Mooring, and service Features	(Same as Those Listed Under Road Construction)	
			Aesthetics	Recreation
	Optimum Use Intensity	Developing Facilities in Accordance to Demand	Adverse Ecological Effects	Wildlife Recreation
			Interference with Other Possible Uses	Recreaction Industry Agriculture
		Reservation Policies	Reduced Per Capita Recreational Opportunity	Recreation
		Charges for Use	Some Limitations of Use to Lower Income Groups	Recreation
	Low Health Hazard	Adequate Sewage Treatment	Installation and Operation of Plants	Recreation Tourism
		Solid Waste Disposal	Implementation and Operation of Collection and Disposal Facilities	Recreation Tourism
		Mosquito Control Measures	Marsh Stabilization	Water Supply Wildlife
			Operation and Maintenance of Spray Equipment	Recreation
	Low Insect Population (Brine Fly, Deer Fly, Horse Fly)	Chemical Spraying	Adverse Ecological Effects (Mainly Through Food Chain)	Wildlife
			Problems Associated With Decaying Organic Matter	Recreation
		Biological Control	(Same as Those Listed Under Chemical Spraying)	
Mineral Extraction	Aesthetic Appeal	Structural Design	Economic Feasibility	M.E. Industry
		Low Plant Density	Number of Plants is Restricted	M.E. Industry
		Construction of Plants in Remote Areas	Access	M.E. Industry
	Maintenance of Natural Brince Concentration	Provide for Adequate Flow Through Causeways (Alter Existing Structure and Include in Design of Planned Structures)	Economic Feasibility	M.E. Industry Transportation
			Change in Brine Concentration on Both Sides of Existing Dikes	M.E. Industry
			Objectives Associated With Development of Fresh Water Areas Could Not Be Achieved	Recreation Wildlife

Table 2.1. Continued.

Possible Uses	Desirable System Characteristic Related to Uses	Some Methods of Achieving Desirable System Characteristics	Some Possible Problem Areas Influenced by Implementation of Methods (Impact Areas)	Some Social Use Areas Affected by Problems
Mineral Extraction (cont.)	Maintenance of Adequate Brine Concentration for Efficient Plant Operation	Dikes to Produce Evaporation Areas	Maintenance of Dikes	Recreation Tourism
			Interference with Other Possible Uses of Area	Recreation Water Supply M.E. Industry
		Convey Brine From Areas of High Brine Concentration	Economic Feasibility	M.E. Industry
			Maintenance of Equipment and Facilities	M.E. Industry
		Construct Plants at Locations of High Brine Concentration	Economic Feasibility	M.E. Industry
		Limit Number of Plants on Lake	Regulation	M.E. Industry
		Limit the Extraction Rate of Each Plant	Economic Feasibility	M.E. Industry
			Regulation	M.E. Industry
	Adequate Transportation Facilities	Roads	Maintenance Problems	M.E. Industry
			Acquisition of Right-of-Ways	Agriculture Wildlife
			Interference with Lake Circulation Patterns	M.E. Industry
			Physical Barriers to Free Access to Entire Lake	Transportation Recreation
	Minimize Ecological Effects	Appropriate Location of Plants and Evaporation Ponds	Access	M.E. Industry Wildlife Recreation
			Economic Feasibility	M.E. Industry
			Adequate Brine Concentration at Point of Diversion	M.E. Industry
		Limit Extraction Rates so as to Maintain Brine Concentrations and Constituents in the Lake	Regulations	M.E. Industry
			Economic Feasibility	M.E. Industry

Table 2.1. Continued.

Possible Uses	Desirable System Characteristic Related to Uses	Some Methods of Achieving Desirable System Characteristics	Some Possible Problem Areas Influenced by Implementation of Methods (Impact Areas)	Some Social Use Areas Affected by Problems
Transportation	Stable Road	Causeway and Roadbed Construction	Economic Feasibility	Transportation Industry
			Aesthetics	Recreation
			Disturbance of Lake Circulation	M.E. Industry
			Disturbance of Brine Concentration	M.E. Industry Brine Shrimp Harvesting
			Interference with Ecological Habitat	Brine Shrimp Harvesting Wildlife
			Interference with Other Possible Uses	Recreation Water Transportation
	Minimum of Obstacles	Open Channels for Water Transport	Interference with Other Possible Uses	M.E. Industry Land Based Transportation
		Flat Road Grades (Such as Railroad Causeway)	(Same as Those Listed Above Under Causeway and Roadbed Construction)	
		Smooth Road Surfaces	Economic Feasibility	Transportation Industry
			Maintenance (Such as Erosion by Wave Action)	Transportation Industry
	Minimum Distance	Construction Method	(Same as Those Listed Above Under Causeway and Roadbed Construction)	
	Pleasing Surroundings	Appropriate Selection of Road Location	(Same as Those Listed Above Under Causeway and Roadbed Construction)	
		Construction Method	(Same as Those Listed Above Under Causeway and Roadbed Construction)	
Brine Shrimp Harvesting	Adequate Nutrients	Maintain Conditions Required for Algae Growth	Enhancement of Brine Fly Population	Recreation
			Interference with Other Possible Uses	Recreation M.E. Industry
	Require Brine Concentration Level	Limit Rate of Mineral Extraction	Economic Feasibility	M.E. Industry
			Regulation	M.E. Industry
		Maintain Natural Circulation Patterns	Interference with Other Possible Uses	Transportation Recreation M.E. Industry

Table 2.1. Continued.

Possible Uses	Desirable System Characteristic Related to Uses	Some Methods of Achieving Desirable System Characteristics	Some Possible Problem Areas Influenced by Implementation of Methods (Impact Areas)	Some Social Use Areas Affected by Problems
Brine Shrimp Harvesting (cont.)		Create Artificial Cultivation Areas	Disturbance of Lake Circulation	M.E. Industry
			Disturbance of Brine Concentration	M.E. Industry
			Interference with Ecological Habitat	Wildlife
			Interference with Other Possible Uses	Recreation Water Transportation M.E. Industry
	Required Oxygen Level in Lake	Natural Processes	None	
		Adequate Sewage Treatment	Installation and Operation of Plants	
	Maintenance of Conditions Free From Harmful Pollutants	Utilize Adequate Control Measures	Interference with Other Possible Uses	Oil Drilling Recreation Industry
			Regulation	Oil Drilling Industry
Oil Drilling	Aesthetic Appeal	Structural Design	Economic Feasibility	Oil Industry
		Construction of Facilities in Remote Areas	Economic Feasibility	Oil Industry
			Access	Wildlife Oil Industry
	Adequate Transport Facilities	Road	(Same as Those Listed Under Minearl Extraction)	
		Pipeline	Line Oil Spill	Recreation M.E. Industry Wildlife
			Physical Barrier to Free Access to Lake	Wildlife Recreation M.E. Industry
	Maximum Production of Oil	Appropriate Location of Drilling Facilities	Interference with Other Possible Uses	Wildlife Recreation M.E. Industry
	Minimize Ecological Effect	Appropriate Location of Drilling Facilities	Lack of Adequate Oil at Location of Drilling Facilities	Oil Industry

Table 2.1. Continued.

Possible Uses	Desirable System Characteristic Related to Uses	Some Methods of Achieving Desirable System Characteristics	Some Possible Problem Areas Influenced by Implementation of Methods (Impact Areas)	Some Social Use Areas Affected by Problems
Oil Drilling (cont.)		Minimize Oil Spill Problem	Regulation	
			Appropriate Transportation of Oil	Oil Industry
Water Supply	Fresh Water Storage	Dike Construction in GSL	(Same as Those Listed Under Recreation and Stable Water Level)	
		Construction of Tributary Storage Reservoirs	(Same as Those Listed Under Recreation and Stable Water Level)	
	Supplement Natural Supply	Transbasin Diversions	Interrupted Deliveries During Low Flow Periods	Water Supply
		Weather Modification	Alteration of Biological Habitat	Wildlife Recreation
			Control Processes Not sufficiently well established	Agriculture Recreation
		Recycle Wastewater	Reduced Inflow to GSL	Recreation M.E. Industry Wildlife
		Desalt Flow	Reduced Inflow to GSL	Recreation M.E. Industry Wildlife

Table 2.2. Information matrix for assessment of environment impacts on the water resource system of the of the Great Salt Lake (modified from Leopold et al., 1971).

Instructions

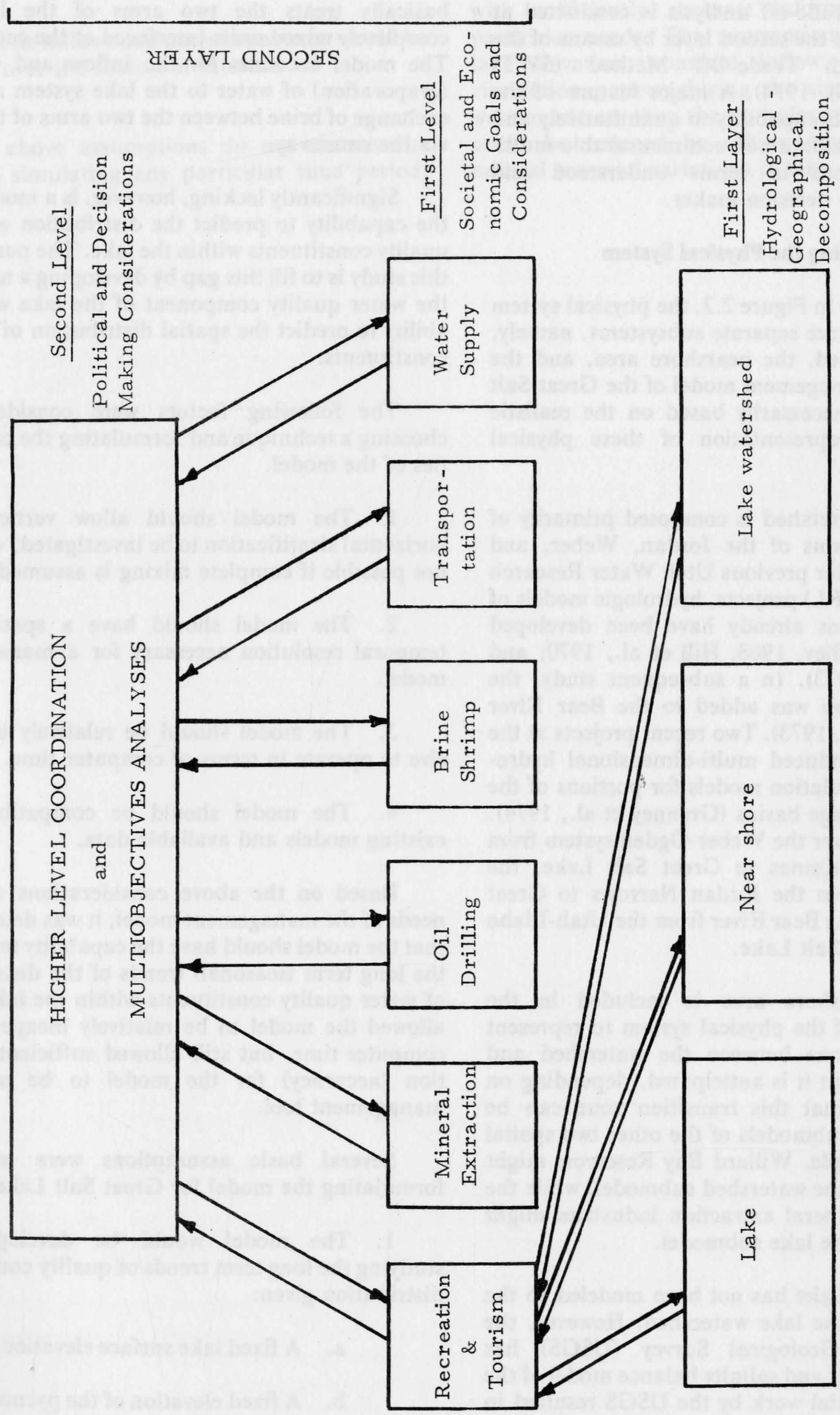
1. Identify all actions top of the matrix that might be part of proposed development plans.
2. Beneath each proposed action a slash is placed at the intersection with each condition (side of matrix) if a significant impact is considered to be possible.
3. The number above each slash indicates the relative magnitude of the possible impact, with 10 representing the greatest magnitude and 1 the least.
4. The number beneath each slash indicates the relative importance of each possible impact (e.g. regional versus local).

II. CHANGES TO THE PHYSICAL SYSTEM WHICH MIGHT CAUSE ENVIRONMENTAL IMPACT

(In each cell, magnitude/importance.)

I. EXISTING CHARACTERISTICS & CONDITIONS OF THE LAKE ENVIRONMENT		A. Mod. of Regime					B. Land Transformation and Construction									C. Resour. Extraction			D. Processing									E. Waste Treat.			F. Chemical Treat.		G. Others
	Proposed Actions	a. Biological controls (Brine fly)	b. Modification of habitat	c. Transbasin diversions	d. Irrigation, drainage	e. Weather modification	a. Urbanization	b. Industrial sites and buildings	c. Airports	d. Highways and bridges	e. Railroads	f. Dams and reservoirs	g. Dikes and causeways	h. Recreation structures	i. Roads and trails	a. Mineral extraction	b. Well drilling and pumping	c. Dredging	a. Farming	b. Ranching and grazing	c. Feed lots	d. Food processing	e. Energy generation	f. Mineral processing	g. Chemical industry	h. Oil refining	i. Other	a. Landfill	b. Oil well flooding	c. Municipal discharges	a. De-icing of highways	b. Insect control	
A. Physical & Chemical Characteristics – 1. Water	a. Surface streams			10/10	8/8	5/10	3/2					10/7			2/1				2/8	5/8	4/5		8/2					1/1					
	b. Salt Lake			10/10	7/8	8/10		3/2				9/10	10/10						2/8	5/8	2/3								8/9	2/7			
	c. Underground			10/10	9/8	5/10	3/2					10/6					7/7				2/5												
	d. Quality			10/10	9/8	3/9	7/9					10/8					3/1		5/8	7/8	2/5	8/3		8/3	8/3	8/5		2/2	8/6	9/7	3/2		
	e. Recharge			10/8	8/8	9/9	5/7					10/7							7/7		2/5							2/1					
A. – 2. Processes	a. Floods			10/7		10/9	7/8					10/5								5/8			9/5										
	b. Erosion, sediment			7/4		7/5	4/3			7/4		9/4							4/3	6/4			7/5										
	c. Precipitation					9/10																											
B. Biological Conditions – 1. Flora	a. Trees		10/3			9/9	10/3					6/2							4/3	6/5												8/3	
	b. Grass		10/3	2/3	10/7	8/9	9/3					7/1							5/4	8/7													
	c. Crops		10/9	10/9	10/10	9/10						9/9							10/9													8/9	
	d. Microflora		10/3		10/2	10/4	10/3					10/2	10/2					9/2	9/2	9/2	9/2			8/2	8/2			8/1		8/2		8/2	
	e. Aquatic plants		10/3	10/2	8/2	6/3	9/1					9/1	10/2					9/2	5/2	3/2				5/3	5/3				8/3	8/3			
B. – 2. Fauna	a. Birds	7/8	10/8		5/8	4/8	5/3	4/3	4/3			5/5	7/6					4/7	3/7	3/2												3/4	
	b. Land animals, reptiles	3/2	10/4		3/4	4/3	5/3		2/1			8/2						4/2	5/4	3/3								8/1				2/2	
	c. Fish, shrimp	8/7	10/8	10/7	3/8	3/8	3/8	2/1				9/8	9/8	9/8				2/8						8/2	8/2				8/8	1/8			
	d. Benthic organisms			10/1	7/2	2/2						10/1	8/1					1/1			4/3								3/2	8/1			
	e. Insects	10/8	10/8		6/8	2/8						9/2	7/5					7/5	5/4	2/2	4/4								3/2			10/8	
	f. Microfauna	5/3	10/3		3/3	7/3	8/2					9/2	8/2	8/2				8/1	8/3	2/2	3/3			8/2	8/2			8/1	7/2	8/1		8/8	
Cultural or Societal Factors Relating to the Great Salt Lake – 1. Recreation and Tourism	a. Hunting		10/9			3/10				3/8		3/1	7/3		7/8					5/8												2/3	
	b. Fishing	5/8	10/9	10/5	3/7	4/8				7/8		10/8	8/6	7/4	5/8			2/3		4/4										4/4		4/4	
	c. Boating	3/2		10/5		4/3		7/2		7/5		10/8	8/7	8/7		2/7	7/7	2/2					7/7						8/7	3/4		3/2	
	d. Swimming	7/7		10/7		4/4		2/3		4/4		10/7	8/7	8/8		2/8	2/8	2/2					8/7						8/7	8/2		7/7	
	e. Camping, hiking	7/3	10/9	3/2		2/9		2/3		7/8		8/9		4/9	9/9	2/9			3/4	5/3									4/2	2/5		7/3	
	f. Resorts	3/5		7/2		2/2		2/8		8/4		8/4	8/3	8/3		2/3	7/3	2/2											7/3	8/3		3/5	
	g. Scenic views, vistas						10/9	10/7	9/2	7/3		8/3	8/4	8/5	2/5	8/7	6/7						8/7					10/2					
	h. Wilderness qualities				8/5		10/9	10/6	10/3	10/4	10/4	10/3	10/3	8/3	3/3	8/3	8/3		9/3	8/4			8/5					8/2					
	i. Open space qualities				7/5		10/9	10/7	8/3	9/3	9/3	3/3		8/3		8/3	8/3		7/3	3/3			5/4					8/2					
	j. Landscape design						10/7	10/3	9/3	7/2		9/2		8/2		8/2	8/2		9/2		7/3		8/3					10/1					
	k. Parks & reserves			5/2						8/2		9/2	9/2	9/6		3/2	3/2		3/2									10/5	7/4				
	l. Monuments			4/2		2/2				8/1		9/3	9/3	9/3		3/2	3/2											8/5					
	m. Rare ecosystems			10/1	10/3	7/3				10/1		10/2	10/2	9/2	7/1	8/1	2/1	2/1		5/2								10/1	10/1	1/1			
	n. Picnicking	9/8	9/8	3/2		4/8		3/8	3/4	9/8		10/9	4/9	9/9	5/9	2/9	2/9				7/2							10/2	8/4	7/5		9/8	
	o. Historical sites			2/2		2/2		8/3		8/9	8/9	10/2	5/3	7/4		2/8	2/8						10/3					8/1	8/7	1/1			
2. Mineral Extraction	a. Dike maintenance			3/8									2/1																				
	b. Other structures												2/2																				
	c. Brine concentrations			3/10	3/5	5/8						3/8	9/8	2/8		2/8		2/3	2/8	2/8				2/8	2/8						1/1		
	d. Transportation			2/8									9/9																				
3. Transportation	a. Causeways			1/1																													
	b. Open water									6/3	6/3	6/3	6/3				3/3																
	c. Road maintenance					5/2																											
4. Brine Shrimp Harvesting	a. Nutrients in water	10/7	5/9	2/9	5/4			9/9					7/7			3/7		1/1	5/8	2/8	5/3	8/3		2/8	5/5	2/5				1/2	1/2	9/7	
	b. Oxygen in water			1/9				9/9								3/3		1/1	7/8	1/8	5/3									1/2			
	c. Brine concentrations			1/9		5/5		8/9				3/8	9/8	2/8		2/8		2/3	2/8	2/8				2/8	2/8						1/1		
	d. Pollution conditions			1/9	2/4			9/7					5/3			1/3	8/8	3/3	8/8										10/8	7/8	1/1		
5. Oil Drilling	a. Pollution control requirements																		5/7											3/5	1/1		
	b. Access to sites					2/3												3/2	2/3														
6. Water Supply	a. Fresh water reservoirs			10/10	7/9	7/9	8/9	7/9				2/10	8/8	2/3			8/8	2/2	8/8	2/8	7/5								9/8	9/8			
	b. Quality			10/10	8/9	5/9	9/9	7/9				9/9	9/8	2/3	2/1		8/8	2/2	8/8	3/8	7/6	8/3		6/4	6/4	6/4		5/5	9/8	9/8	3/5	2/7	
	c. Dike maintenance			2/3								3/2																					
Others																																	

Figure 2.2. First level hydrological-geographical decompostion (Riley et al., 1975).



In particular, all the information needed for analyzing and evaluating the trade-offs among all the social uses is provided at this level of the hierarchy. The trade-off analysis is conducted at the second level of the second layer by means of the Surrogate Worth Trade-Off Method (SWT) (Haimes and Hall, 1974). A major feature of the SWT method is its capability to quantitatively and systematically evaluate non-commensurable multi-objective functions in terms understood and acceptable to the decision-maker.

Modeling the Physical System

As indicated in Figure 2.2, the physical system is divided into three separate subsystems, namely, the lake watershed, the nearshore area, and the lake itself. A management model of the Great Salt Lake system is necessarily based on the realistic and adequate representation of these physical subsystems.

The lake watershed is composed primarily of the drainage basins of the Jordan, Weber, and Bear Rivers. Under previous Utah Water Research Laboratory (UWRL) projects, hydrologic models of these three basins already have been developed (Israelsen and Riley, 1968; Hill et al., 1970; and Wang et al., 1973). In a subsequent study, the salinity dimension was added to the Bear River model (Hill et al., 1973). Two recent projects at the UWRL have produced multi-dimensional hydrologic-quality simulation models for portions of the three river drainage basins (Grenney et al., 1974). These models cover the Weber-Ogden system from Park City and Kamas to Great Salt Lake, the Jordan River from the Jordan Narrows to Great Salt Lake, and the Bear River from the Utah-Idaho border to Great Salt Lake.

The near shore area is included in the decomposition of the physical system to represent the transition zone between the watershed and lake. At this point it is anticipated, depending on circumstances, that this transition zone can be included in the submodels of the other two spatial units. For example, Willard Bay Reservoir might be contained in the watershed submodel, while the effects of the mineral extraction industries might be included in the lake submodel.

Great Salt Lake has not been modeled to the same extent as the lake watershed. However, the United States Geological Survey (USGS) has developed a water and salinity balance model of the lake system. Initial work by the USGS resulted in the development of equations which predict the flow of brine through the railroad causeway which separates the north and south arms of the lake (Waddell and Bolke, 1973). These flow equations were included in the USGS water and salinity balance model of the lake. The USGS model basically treats the two arms of the lake as completely mixed units interfaced at the causeway. The model accounts for the inflow and outflow (evaporation) of water to the lake system and the exchange of brine between the two arms of the lake via the causeway.

Significantly lacking, however, is a model with the capability to predict the distribution of water quality constituents within the lake. The purpose of this study is to fill this gap by developing a model of the water quality component of the lake with the ability to predict the spatial distribution of quality constituents.

The following factors were considered in choosing a technique and formulating the capabilities of the model.

1. The model should allow vertical and horizontal stratification to be investigated, which is not possible if complete mixing is assumed.

2. The model should have a spatial and temporal resolution necessary for a management model.

3. The model should be relatively inexpensive to operate in terms of computer time.

4. The model should be compatible with existing models and available data.

Based on the above considerations and the needs of the management model, it was determined that the model should have the capability to predict the long term (seasonal) trends of the distribution of water quality constituents within the lake. This allowed the model to be relatively inexpensive in computer time, but still allowed sufficient resolution (accuracy) for the model to be a useful management tool.

Several basic assumptions were made in formulating the model for Great Salt Lake:

1. The model would be developed for studying the long term trends of quality constituent distribution given:

   a. A fixed lake surface elevation.

   b. A fixed elevation of the pycnocline.

2. Initial emphasis would be placed on modeling the complex south arm of the lake.

3. Current (velocity) patterns within the lake would be input to the model based on observed data.

4. The inflows and current patterns would be averaged over the season of interest.

The above assumptions do not restrict the model to simulating any particular time period. Since the model was formulated as a time varying model it can be applied to any time period for which constant lake conditions provide the user with sufficiently accurate information for his particular needs. The assumption of a constant lake elevation, constant inflow, and constant circulation pattern during the simulation period were made so that the complexity of the model could be reduced by taking advantage of the natural seasonal variations in lake conditions.

[illegible]

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CHAPTER III

REVIEW OF LITERATURE

Background of the Advection-Diffusion Equation

The distribution of a water quality constituent within a natural water body is dependent on the processes which transport the constituent through the system and the processes within the system which concentrate or dilute the constituent. The three-dimensional advection-diffusion equation, alternatively the conservation of mass equation, which describes the distribution of a constituent in turbulent incompressible flow is given by Harleman (1966) as:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} e_x \frac{\partial C}{\partial x} + \frac{\partial}{\partial y} e_y \frac{\partial C}{\partial y} + \frac{\partial}{\partial z} e_z \frac{\partial C}{\partial z} - u \frac{\partial C}{\partial x} - v \frac{\partial C}{\partial y} - w \frac{\partial C}{\partial z} \quad \text{(transport terms)}$$

$$+ \Sigma S \quad \text{(summation of sources and sinks term)} \qquad \text{........(3.1)}$$

in which

C	=	local concentration
u, v, w	=	time averaged velocity components associated with turbulent flow
e_x, e_y, e_z	=	turbulent or eddy diffusivities
t	=	time
ΣS	=	summation of sources and sinks of C

The transport terms of Equation 3.1 represent the advective and diffusive processes in the three spatial dimensions. The terms of the first line of Equation 3.1, with the exception of $\partial C/\partial t$, represent the transport of the constituent by turbulent or eddy diffusion. The second line of Equation 3.1 contains the advective mass transport terms which are associated with the fluid flow velocities. The summation of sources and sinks term encompasses all the nontransport terms which either increase (source) or decrease (sink) the constituent concentration. The source and sink processes may be biological, physical, or chemical in nature.

The eddy diffusivities which appear in the transport terms of Equation 3.1 arise from the random processes associated with the turbulent flow of a fluid [a detailed discussion is given in Ippen (1966)]. By analogy with Fick's law of diffusion, it is assumed that the mass flux is proportional to the concentration gradient. Thus, the random transport in the x - direction is described by

$$e_x \frac{\partial C}{\partial x},$$

in which e_x is the eddy diffusivity and $\partial C/\partial x$ is the spatial gradient of C in the x - direction. Similar terms exist for the y - and z - directions.

Equation 3.1 represents the fundamental equation governing the distribution of a water quality constituent within a natural water body. The form of Equation 3.1 is actually a simplification of the general advection-diffusion equation, in that molecular diffusion has been eliminated due to the empirical fact that in most natural systems the transport by molecular diffusion is much smaller than by turbulent diffusion. This simplification still results in a form of the advection-diffusion equation which is generally insolvable with existing analytical mathematical techniques. The complexity of Equation 3.1 can be simplified by reducing its effective dimensionality.

In many shallow lakes and estuaries the vertical variation in constituent is small compared to the variation in the horizontal dimension. For such systems, the vertical dimension can be eliminated in Equation 3.1 without significant losses in the accurate prediction of the distribution of constituent concentrations. The vertical dimension is eliminated by integrating Equation 3.1 from the bottom to surface of the water body. The vertically integrated advection-diffusion equation is

$$\frac{\partial \overline{CD}}{\partial t} = \frac{\partial}{\partial x} DE_x \frac{\partial \overline{C}}{\partial x} + \frac{\partial}{\partial y} DE_y \frac{\partial \overline{C}}{\partial y} - D\overline{u} \frac{\partial \overline{C}}{\partial x}$$

$$-D\overline{v} \frac{\partial \overline{C}}{\partial y} + \Sigma D\overline{S} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

with

$$\overline{C} = \frac{1}{D} \int_{d_o}^{d_s} C dz$$

$$\overline{u} = \frac{1}{D} \int_{d_o}^{d_s} u dz$$

$$\overline{v} = \frac{1}{D} \int_{d_o}^{d_s} v dz$$

$$\overline{S} = \frac{1}{D} \int_{d_o}^{d_s} S\, dz$$

and

$$D = d_s - d_o = \text{depth of integration}$$

The turbulent diffusivities, e_x and e_y, are redefined as effective diffusivities, E_x and E_y. The effective diffusivities differ from the turbulent diffusivities in that, in addition to representing the diffusive effects of turbulent velocity fluctuations, they also represent all other random diffusive processes resulting from sources such as vertical shear in the current and wind induced mixing.

The advection-diffusion equation can alternatively be expressed as the mass transport equation. This form of the equation is more convenient for certain numerical solution techniques. The three-dimensional mass transport equation is

$$\frac{\partial M}{\partial t} = -uA_xC - vA_yC - wA_zC + E_xA_x \frac{\partial C}{\partial x}$$

$$+ E_yA_y \frac{\partial C}{\partial y} + E_zA_z \frac{\partial C}{\partial z} + \Sigma SV \qquad \ldots\ldots\ldots (3.3)$$

in which M is mass of constituent in the volume element, V, and A_x, A_y, and A_z, are the cross-sectional areas in the x -, y -, and z - coordinate directions respectively. All other terms are previously defined. As with Equation 3.1, the effective dimensionality of Equation 3.3 can be reduced through integration.

Application of the Advection-Diffusion Equation

The application of the advection-diffusion equation to the study of the distribution of water quality constituents within natural systems has resulted in the development of a number of mathematical modeling techniques. A review of the procedures which actually have been applied to the study of natural systems resulted in the identification of three modeling techniques, which were developed to study the San Francisco Bay-Delta, Galveston Bay, and Jamaica Bay. These techniques have been applied only to systems which can be considered vertically well mixed and thus are represented spatially as two-dimensional.

San Francisco Bay-Delta Model

The San Francisco Bay-Delta model (Feigner and Harris, 1970) was developed in connection with a comprehensive study of the system formed by San Francisco Bay and the delta at the confluence of the Sacramento and San Joaquin Rivers. The numerical hydraulic-water quality model for this system was developed principally by Water Resources Engineers, Inc., (WRE) under contract from the Federal Water Quality Administration. The model was structured conceptually to represent the two horizontal spatial dimensions and is applicable to systems which are well mixed vertically.

The unique approach used in the Bay-Delta model was that of representing the system as a network of volumetric units or nodes connected by flow channels or links. This link-node technique allows a two-dimensional system to be treated mathematically as one-dimensional. In the Bay-Delta model, the quality constituents were associated with each node and were assumed to be evenly distributed through the node's volume. The surface area of each node was formed by the perpendicular bisectors of the associated links. The function of the links was the transport of quality constituents between nodes. Each link was assumed to have the properties of a broad open channel; length, depth, width, and velocity. Figure 3.1 illustrates how a link-node network is used to represent one- and two-dimensional components of a system and identifies the important components of the network.

WRE employed an advection-diffusion equation based on a form of the mass transport equation adapted to the link-node representation of the system. In the link-node system, provision was made for a variable number of channels to enter and leave a node. This provision is reflected in the advection-diffusion equation used in the Bay-Delta model:

$$\frac{\partial (VC)_j}{\partial t} = -\sum_{i=1}^{n} (QC)_i + \sum_{i=1}^{n} (AE \frac{\partial C}{\partial l})_i + \Sigma S_j \quad (3.4)$$

in which

$(VC)_j$ = mass of quality constituent carried in node j

$\Sigma(QC)_i$ = algebraic sum of advective mass transport rates for links i connected to node j

Q_i = flow in link i

C_i = concentration of quality constituent in link i

$\Sigma(AE \frac{\partial C}{\partial l})_i$ = algebraic sum of diffusional mass transport rates for links connected to node j

l_i = length of link i

A_i = cross-sectional area of link i

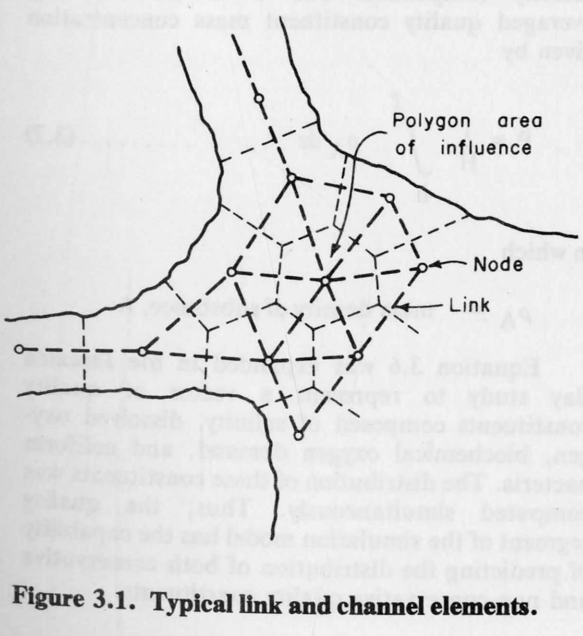

Figure 3.1. Typical link and channel elements.

E_i = effective diffusion coefficient for link i

S_j = source and/or sinks of mass in node j

The versatility of the modeling technique is evident from the fact that it has been successfully applied to other systems, including Lake Washington, San Diego Bay, and the Columbia River.

The Galveston Bay Model

The Galveston Bay project was undertaken by the Texas Water Quality Board in order to produce a practical and detailed understanding of Galveston Bay upon which alternative plans of water quality management for the system could be evaluated. The responsibility for development of mathematical models for the project was delegated to TRACOR, a consulting firm from Austin, Texas. The mathematical models developed by TRACOR (Espey et al., 1971) included both a hydraulic model, which describes hydrodynamics interactions in the bay, and the water quality models. Both time dependent and steady state models for various water quality parameters were developed, including temperature, salinity, biochemical oxygen demand, and dissolved oxygen.

Galveston Bay is typical of many of the estuaries along the Gulf Coast in that the bay is shallow with an average depth of 8 feet with, in general, negligible vertical variation of constituent concentration. Due to the vertically well mixed nature of Galveston Bay, TRACOR based the development of the computerized mathematical model of the distribution of water quality constituents within the bay on the vertically averaged conservation of mass equation, which is restated here as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} E_x \frac{\partial C}{\partial x} - u\frac{\partial C}{\partial x} + \frac{\partial}{\partial y} E_y \frac{\partial C}{\partial y} - v \frac{\partial C}{\partial y} + \Sigma S \quad \ldots\ldots\ldots\ldots\ldots (3.5)$$

All terms in Equation 3.5 are previously defined (see Equations 3.1, 3.2, and 3.3). The vertically averaged continuity equation formed the basis for nearly all the water quality models developed for the Galveston Bay system.

The model was applied by superposition of a computational grid upon Galveston Bay. The grid was composed of a system of square cells, with the cell dimension designed for the required spatial resolution. Unlike the Bay-Delta model, the cells were treated as both flow and volume elements.

The grid network and cell parameters are illustrated in Figure 3.2.

Flexibility in adapting the grid to the system was provided by the use of a "flag field." The flag field was simply a coding procedure which controlled the type of computation that was performed at each grid point and was used to prevent flow and the transport of quality constituents across impermeable boundaries or into the land areas surrounding the bay.

In the finite difference solution of Equation 3.5, C, u, v, and S were taken as being at the center of each cell and E_x and E_y were defined at the walls, as illustrated in Figure 3.2. Several differencing techniques have been employed in the computer solution of Equation 3.3.

The Galveston Bay model has been successfully applied to other Gulf Coast estuaries including San Antonio Bay and Matagordo Bay. The modeling technique provides a useful method for studies involving the management of shallow vertically well mixed estuaries subject to salt water intrusion.

The Jamaica Bay Model

Leendertse (1970) and later Leendertse and Gritton (1971a, 1971b) developed a water quality simulation model which allowed the investigation of the effects of various management alternatives involving fluid waste discharge into well mixed estuaries and coastal seas. The original model

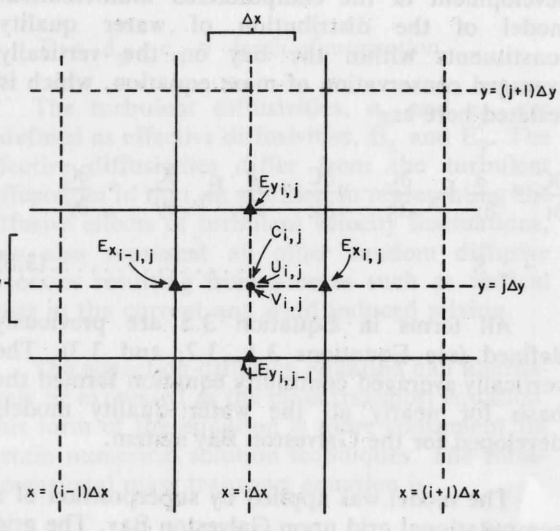

Figure 3.2. Parameter definition for the finite-difference representation of the Galveston Bay system (Espey et al., 1971).

development was sponsored by the Rand Corporation. Subsequent refinement of the model and application of the model to the study of Jamaica Bay, Long Island, New York was performed by Rand under contract with the City of New York.

A unique feature of the model was that the hydrodynamics and water quality segments of the model were incorporated directly into a single simulation model. The quality segment of the model was based on the mass balance equation for two-dimensional transport of quality constituents in a vertically well mixed system and is given as

$$\frac{\partial (HP)}{\partial t} + \frac{\partial (HUP)}{\partial x} + \frac{\partial (HVP)}{\partial y} - \frac{\partial \, HD_x \frac{\partial P}{\partial x}}{\partial x} - \frac{\partial \, HD_y \frac{\partial P}{\partial y}}{\partial y} - HS_A = 0 \quad \ldots\ldots (3.6)$$

in which

H = $h + \zeta$ the sum of the water level elevation, ζ relative to the reference plane and the distance, h, from the reference plane to the bottom of the lake

S_A = source function

D_x and D_y = dispersion coefficients

The variables U and V are vertically averaged fluid velocity components and P is the vertically averaged quality constituent mass concentration given by

$$P = \frac{1}{H} \int_{-h}^{\zeta} \rho_A \, dz \quad \ldots\ldots (3.7)$$

in which

ρ_A = mass density of substance, A

Equation 3.6 was expanded in the Jamaica Bay study to represent a vector of quality constituents composed of salinity, dissolved oxygen, biochemical oxygen demand, and coliform bacteria. The distribution of these constituents was computed simultaneously. Thus, the quality segment of the simulation model has the capability of predicting the distribution of both conservative and non-conservative quality constituents.

The physical system was represented in the Rand model as a two-dimensional grid, similar in certain respects to the grid employed in the Galveston Bay study. Both the hydrodynamic and quality components of the model were formulated on the same grid system which is illustrated in Figure 3.3. The set of quality equations represented by Equation 3.6 was solved in finite difference form by an alternating direction implicit-explicit technique written in a staggered scheme over the grid space. The simulation model is general in nature and could prove useful in the study of other vertically well mixed estuaries and coastal seas.

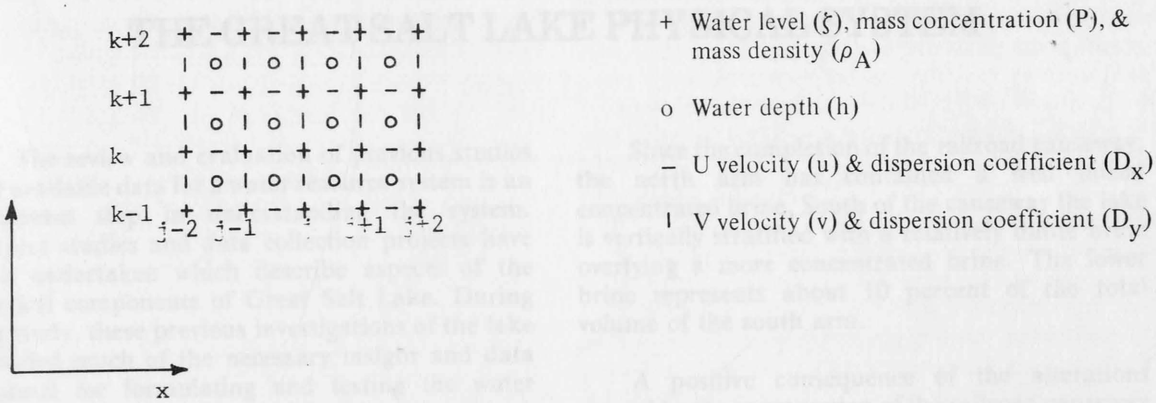

Figure 3.3. Space-staggered grid (Leendertsen and Gritton, 1971).

[illegible] controlled the type of computation that was performed at each grid point and was used to [illegible] flow and the transport of quality constituents [illegible] the land areas surrounding the [illegible].

In the finite difference solution of Equation 3.5, C, u, v, and S were taken as being at the center of grid cells and [illegible] at the walls, as illustrated in Figure 3.2. Several different [illegible] were employed in the computer solution of Equation 3.5.

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$$\frac{\partial (HP)}{\partial t} + \frac{\partial (HUP)}{\partial x} + \frac{\partial (HVP)}{\partial y} - \frac{\partial \left(HD_x \frac{\partial P}{\partial x}\right)}{\partial x} - \frac{\partial \left(HD_y \frac{\partial P}{\partial y}\right)}{\partial y} - HS_A = 0 \qquad (3.6)$$

in which

H = $h + \zeta$ the sum of the water level elevation, ζ relative to the reference plane and the distance, h, from the reference plane to the bottom of the lake

S_A = source function

D_x and D_y = dispersion coefficients

The variables U and V are vertically averaged fluid velocity components and P is the vertically averaged quality constituent mass concentration given by

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Equation 3.6 was expanded in the Jamaica Bay study to represent a vector of quality constituents composed of salinity, dissolved oxygen, biochemical oxygen demand, and coliform bacteria. The distribution of these constituents was computed simultaneously. Thus, the quality segment of the simulation model has the capability of predicting the distribution of both conservative and nonconservative quality constituents.

CHAPTER IV

THE GREAT SALT LAKE PHYSICAL SYSTEM

The review and evaluation of previous studies and available data for a water resource system is an important step in understanding the system. Various studies and data collection projects have been undertaken which describe aspects of the physical components of Great Salt Lake. During this study, these previous investigations of the lake provided much of the necessary insight and data required for formulating and testing the water quality distribution model of the lake.

Description of Great Salt Lake

Great Salt Lake (Figure 4.1) is the largest salt water lake in the United States. The lake lies at the bottom of a closed basin and is fed principally by flow from the Bear, Weber, and Jordan Rivers. Because it is a terminal lake, the only outflow from the lake is by evaporation. At a surface elevation of 4,200 feet the lake has a surface area of approximately 1,600 square miles and an average depth of 13 to 16 feet.

The natural features of the lake have been significantly affected by the construction of dikes and causeways. The construction of evaporation ponds to facilitate the recovery of minerals from the lake brine has altered the natural surface area of the lake. Other causeways have altered the natural lake circulation patterns and induced local changes in salinity levels. For example, previous efforts at constructing a causeway from the mainland to a state park on the north end of Antelope Island have indicated that a permanent structure will impound the inflow from the Jordan River. This situation will cause a dilution of the brine in Farmington Bay which may create a fresh water environment in the bay (Utah Division of Water Resources, 1974).

A semi-permeable, rock-fill railroad causeway was completed across the lake in 1959 by the Southern Pacific Railroad Company. As a result the lake was divided into two arms with the south arm containing approximately twice the volume of the north arm. The causeway has altered the concentration of brine within the lake and changed the hydrology of the lake.

Since the completion of the railroad causeway, the north arm has contained a well mixed concentrated brine. South of the causeway the lake is vertically stratified with a relatively dilute brine overlying a more concentrated brine. The lower brine represents about 10 percent of the total volume of the south arm.

A positive consequence of the alterations caused by the construction of the railroad causeway has been renewed interest in proper management of the entire lake system. This has led to data collection programs and research aimed at understanding the various components of the physical lake system.

Lake Hydrology

Data on the elevation of the surface of Great Salt Lake has been gathered since 1951. The historic fluctuation of the surface elevation of the lake is given in Figure 4.2. The lake has varied from a high of 4,211.5 feet in 1873 to a low of 4,191.6 feet in 1963.

Other hydrologic data related to the lake are not as well documented as the variation of the surface elevation. Several investigators have performed water budget analyses of the lake in order to establish the magnitude of the various inflows and the outflows. Steed (1972) performed a monthly water budget analysis on the lake for the 1944-1970 water years. The study was undertaken to provide a sound hydrologic background of the lake by identifying the terms which comprise the water budget; namely, surface inflow, groundwater inflow, precipitation input, and the outflow by evaporation. Steed was able to obtain an excellent yearly water budget for the lake, but the monthly budgets were subject to wider fluctuations. Average annual inflows to the lake for this period were found to be 1,756,000 acre-feet of surface inflow, 206,000 acre-feet of groundwater inflow, and 685,000 acre-feet of precipitation. The mean annual outflow by evapotranspiration was found to be 2,644,000 acre-feet.

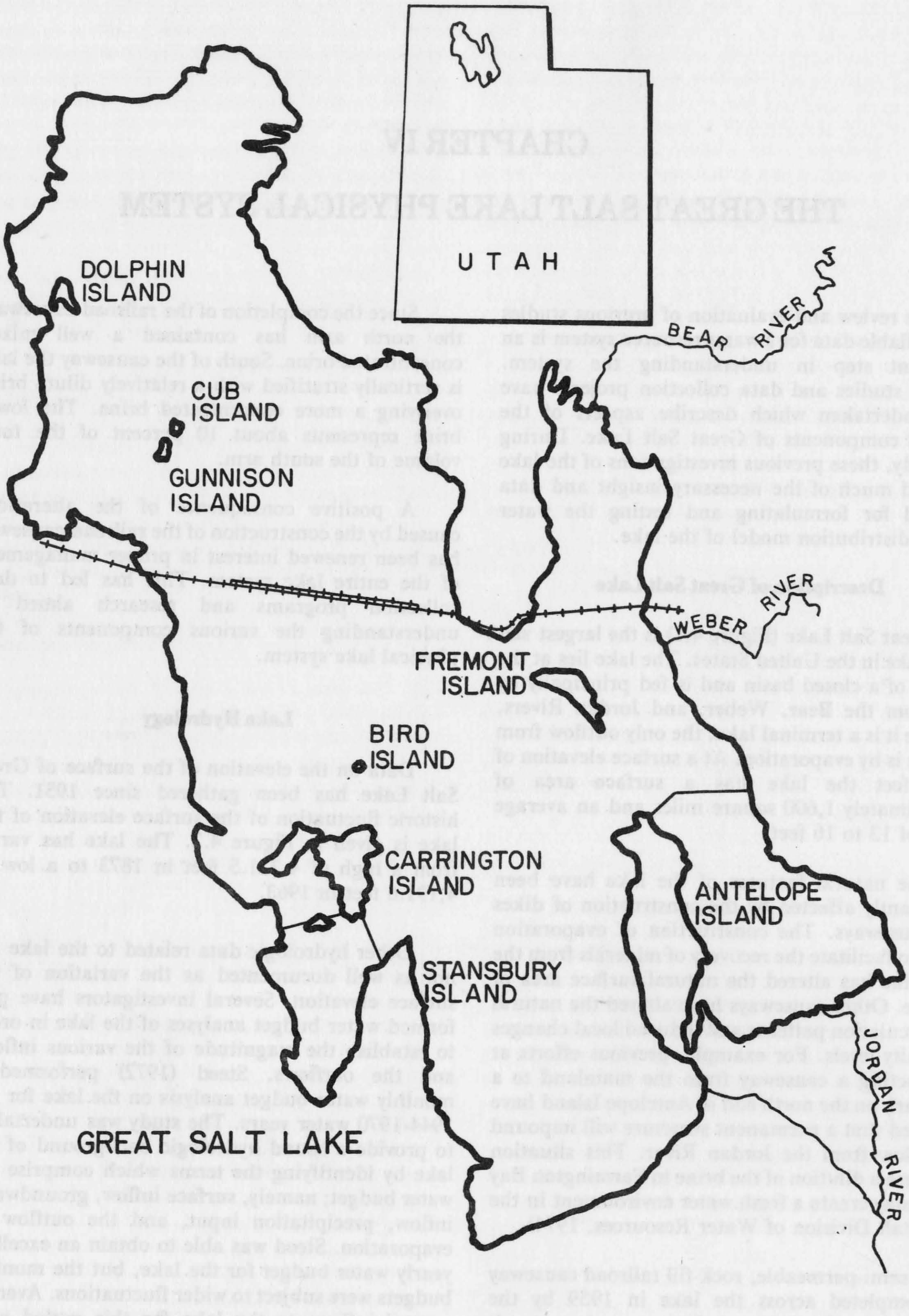

Figure 4.1. Map of Great Salt Lake.

Under present lake conditions the south arm receives 95 percent of the surface inflow to the lake, while the major inflow to the north arm is brine from the south arm. This inflow pattern has created a head difference across the causeway, with the south arm elevation being greater than the north arm.

Hahl and Handy (1969), Madison (1970), and Whelan (1972) all reported a net movement of salt from the south to the north arm of the lake since the completion of the causeway. Since 1963 the south arm has freshened while the north arm has remained at a concentration at or near salt saturation. This net movement of salt northward has resulted in the complete dissolving of a salt crust which was known to exist on the bottom of the south arm in 1963. During the summer of 1969, Hedberg (1970) sampled the remaining salt crust on the bottom of the south arm and estimated that it contained 100 million tons of essentially pure halite. By 1972, measurements indicated that the salt crust had dissolved (Whelan, 1973). The dissolving of the salt crust in the south arm was accompanied by an increase of the salt crust on the bottom of the north arm. Cores taken from the salt crust in the north arm in 1970 and 1972 showed that up to 5 feet of salt had accumulated (Goodwin, 1973). The rapid rise of the lake after 1970 caused a slight dissolving of the layer. Whelan (1973) estimates that about 2 million metric tons of salt re-dissolved in the north arm from 1970 to 1972.

The reduced concentration of the south arm brine resulted from the causeway flow conditions. As early as 1963 (Hahl and Handy, 1969) it was observed that brine flows northward through the upper portion of the causeway fill and culverts due to the head difference between the two arms, and that a more concentrated brine flows southward through the lower portion of the causeway due to the density difference.

During 1970-1972, the U.S. Geological Survey (USGS) in cooperation with the Utah Geological and Mineral Survey (UGMS) carried out an investigation to establish (1) the net movement of dissolved solids load through the causeway for the 1971 and 1972 water years, (2) salt load movement through the causeway for simulated rising and falling lake stages, and (3) the effects on salt movement patterns of enlarging the present culverts through the causeway. Flow through the causeway presently occurs through the semi-

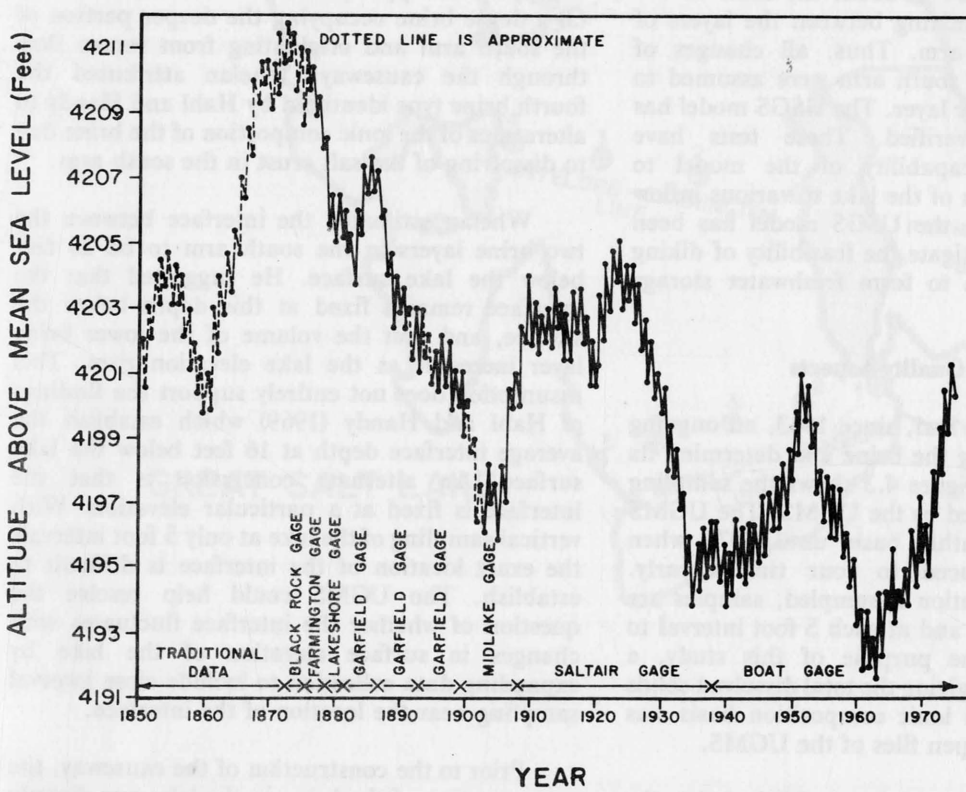

Figure 4.2. Historic surface elevation of Great Salt Lake.

permeable fill and two 15 foot wide concrete culverts which breach the causeway. The results of the USGS study are reported by Waddell and Bolke (1973). A major contribution of this study was the development of a procedure for predicting the flow of salt through the culverts and fill for various head and density differences across the causeway. The equations were developed mainly from regression analyses based on fill and culvert flow data gathered for the study.

In order to complete the objectives of their study, Waddell and Bolke (1973) included the equations of flow through the causeway in a preliminary water and salinity balance model of the lake. Using this model they found that the net movement of dissolved solids load through the causeway reversed under various rates of rising or falling lake stage. These simulated results are supported by their analysis of data which indicated that the salt balance between the two parts of the lake was near equilibrium for the 1972 water year.

The USGS subsequently has refined the water balance portion of the model (Waddell, 1974). The present USGS water and salt balance model treats the two arms of the lake as completely mixed units. The model was developed under the assumptions that the deep layer of brine in the south arm contains a constant dissolved solids load and that the north-to-south flow is about the same as the rate of diffusion or mixing between the layers of brine in the south arm. Thus, all changes of concentration in the south arm were assumed to occur within the upper layer. The USGS model has been tested and verified. These tests have demonstrated the capability of the model to simulate the response of the lake to various inflow conditions. To date, the USGS model has been used mainly to investigate the feasibility of diking portions of the lake to form freshwater storage areas.

Water Quality Aspects

The UGMS has had, since 1963, an ongoing program of sampling the brine and determing its ionic composition. Figure 4.3 shows the sampling stations presently used by the UGMS. The UGMS sampled on a monthly basis until 1973 when sampling was reduced to four times yearly. Presently when a station is sampled, samples are taken at the surface and at each 5 foot interval to the bottom. For the purpose of this study, a complete set of data giving the total dissolved solids concentration on an ionic composition basis was obtained from the open files of the UGMS.

Two reports have been published by the UGMS which analyze the chemical and physical variation of the brine (Hahl and Handy, 1969, and Whelan, 1973). The study by Hahl and Handy was the first major effort designed to study the spatial and temporal variations in the brine characteristics of the lake. Based on data gathered from 1963 to 1966, Hahl and Handy identified four types of brine in the lake by location, concentration of total dissolved solids, and concentration of specific ions. The north arm was characterized by a typical saturated brine. The brine in the south arm was divided into three categories, namely; (1) a zone from the surface to a depth of about 16 feet, (2) a zone below 16 feet south of the causeway, and (3) a zone below 16 feet in the south end of the lake. The various brine zones are illustrated in Figure 4.4. The upper zone of the south arm was found to be the most dilute of any brine in the lake. The two deep brines of the south arm (zones 2 and 3) were about the same in concentration of total dissolved solids but varied in concentration with respect to certain specific ions. However, the averaging concentration of total dissolved solids in these two zones of the south arm deep brine was found to be less than that of the north arm brine.

Whelan (1973) performed a similar analysis of the brine characteristics for data gathered from 1966 to 1972, and identified three major brine types in the lake; (1) a brine near saturation in the north arm, (2) a relatively less concentrated brine occupying the upper portion of the south arm, and (3) a dense brine occupying the deeper portion of the south arm and originating from return flow through the causeway. Whelan attributed the fourth brine type identified by Hahl and Handy to alterations of the ionic compostion of the brine due to dissolving of the salt crust in the south arm.

Whelan estimated the interface between the two brine layers in the south arm to be 20 feet below the lake surface. He suggested that the interface remains fixed at this depth below the surface, and that the volume of the lower brine layer increases as the lake elevation rises. This assumption does not entirely support the findings of Hahl and Handy (1969) which establish the average interface depth at 16 feet below the lake surface. An alternate conclusion is that the interface is fixed at a particular elevation. With vertical sampling of the lake at only 5 foot intervals the exact location of the interface is difficult to establish. The UGMS could help resolve the question of whether the interface fluctuates with changes in surface elevation of the lake by expanding data collection to include close interval sampling near the location of the interface.

Prior to the construction of the causeway, the concentration of the brine in the lake was directly related to the lake stage (Glassett, 1974). As shown

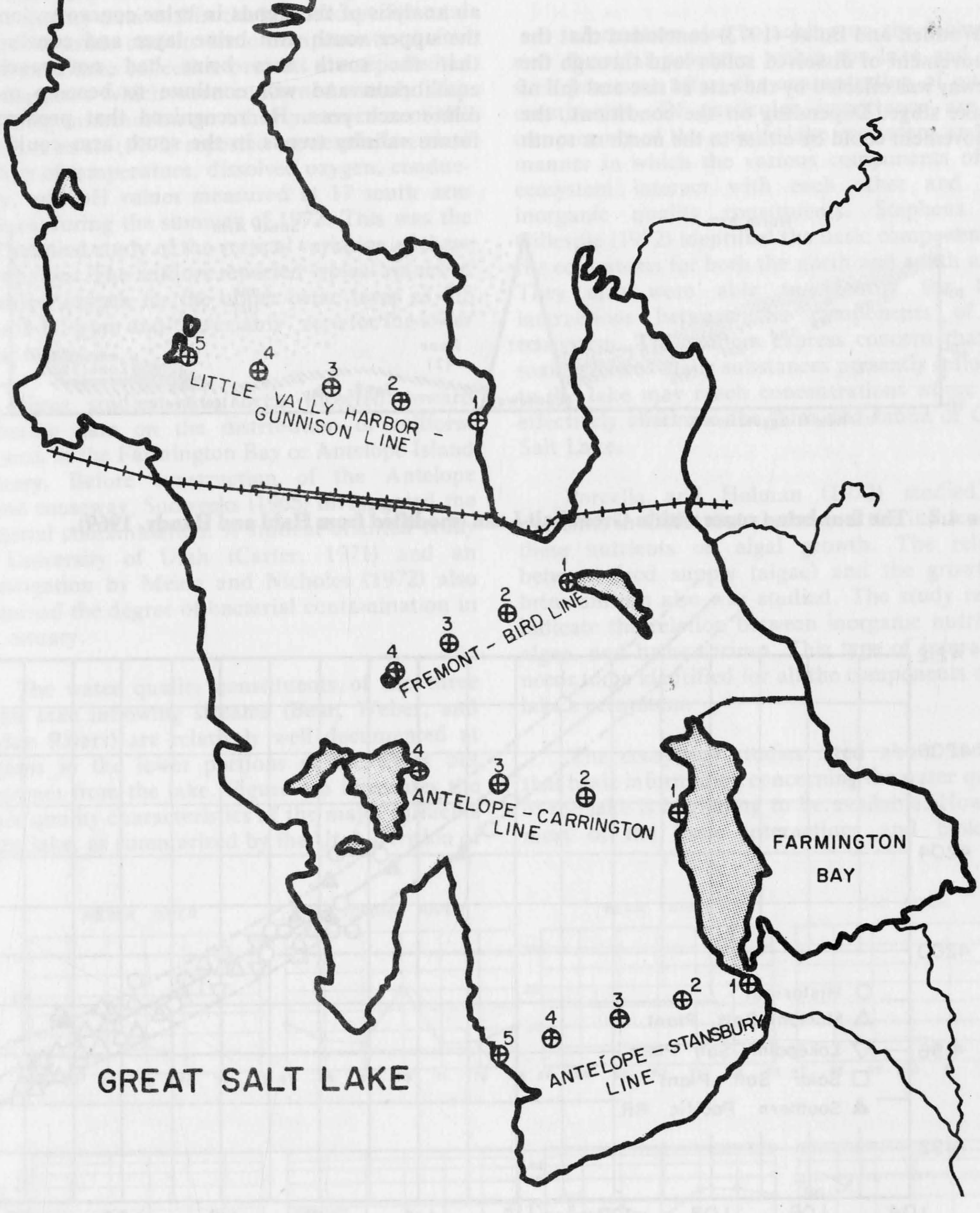

Figure 4.3. UGMS brine sampling sites within Great Salt Lake.

in Figure 4.5 the lake brine was diluted during periods of increasing lake stage. Dilution still plays an important role in the brine concentration for both arms of the lake. The rapid rise of the lake after 1970 reduced the mean concentration of both the north and south arms.

Waddell and Bolke (1973) concluded that the net movement of dissolved solids load through the causeway was effected by the rate of rise and fall of the lake stage. Depending on the conditions, the net movement could be either to the north or south arm of the lake and, thus, the current trend of the lake to freshen is reversible. The theory is supported by the near equilibrium exchange of dissolved solids load through the causeway which occurred under 1972 hydrologic conditions (Waddell and Bolke, 1973). Glassett (1974) performed an analysis of the trends in brine concentration in the upper south arm brine layer and concluded that the south arm brine had not reached equilibrium and will continue to become more dilute each year. He recognized that predicting future salinity trends in the south arm could be

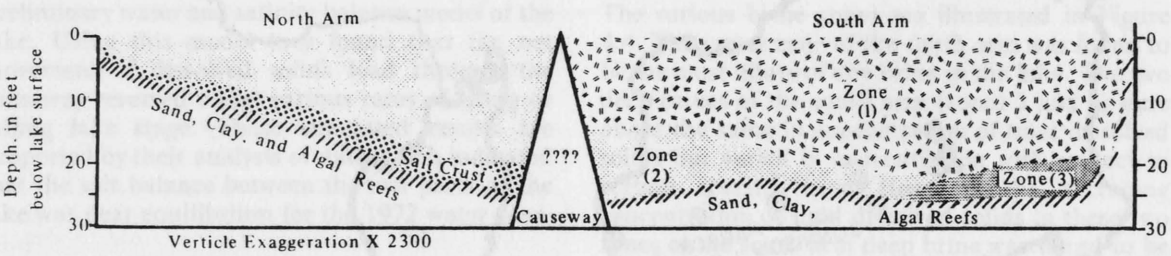

Figure 4.4. The four brine zones within Great Salt Lake (modified from Hahl and Handy, 1969).

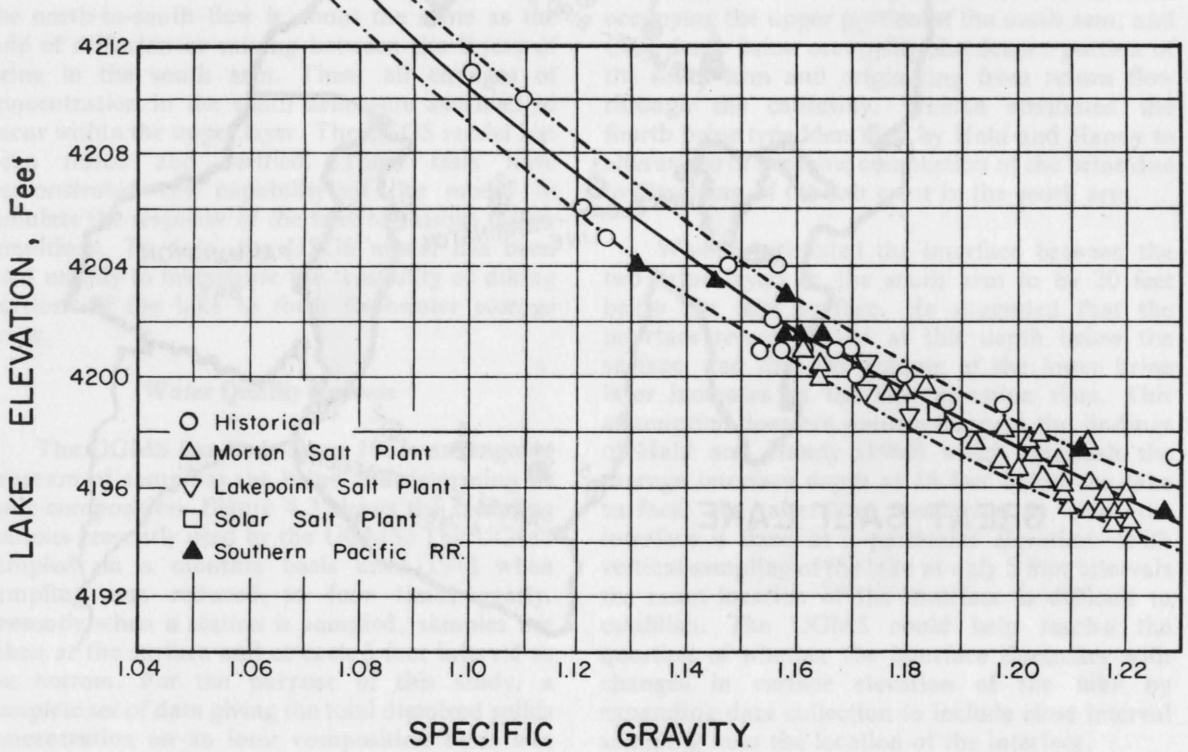

Figure 4.5. Variation of specific gravity with lake elevation prior to construction of the railroad causeway (Glassett, 1974).

improved if information on the diffusion of dissolved solids between the south arm brine layers were available.

Currently there is no systematic gathering of water quality data within the lake except for total dissolved solids and its ionic components. A few short term data collection projects are reported in the literature which were concerned mainly with obtaining information on other parameters of the lake. Lin et al. (1972) reported on detailed vertical profiles of temperature, dissolved oxygen, conductivity, and pH values measured at 17 south arm stations during the summer of 1972. This was the first detailed study of the vertical variation of these parameters. The authors reported typical values of dissolved oxygen for the upper brine layer as 3.5 ppm to 1.5 ppm and "invariably" zero for the lower brine layer.

Three studies have been directed toward gathering data on the distribution of coliform bacteria in the Farmington Bay or Antelope Island Estuary. Before construction of the Antelope Island causeway, Sudweeks (1965) investigated the bacterial contamination. A student oriented study by University of Utah (Carter, 1971) and an investigation by Meide and Nicholes (1972) also examined the degree of bacterial contamination in the estuary.

The water quality constituents of the three major lake inflowing streams (Bear, Weber, and Jordan Rivers) are relatively well documented at stations in the lower portions of the rivers but upstream from the lake. Figure 4.6 illustrates the water quality characteristics of the major influents to the lake, as summarized by the Utah Division of Water Resources (1974). However, much of this flow subsequently passes through the marshland area around the lake and information on any alterations of the water quality which occurs within the marshlands is not available.

Information also is lacking on the biological and chemical processes within the lake and how such processes affect the concentration of quality constituents. Of particular importance are the components of the unique lake ecosystem and the manner in which the various components of the ecosystem interact with each other and with inorganic quality constituents. Stephens and Gillespie (1972) identified the basic components of the ecosystems for both the north and south arms. They also were able to identify the basic interactions between the components of the ecosystem. The authors express concern that the toxic effect of many substances presently inflowing to the lake may reach concentrations where they effectively eliminate the flora and fauna of Great Salt Lake.

Porcella and Holman (1972) studied the nutrients in Great Salt Lake and the influence of these nutrients on algal growth. The relation between food supply (algae) and the growth of brine shrimp also was studied. The study results indicate the relation between inorganic nutrients, algae, and brine shrimp. This type of interaction needs to be identified for all the components of the lake's ecosystem.

The ecosystem studies cited above indicate that basic information concerning the water quality of the lake is beginning to be available. However, most of the basic interactions and biological

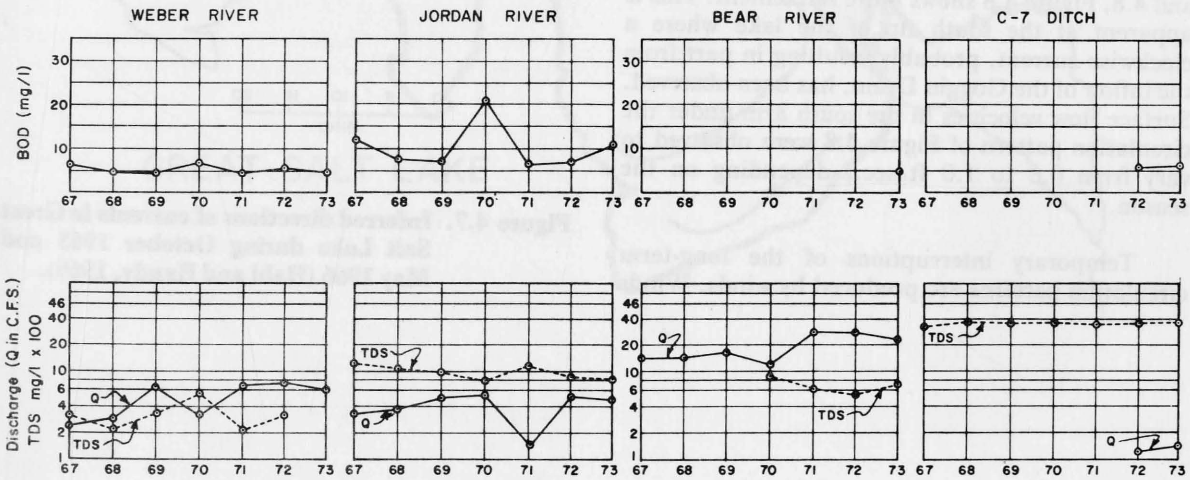

Figure 4.6. Water quality characteristics of major influents to Great Salt Lake (Utah Division of Water Resources, 1974).

processes, including growth and decay rates for organisms within the lake, have not yet been investigated.

Circulation and Diffusion

Programs to study the circulation patterns and diffusion within Great Salt Lake have been initiated by the Utah Division of Water Resources. This represents the first effort to systematically gather data on circulation and diffusion within the lake. Presently, data on general circulation patterns are available from observations made during previous studies of the lake and field data gathered during the past few years.

Mechanisms which produce current within Great Salt Lake are Coriolis forces, water inflows, wind, density gradients, and evaporation. In the northern hemisphere, Coriolis forces are known to produce counterclockwise circulation within large water bodies. Observed currents within Great Salt Lake indicate the Coriolis forces influence long term circulation patterns. Figure 4.7 shows the general circulation pattern in the lake inferred by Hahl and Handy (1969) from observations made during trips on the lake during 1965 and 1966. This circulation pattern is supported by the spits which have formed along the west edge of the lake. Hahl and Handy concluded that circulation due to Coriolis forces are reinforced by the tangential entry of flow from the Bear, Weber, and Jordan Rivers. No circulation velocities are reported by this reference.

More recent observations of the circulation patterns and velocities within Great Salt Lake suggest the pattern show in Figure 4.8 (Katzenburger, 1974). While there is general agreement between the circulation pattern shown in Figure 4.7 and 4.8, Figure 4.8 shows more refinement. This is apparent at the south tip of the lake where a clockwise current, probably resulting in part from the inflow of the Goggin Drain, has been observed. Surface flow velocities in the south arm under the circulation pattern of Figure 4.8 were observed to vary from 0.3 to 1.0 ft/sec., depending on the season.

Temporary interruptions of the long-term circulation patterns are produced by winds. Winds produce wave action which may temporarily shift or interrupt the general circulation patterns. Additionally, the wind produced wave action is primarily responsible for the well mixed condition of the upper layer of brine in the south arm (Hahl and Handy, 1969).

Preliminary data related to establishing horizontal diffusion coefficients were gathered during an investigation of the lake by the Utah Division of Water Resources, Wildlife Resources, and Geological and Mineral Survey in July, 1974. The diffusivity was then measured by releasing 40 plastic bottles into the lake and tracing their location with time. On the basis of this study, the investigators established a value of .35 m^2/sec for the horizontal diffusion coefficient.

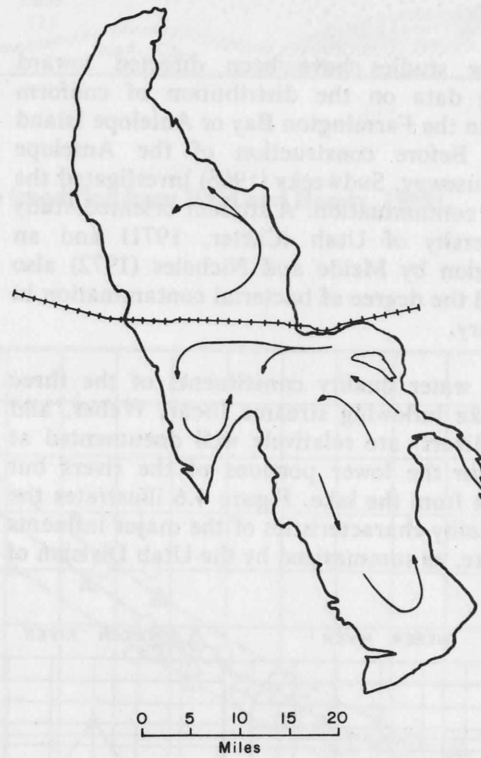

Figure 4.7. Inferred directions of currents in Great Salt Lake during October 1965 and May 1966 (Hahl and Handy, 1969).

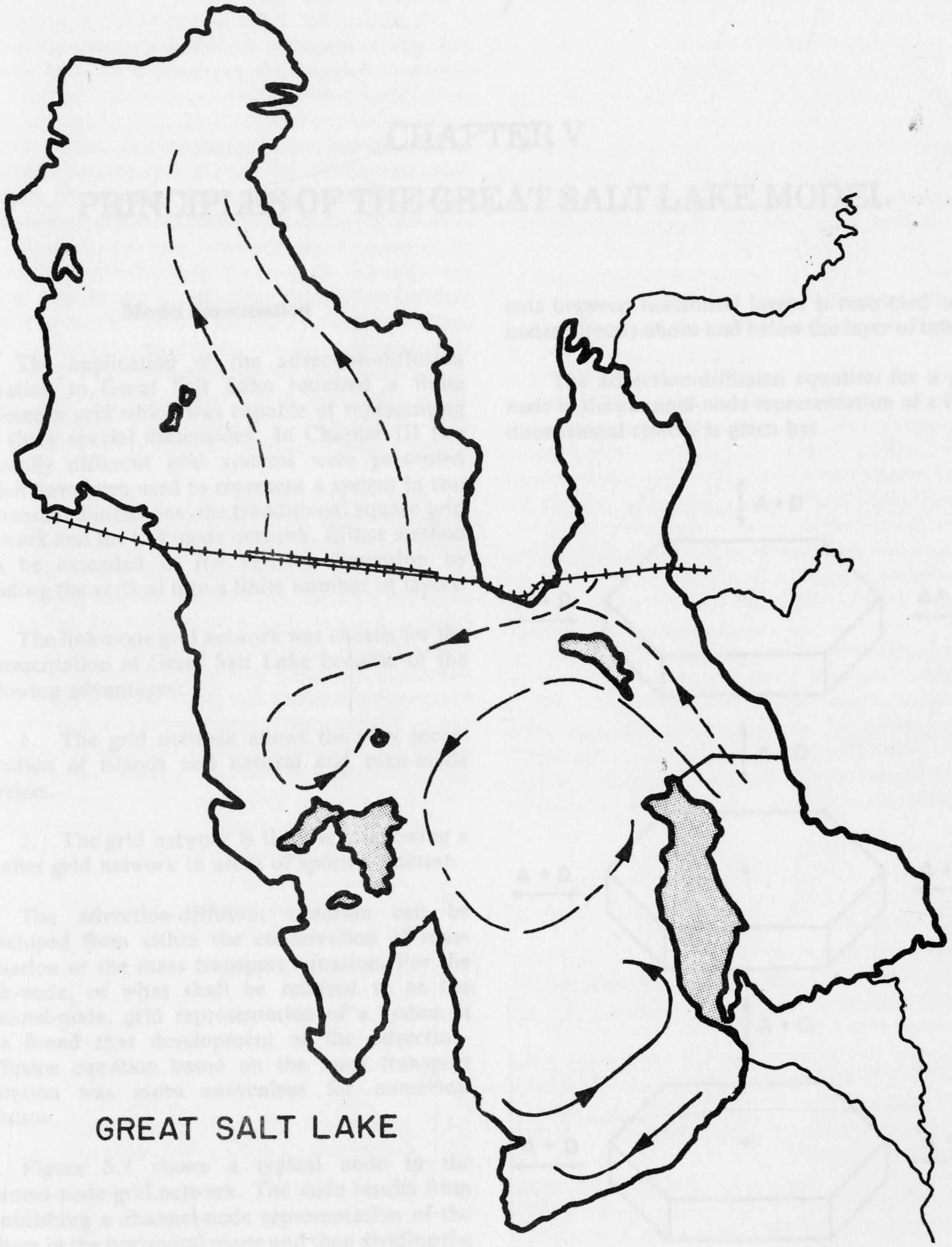

Figure 4.8. General circulation patterns within Great Salt Lake (Katzenburger, 1974).

CHAPTER V

PRINCIPLES OF THE GREAT SALT LAKE MODEL

Model Formulation

The application of the advection-diffusion equation to Great Salt Lake required a finite difference grid which was capable of representing the three special dimensions. In Chapter III two basically different grid systems were presented which have been used to represent a system in two horizontal dimensions; the tranditional square grid network and the link-node network. Either method can be extended to the vertical dimension by dividing the vertical into a finite number of layers.

The link-node grid network was chosen for the representation of Great Salt Lake because of the following advantages:

1. The grid network allows the easy incorporation of islands and natural and man-made barriers.

2. The grid network is flexible in allowing a smaller grid network in areas of specific interest.

The advection-diffusion equation can be developed from either the conservation of mass equation or the mass transport equation. For the link-node, or what shall be referred to as the channel-node, grid representation of a system it was found that development of the advection-diffusion equation based on the mass transport equation was more convenient for numerical solution.

Figure 5.1 shows a typical node in the channel-node grid network. The node results from establishing a channel-node representation of the system in the horizontal plane and then dividing the vertical dimension into a finite number of horizontal layers. The mass transport between nodes in both the horizontal and vertical dimensions occurs through connecting channels. The vertical node system can be visualized as a "Stack" of nodes with the same surface configuration, but variable depth, extending from the water surface to the lake bottom. The vertical movement of quality constituents between horizontal layers is restricted to the nodes directly above and below the layer of interest.

The advection-diffusion equation for a given node in the channel-node representation of a three-dimensional system is given by:

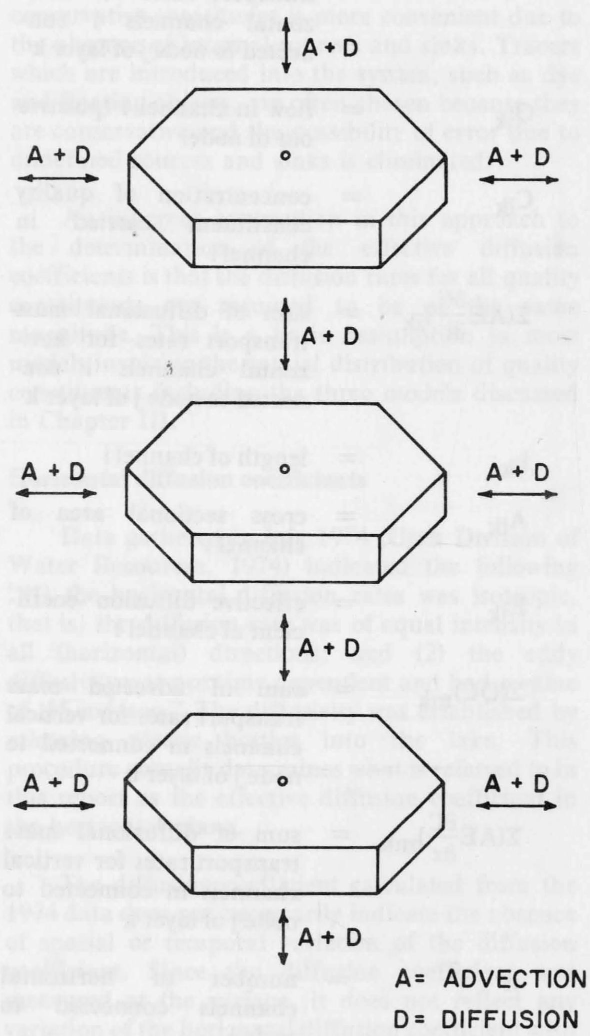

Figure 5.1. Typical vertical nodes in channel-node network.

$$\frac{\partial (VC)_{jk}}{\partial t} = - \sum_{i=1}^{n} (QC)_{ik} + \sum_{i=1}^{n} (AE \frac{\partial C}{\partial l})_{ik}$$

$$- \sum_{m=1}^{2} (QC)_{mk} + \sum_{m=1}^{2} (AE \frac{\partial C}{\partial z})_{mk} + \Sigma S_{jk} \quad (5.1)$$

in which

$(VC)_{jk}$	=	mass of quality constituent in node j of layer k
V_{jk}	=	volume of node j of layer k
C_{jk}	=	concentration of quality constituent in node j of layer k
$\Sigma(QC)_{ik}$	=	sum of advected mass transport rates for horizontal channels i connected to node j of layer k
Q_{ik}	=	flow in channel i (positive out of node)
C_{ik}	=	concentration of quality constituent carried in channel i
$\Sigma(AE\frac{\partial C}{\partial l})_{ik}$	=	sum of diffusional mass transport rates for horizontal channels i connected to node j of layer k
l_{ik}	=	length of channel i
A_{ik}	=	cross sectional area of channel i
E_{ik}	=	effective diffusion coefficient of channel i
$\Sigma(QC)_{mk}$	=	sum of advected mass transport rates for vertical channels m connected to node j of layer k
$\Sigma(AE\frac{\partial C}{\partial z})_{mk}$	=	sum of diffusional mass transport rates for vertical channels m connected to node j of layer k
n	=	number of horizontal channels connected to node j
ΣS_{jk}	=	sum of sources and sinks of mass in node j of layer k
t	=	time

Equation 5.1 is the advection-diffusion equation which describes the three-dimensional mass transport in a system represented by a channel-node grid network. Only one spatial dimension is required to represent the horizontal dimension due to the channel-node representation of the system. Equation 5.1 is general in nature and can be applied to the study of the variation of quality constituents over either large or small time and space units. The spatial and temporal averaging of the channel flows and the effective diffusion coefficients directly influence the time and space scales to which Equation 5.1 should be applied. For example, with the proper temporal averaging of the flows and diffusion coefficients, Equation 5.1 is applicable to the study of either the short term transcient variation of quality constituents or the long term (seasonal) variation.

Figure 5.2 shows the variation of total dissolved solids with depth for both the south and north arms of Great Salt Lake. The north arm and the shallow portion of the south arm of the lake show little variation of total dissolved solids with depth. However, data from the deeper portions of the south arm indicate the presence of an interface between a vertically well mixed upper brine and a vertically well mixed but more concentrated lower brine. This natural layering indicated that the lake could be represented as a two layered vertical network interfaced at the pycnocline with the

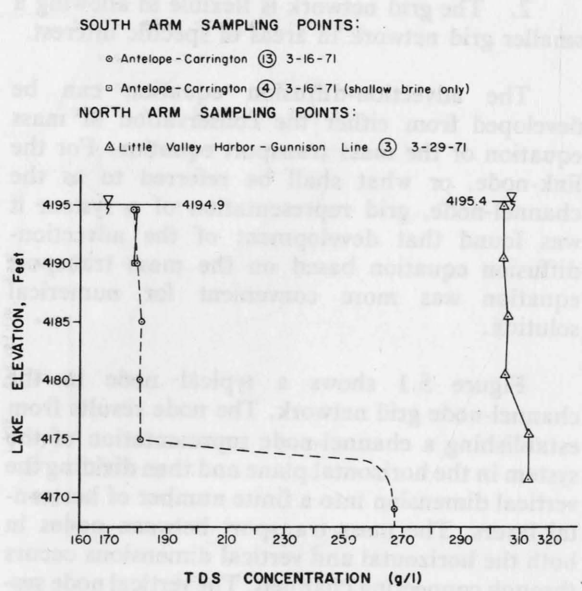

Figure 5.2. Typical variation of total dissolved solids with depth for south and north arm brines.

vertical exchange of quality constituents occurring across the pycnocline.

All vertical transport mechanisms were assumed to be represented by the diffusion coefficient thus eliminating the vertical advection term. The elimination of the vertical advection term should not imply that all vertical transport is due to vertical diffusion alone, but rather that, as an approximation, all vertical transport mechanisms are expressed in the diffusion coefficient. This assumption is supported by the lack of physical evidence of any strong vertical currents within the lake.

With the lake represented as two vertical layers and the vertical transport described by diffusion alone, Equation 5.1 reduces to the following form for application to Great Salt Lake:

$$\frac{\partial\,(VC)_{jk}}{\partial t} = -\sum_{i=1}^{n} (QC)_{ik} + \sum_{i=1}^{n} \left(AE\,\frac{\partial C}{\partial l}\right)_{ik}$$

$$+ \left(AE\,\frac{\partial C}{\partial z}\right)_{vk} + \Sigma S_{jk} \quad \ldots\ldots\ldots\ldots\ldots (5.2)$$

in which $(AE\ \partial C/\partial Z)_{vk}$ represented the diffusional mass transport rate across the interface.

Due to the exchange of salt and other quality constituents between the lake bottom and the overlying brine, it was necessary to include a grid network to represent the lake bottom. The lake was therefore represented as three layers:

1. A channel-node network representing the brine above the pycnocline.

2. A channel-node network representing the brine below the pycnocline.

3. A node network representing the bottom characteristics.

With the absence of flow in the bottom node network, the mass transport equation reduces to:

$$\frac{\partial (CA)_{jb}}{\partial t} = \Sigma S_{jb} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.3)$$

in which

$(CA)_{jb}$ = mass of quality constituents associated with node j of the lake bottom

A_{jb} = area associated with node j of the lake bottom

C_{jb} = mass of constituent C per unit area of the lake bottom associated with node j.

Effective Diffusion Coefficients

A general method for predicting the diffusion coefficients for a natural body based on the theoretical consideration does not presently exist. Rather, empirical methods have been developed for predicting the effective diffusion coefficients. The empirical methods generally contain parameters or coefficients which are based on the physical characteristics of the system or the measurements of the distribution of a tracer over time. Tracers used for this purpose can be of two types, natural or introduced. The natural tracer is a quality constituent naturally present in the system. Any natural constituent can be used as a tracer but a conservative constituent is more convenient due to the absence of internal sources and sinks. Tracers which are introduced into the system, such as dye and floating objects, are often chosen because they are conservative and the possibility of error due to undefined sources and sinks is eliminated.

An inherent assumption in this approach to the determination of the effective diffusion coefficients is that the diffusion rates for all quality constituents are assumed to be of the same magnitude. This is a basic assumption in most models involving the spatial distribution of quality constituents including the three models discussed in Chapter III.

Horizontal diffusion coefficients

Data gathered in July 1974 (Utah Division of Water Resources, 1974) indicated the following "(1) the horizontal diffusion rates was isotropic, that is, the diffusion rate was of equal intensity in all (horizontal) directions; and (2) the eddy diffusivity was not time dependent and had a value of .35 m^2/sec." The diffusivity was established by releasing plastic bottles into the lake. This procedure actually determines what is referred to in this report as the effective diffusion coefficient in the horizontal plane.

The diffusion coefficient calculated from the 1974 data does not necessarily indicate the absence of spatial or temporal variation of the diffusion coefficient. Since the diffusion coefficient was measured at the surface, it does not reflect any variation of the horizontal diffusion coefficient with depth. Rather, the value indicates the magnitude of the horizontal diffusion coefficient which can be expected to be found in Great Salt Lake. This knowledge allowed the importance of horizontal diffusion in the transport process to be assessed during the model operation.

Vertical diffusion coefficients

No suitable method for predicting the vertical diffusion was available. Water Resources Engineers Inc. (WRE) (1968) developed a procedure for determining the effective vertical diffusion from temperature profiles within a reservoir. This work suggested that a procedure could be developed for determining the vertical diffusion coefficient from vertical profiles of total dissolved solids gathered by the UGMS.

The first step in developing the technique was to conceptualize the system as a series of horizontal slices. Thus, the water body was segmented only along the vertical axis. Figure 5.3 shows the one-dimensional representation of the system in which only the vertical transport of salinity was allowed within the system and illustrates the transport, inflow and outflow terms which were included in the mass balance. For a slice of constant volume,

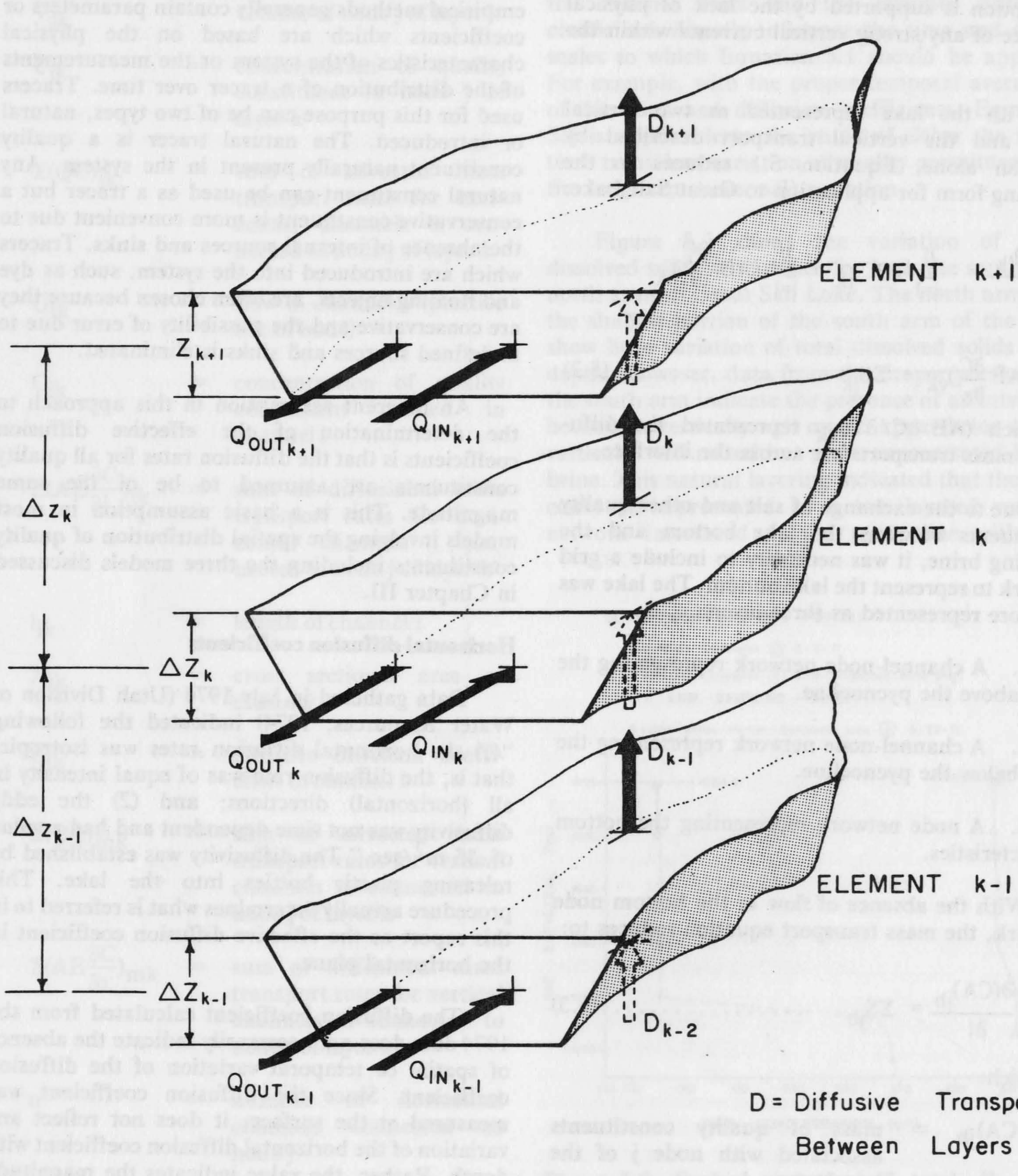

Figure 5.3. One-dimensional representation of the south arm with vertical diffusion.

the equation for the rate at which mass is stored in the volume is given by:

$$\frac{A_{k+1} + A_k}{2} \Delta Z_k \frac{\Delta C_k}{\Delta t}$$

$$= \left[Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k} \right]$$

$$+ A_{k+1} E_{k+1} \left[\frac{C_{k+1} - C_k}{(\Delta Z_{k+1} + \Delta Z_k)/2} \right]$$

$$+ A_k E_k \left[\frac{C_{k-1} - C_k}{(\Delta Z_{k-1} + \Delta Z_k)/2} \right] \quad \ldots\ldots (5.4)$$

in which

$\frac{A_{k+1} + A_k}{2} \Delta Z_k$	=	volume of the slice
A_{k+1}, A_k	=	area of water plane at the associated elevation
$\Delta Z_{k+1}, \Delta Z_k, \Delta Z_{k-1}$	=	thickness of layers k+1, k, and k-1
$\frac{\Delta C_k}{\Delta t}$	=	rate of accumulation of constituent C in layer k
$Q_{in_k} C_{in_k}$	=	rate of mass inflow to layer k
Q_{in_k}	=	rate of inflow to layer k
C_{in_k}	=	concentration of constituent C in the inflow
$Q_{out_k} C_k$	=	rate of mass outflow from layer k
Q_{out_k}	=	rate of outflow from layer k
C_{k+1}, C_k, C_{k-1}	=	concentration constituent C in layers k+1, k, and k-1
R_{D_k}	=	rate of mass dissolving from lake bottom into layer k
E_{k+1}, E_k	=	effective diffusion coefficients at the associated elevation

The first term on the right side of Equation 5.4 represents the flows which cross the physical boundaries of the system. These flows determine the rate of mass input and extraction from layer j by external sources and sinks. The last two terms on the right side represent the diffusive transport between layers based on Fick's law of diffusion.

Dividing through Equation 5.4 by ΔZ_k and rearranging terms yields:

$$\frac{A_{k+1} + A_k}{2} \frac{\Delta C_k}{\Delta t}$$

$$= \frac{1}{\Delta Z_k} \left[Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k} \right]$$

$$+ \frac{1}{\Delta Z_k} \left[A_{k+1} E_{k+1} \left[\frac{C_{k+1} - C_k}{\frac{1}{2}(\Delta Z_{k+1} + \Delta Z_k)} \right] \right.$$

$$\left. + A_k E_k \left[\frac{C_{k-1} - C_k}{\frac{1}{2}(\Delta Z_{k-1} + \Delta Z_k)} \right] \right\} \quad \ldots\ldots (5.5)$$

By taking Equation 5.5 to the limit as ΔZ_k approaches zero, the parameters with subscript k+1 will merge to the parameters with subscript k, and

$$\frac{A_{k+1} + A_k}{2} \rightarrow A_k$$

$$\frac{\Delta C_k}{\Delta t} \rightarrow \frac{\partial C_k}{\partial t}$$

$$\frac{1}{\Delta Z} \left[Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k} \right]$$

$$\rightarrow \frac{\partial}{\partial z} \left[Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k} \right]$$

and

$$\frac{1}{\Delta Z_k} \left[A_{k+1} E_{k+1} \frac{C_{k+1} - C_k}{\frac{1}{2}(\Delta Z_{k+1} + \Delta Z_k)} + A_k E_k \left[\frac{C_{k-1} - C_k}{\frac{1}{2}(\Delta Z_{k-1} + \Delta Z_k)} \right] \right]$$

$$\rightarrow \frac{\partial}{\partial C} \left[A_k E_k \frac{\partial C_k}{\partial z} \right]$$

Substituting the above reductions into Equation 5.5 and rearranging terms results in

$$\frac{\partial}{\partial z}\left[A_k E_k \frac{\partial C_k}{\partial z}\right] = A_k \frac{\partial C_k}{\partial t}$$

$$\frac{\partial}{\partial z}\left[Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k}\right] \quad .(5.6)$$

Integrating Equation 5.6 with respect to z by a forward integration technique from $z = z_o$ to $z = z_K$ yields

$$A_k E_k \frac{\partial C_k}{\partial z}\Bigg|_{z_o}^{z_K} = \int_{z_o}^{z_K} A_k \frac{\partial C_k}{\partial t} dz$$

$$- \sum_{k=1}^{K} (Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k}) \quad ..(5.7)$$

Assuming there is no diffusive transport across the lake bottom eliminates the diffusion at z_o. Rearranging Equation 5.7 under this assumption produces

$$E_K = \frac{\int_{z_o}^{z_K} A_k \frac{\partial C_k}{\partial t} dz - \sum_{k=1}^{K} (Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k})}{A_k \frac{\partial C_K}{\partial t} \, z_K} \quad ....(5.8)$$

The effective vertical diffusion rate, E_K can be evaluated for a given time and place by a finite difference approximation

$$E(z_K, t) = \frac{\sum_{k=1}^{K} A_k \frac{\Delta C_k}{\Delta t} \Delta z_k - \sum_{k=1}^{K} (Q_{in_k} C_{in_k} - Q_{out_k} C_k + R_{D_k})}{A_K \frac{\Delta C_K}{\Delta z_K}} \quad ....(5.9)$$

All the necessary terms in Equation 5.9 are to be taken as mean values during the time period.

The numerical solution for the effective vertical diffusion coefficient for the south arm of Great Salt Lake required information pertaining to two successive vertical profiles of total dissolved solids, flows through the causeway, and the rate of dissolving of salt from the bottom of the south arm. The data available on the vertical distribution of salinity in the south arm restricted the estimation of the vertical diffusion coefficients to the temporal and spatial averaged form.

Since 1966 the UGMS has sampled the south arm periodically along the three lines shown in Figure 4.3. During the early stages of this program, samples were taken monthly at 13 stations along the three lines. Since 1969 the UGMS has reduced the number of stations sampled to six. The six stations include the four stations along the Antelope-Carrigton line, one station in the deeper portion of the lake for the Fremont-Bird line and for the Antelope-Stansbury line. The data from these stations were used to develop concentration profiles of the south arm for the various sampling dates. Data for the years 1970 and 1971 were used in developing the diffusion coefficient due to the availability of causeway flow data (Waddell and Bolke, 1973) and the approximate monthly time spacing between sampling dates.

During most of the 1970-1971 period only one station was sampled by the UGMS on the Antelope-Stansbury line and one station on the Fremont-Bird line. The single station data were extended to represent the entire line by correlation coefficients developed between the single station and the entire line for data gathered from 1966 to 1968. The concentration profiles for each date used in the analysis were obtained by averaging the various stations to produce a single profile of the variation of the south arm concentration with depth. Several sampling dates during the 1970 to 1971 period could not be used in the analysis due to either the lack of data or the extended time period between sampling. Six sets of data were identified and used in the analysis.

The following assumptions were made in applying Equation 5.9 to the calculation of the spatial and temporal averaged vertical-diffusion coefficients:

1. The pycnocline was fixed at an elevation of 4,175 feet.

2. All flow south through the causeway entered the south arm below the pycnocline.

3. All flow north through the causeway was from the south arm brine above the pycnocline.

4. Salt dissolving from the bottom only entered the bottom brine layer.

5. Inflow of total dissolved solids from streams was negligible.

Under these assumptions, Equation 5.9 was applied to the south arm of the lake by dividing the lake into one 6-foot layer to represent the concentrated brine below the pycnocline and approximately twenty 1-foot layers to represent the upper less concentrated brine. The determination of the vertical diffusion coefficient was complicated because the rate at which salt dissolves from the bottom of the lake was unknown. This rate was represented by the following equation:

$$R_D = K_A (C_s - C) V \quad \text{...........(5.10)}$$

in which

R_D = rate of salt dissolving (mass/unit time)

K_A = dissolving constant (time^{-1})

C = concentration of total dissolved solids in overlying layer

C_s = saturation concentration of total dissolved solids

V = volume of overlying layer

The dissolving rate was estimated by performing a mass balance on the south arm of the lake.

For each time period the vertical diffusion coefficient and the salt dissolving rate were determined from the mass balance equation and Equation 5.9 and verified with a water and salinity balance model of the lake. The water and salinity balance model was based on the water budget of the lake by Steed (1972) and the causeway flow equations developed by Waddell and Bolke (1973). This model is detailed in Chapter VI.

Figure 5.4 shows the variation of the vertical diffusion coefficient with depth as predicted by Equation 5.9 for a typical time period. The variation of the diffusion coefficient above the pycnocline is associated with a very small variation (less than one gram per liter per foot of depth) of total dissolved solids with depth. The well mixed nature of the upper brine layer suggested that the diffusion coefficient above the pycnocline might be approximated by a constant as shown in Figure 5.4. The calculated values of the vertical diffusion coefficients above the pycnocline are summarized in Table 5.1. The channel-node simulation study required only the vertical diffusion coefficient

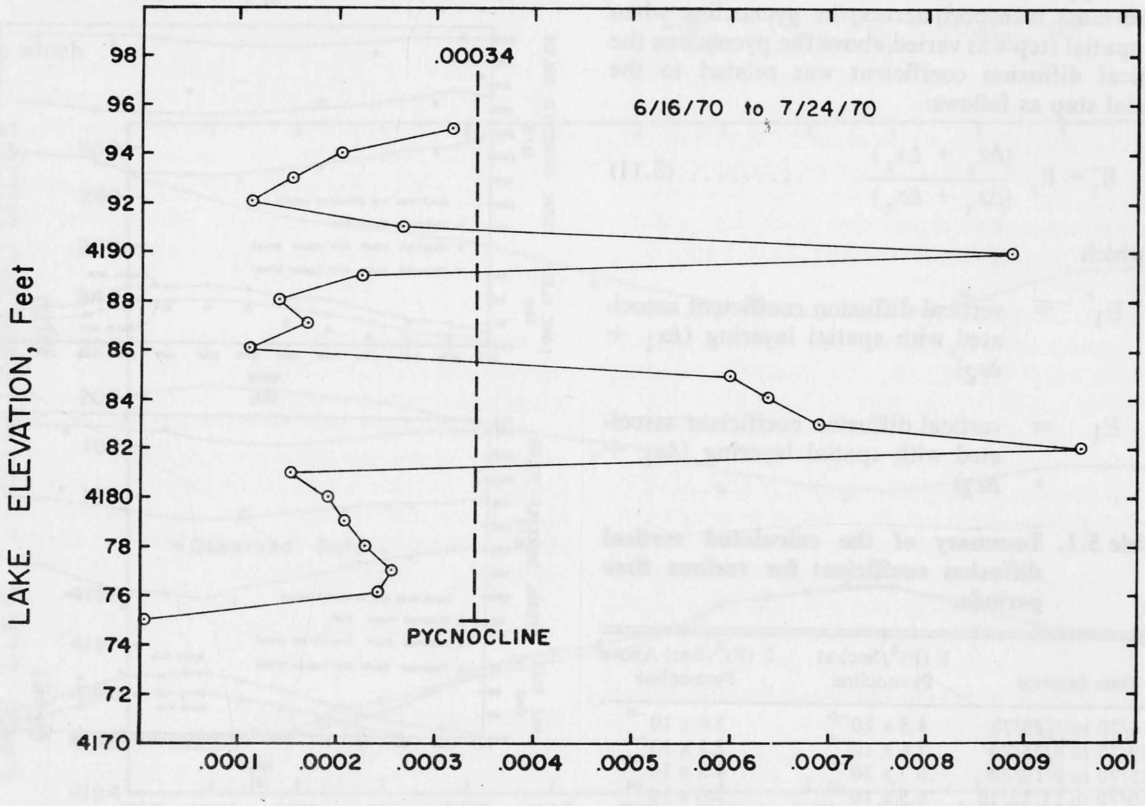

Figure 5.4. Typical calculated variation of the vertical diffusion coefficient with depth.

associated with transport across the pycnocline. The diffusion coefficients which were calculated at the pycnocline also are summarized in Table 5.1.

The water and salinity balance model was used to verify the results obtained for the salt dissolving rate and the effective vertical diffusion coefficients. Figure 5.5 compares the simulated and observed concentration of both south arm brine layers for the 1967 to 1969 water years. After minor adjustments the dissolving constant, K_A, was identified as .006/day and the effective vertical diffusion coefficients as 3.8 x 10^{-6} ft^2/sec at the pycnocline and 2.5 x 10^{-4} ft^2/sec above the pycnocline. These values were used to simulate the 1971 water year as a check and the results are given in Figure 5.6.

In both the calculation and verification of the vertical diffusion coefficient, the bottom brine layer was assumed to be a single 6-foot thick layer. Under this representation, the change in concentration of total dissolved solids across the pycnocline was essentially constant and independent of the spatial step used above the pycnocline. This condition resulted from the well mixed nature of the upper brine layer. In order to maintain the same mass transport across the pycnocline when the spatial step was varied above the pycnocline the vertical diffusion coefficient was related to the spatial step as follows:

$$E_1' = E_1 \frac{(\Delta z_1 + \Delta z_2)'}{(\Delta z_1 + \Delta z_2)} \quad \ldots\ldots\ldots\ldots (5.11)$$

in which

E_1' = vertical diffusion coefficient associated with spatial layering $(\Delta z_1 + \Delta z_2)'$

E_1 = vertical diffusion coefficient associated with spatial layering $(\Delta z_1 + \Delta z_2)$

Table 5.1. Summary of the calculated vertical diffusion coefficient for various time periods.

Time Interval	E (Ft^2/Sec) at Pycnocline	E (Ft^2/Sec) Above Pycnocline
6/16/70 to 7/29/70	4.3 x 10^{-6}	3.4 x 10^{-4}
7/29/70 to 8/25/70	7.6 x 10^{-6}	2.1 x 10^{-4}
8/25/70 to 9/10/70	6.7 x 10^{-6}	4.2 x 10^{-4}
9/10/70 to 11/12/70	6.5 x 10^{-6}	2.0 x 10^{-4}
6/09/71 to 7/28/71	1.3 x 10^{-6}	2.6 x 10^{-4}
7/28/71 to 8/19/71	4.1 x 10^{-6}	3.1 x 10^{-4}
Identified in verification Runs for 1967-68-69	3.8 x 10^{-6}	2.5 x 10^{-4}

Δz_1 = thickness of bottom brine layer (layer 1 was 6 feet throughout study)

Δz_2 = thickness of second brine layer

In the application of Equation 5.9 to the south arm of Great Salt Lake Δz_2 was 1 foot. During verification Δz_2 was set at 5 feet. All values reported in Table 5.1 and in the above discussion are related to a Δz_2 of 1 foot.

The dissolving constant, K_A, (Equation 5.10) was developed for the south arm using the

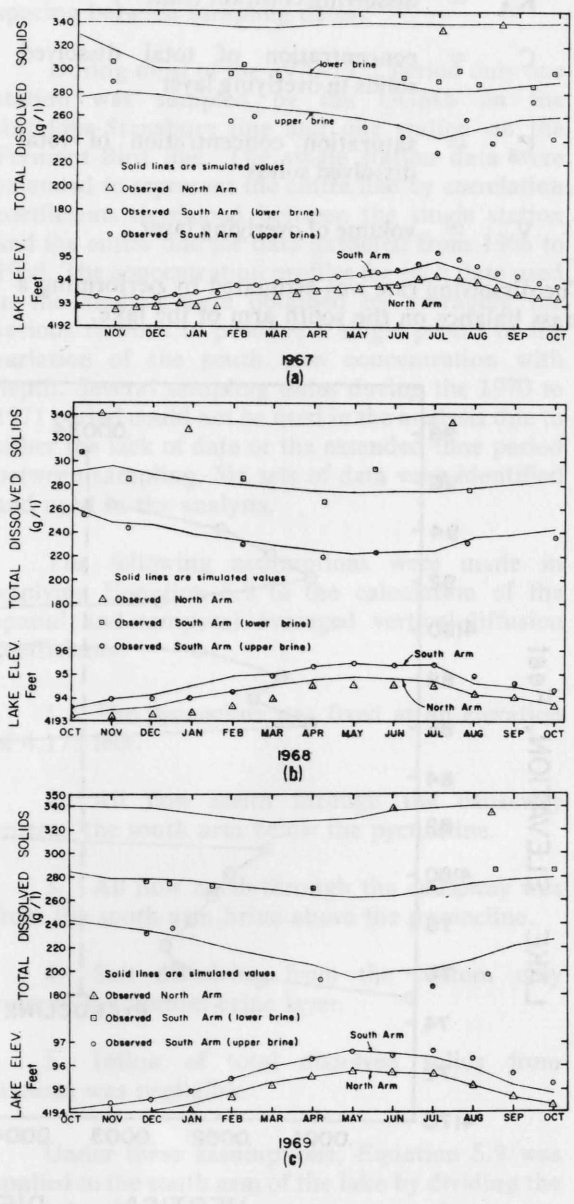

Figure 5.5. Simulated and observed brine concentrations and surface elevations for the 1967, 1968, and 1969 water years.

concentration and volume below the pycnocline. A saturation concentration for total dissolved solids of 340 g/l was used in developing the dissolving constant. Whelan (1973) used a value of 350 g/l to represent the saturation concentration. However, a review of the UGMS salinity data from the north arm indicated precipitation of salt probably occurs below the 350 g/l concentration, and for this reason, 340 g/l was used as the saturation concentration in this study. The verification run for the 1969 water year indicated that 130 million metric tons of salt dissolved in the south arm. This amount compares extremely well with 135 million metric tons of salt estimated by Whelan (1972) to have dissolved during the same period.

The Summation of Sources and Sinks Term

The summation of sources and sinks term of Equation 5.2 and 5.3 can be considered to be composed of external and internal components. The summation of sources and sinks term may then be represented as two terms

$$\Sigma S = \Sigma S_E + \Sigma S_I \quad \text{.............(5.12)}$$

in which

ΣS_E = summation of external sources and sinks of C

ΣS_I = summation of internal sources and sinks of C

The inflow (source) and outflow (sink) of quality constituents across the physical boundaries of the systems represent external sources and sinks. Internal sources and sinks are processes within the system which generate or degrade the quality constituent. Examples of internal sources and sinks are precipitation and dissolving of salts and the decay of biological substances. Constituents which do not have internal sources or sinks are termed conservative constituents. Non-conservative constituents, therefore, are constituents with internal sources and sinks.

All quality constituents can enter or leave the system across the physical boundary of the system. Therefore, there is a summation of external sources and sinks term for each component. This term is expressed for node j as

$$\Sigma S_{E_{jk}} = (Q_{in_{jk}} \; C_{in_{jk}}) - (Q_{out_{jk}} \; C_{jk}) \quad \text{..(5.13)}$$

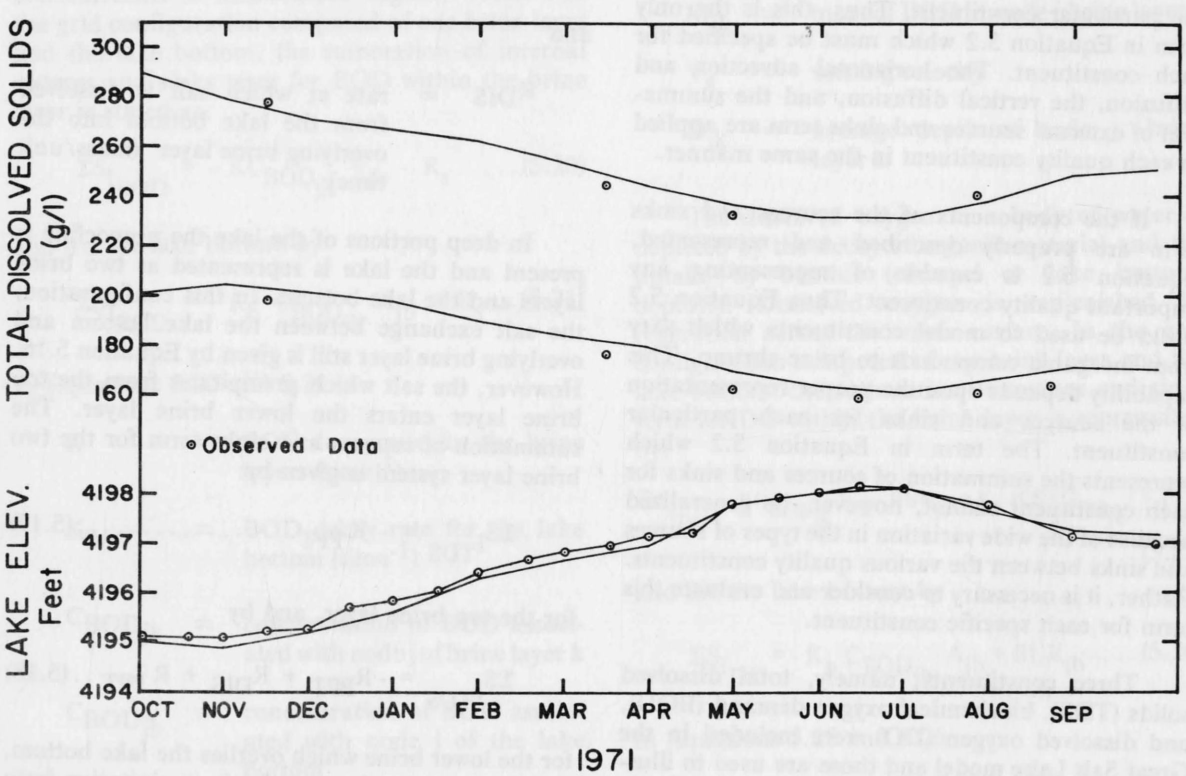

Figure 5.6. Simulated and observed brine concentrations and surface elevations for the 1971 water years.

in which

$Q_{in_j} C_{in_j}$ = rate of external mass inflow to node j brine layer k

Q_{in_j} = rate of inflow to node j brine layer k

C_{in_j} = concentration of constituent C in inflow

$Q_{out_j} C_j$ = rate of external mass outflow from node j brine layer k

Q_{out_j} = rate of outflow from node j brine layer k

C_j = concentration of constituent C in node j

Because external sources and sinks are associated with the flow, Q, across the boundaries they exist only for the brine layers. For the lake bottom Equation 5.12 reduces to

$$\Sigma S = \Sigma S_I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.14)$$

Unlike the external sources and sinks, the internal sources and sinks term is associated with the particular constituent. Thus, this is the only term in Equation 5.2 which must be specified for each constituent. The horizontal advection and diffusion, the vertical diffusion, and the summation of external sources and sinks term are applied to each quality constituent in the same manner.

If the components of the sources and sinks term are properly described and represented, Equation 5.2 is capable of representing any important quality constituent. Thus Equation 5.2 could be used to model constituents which vary from inorganic compounds to brine shrimp. This capability depends upon the proper representation of the sources and sinks for each particular constituent. The term in Equation 5.2 which represents the summation of sources and sinks for each constituent cannot, however, be generalized because of the wide variation in the types of sources and sinks between the various quality constituents. Rather, it is necessary to consider and evaluate this term for each specific constituent.

Three constituents, namely, total dissolved solids (TDS), biochemical oxygen demand (BOD), and dissolved oxygen (DO) were included in the Great Salt Lake model and those are used to illustrate the procedure for establishing the internal sources and sinks term for both coupled and uncoupled constituents. The internal sources and sinks of an uncoupled constituent are independent of other constituents in the system. With coupled constituents the depeletion or replenishing of one constituent directly affects the depletion or replenishing of the other coupled constituents. For example, in the case of BOD and DO, the decay of BOD depletes DO.

The summation of internal sources and sinks for total dissolved solids is composed of terms representing the rate of precipitation and dissolving of salt. In shallow portions of the lake the pycnocline is not present and the grid network reduces to a system comprised of one brine layer and the lake bottom. For this configuration, the summation of internal sources and sinks term for the brine layer is stated as:

$$\Sigma S_{I_{TDS}} = -R_{PPT} + R_{DIS} \quad \ldots\ldots\ldots (5.15)$$

and for the lake bottom as

$$\Sigma S_{I_{TDS}} = + R_{PPT} - R_{DIS} \quad \ldots\ldots (5.16)$$

in which

R_{PPT} = rate of salt precipitation from the lake brine to the lake bottom (mass/unit time)

and

R_{DIS} = rate at which salt is dissolved from the lake bottom into the overlying brine layer (mass/unit time)

In deep portions of the lake the pycnocline is present and the lake is represented as two brine layers and the lake bottom. In this configuration, the salt exchange between the lake bottom and overlying brine layer still is given by Equation 5.16. However, the salt which precipitates from the top brine layer enters the lower brine layer. The summation of sources and sinks term for the two brine layer system is given by:

$$\Sigma S_{I_{TDS}} = - R'_{PPT} \quad \ldots\ldots\ldots\ldots (5.17)$$

for the top brine layer, and by

$$\Sigma S_{I_{TDS}} = - R_{PPT} + R_{DIS} + R'_{PPT} \ldots (5.18)$$

for the lower brine which overlies the lake bottom. R_{PPT} represents the rate of salt precipitation from the top brine layer.

The dissolving rate of salt from the lake bottom is given by:

$$R_{DIS_{jk}} = K_A \,(C_s - C_{jk})\, V_{jk} \quad \ldots\ldots\ldots (5.19)$$

in which

$R_{DIS_{jk}}$ = rate of salt dissolving (mass/unit time)

K_A = dissolving constant (time^{-1})

C_s = saturation concentration for total dissolved solids

C_{jk} = concentration of TDS in node j of the layer overlying the lake bottom

V_{jk} = volume of node j of the layer overlying the lake bottom

Equation 5.19 is applicable only when $C_{jk} \leqslant C_s$.

Biochemical oxygen demand is a measure of the concentration of unstablized organic waste present in a system. BOD is removed from the system by bacterial consumption at a rate proportional to the concentration of unstabilized organic waste. For the grid configuration composed of one brine layer and the lake bottom, the summation of internal sources and sinks term for BOD within the brine layer is stated as:

$$\Sigma S_{I_{BOD}} = -\, K C_{BOD_{jk}} \, V_{jk} - R_s \quad \ldots (5.20)$$

and for the lake bottom by

$$\Sigma S_{I_{BOD}} = -\, K_b \, C_{BOD_{jb}} \, A_{jb} + R_s \quad \ldots (5.21)$$

In Equations 5.20 and 5.21

K = BOD decay rate for the brine layers (time^{-1})

K_b = BOD decay rate for the lake bottom (time^{-1})

$C_{BOD_{jk}}$ = concentration of BOD associated with node j of brine layer k

$C_{BOD_{jb}}$ = concentration of BOD associated with node j of the lake bottom

R_s = settling rate of BOD (mass/unit time)

In the grid configuration composed of two brine layers and the lake bottom, the summation of sources and sinks term for the top layer is given by:

$$\Sigma S_{I_{BOD}} = -\, K C_{BOD_{jk}} \, V_{jk} - R_s' \quad \ldots (5.22)$$

and for the lower brine layer by

$$\Sigma S_{I_{BOD}} = -\, K C_{BOD_{jk}} \, V_{jk} - R_S + R' \quad \ldots (5.23)$$

in which

R_s' = settling rate of BOD from the top brine layer and is assumed equal to R_s

The relationship for the lake bottom is given by Equation 5.21.

The BOD settling rate, R_s (or R_s') represents the rate at which BOD settles out of the brine. The rate of settling is given by:

$$R_s = M_{jk} \frac{V_s}{D_{jk}} \quad \ldots\ldots\ldots\ldots\ldots (5.24)$$

in which

M_{jk} = mass of BOD in node j brine layer k

V_s = settling velocity

D_{jk} = average depth of node j, brine layer k

The dissolved oxygen in a body of water is depleted by the decay of organic material and the uptake by benthic (channel or lake bottom) deposits. Dissolved oxygen is replenished by reaeration across the water surface. In the grid configuration composed of one brine layer and the lake bottom, the summation of sources and sinks term for DO within the brine layer is represented by:

$$\Sigma S_{I_{DO}} = -KC_{BOD_{jk}} \, V_{jk} - BUR_{jb} + K_2 \,(CS - C_{DO_{jk}})\, V_{jk} \quad \ldots\ldots\ldots (5.25)$$

and for the lake bottom by

$$\Sigma S_{I_{DO}} = -\, K_b \, C_{BOD_{jb}} \, A_{jb} + BUR_{jb} \quad \ldots (5.26)$$

In Equations 5.25 and 5.26

BUR_{jb} = benthic uptake rate by node j of the lake bottom from the overlying node in the brine

K_2 = reaction coefficient for DO

CS = saturation concentration of DO

$C_{DO_{jk}}$ = concentration of DO in node j of layer k

and the rest of the terms are as previously defined.

The summation of sources and sinks term for the grid configuration composed of two brine layers and the lake bottom is given by:

$$\Sigma S_{I_{DO}} = - KC_{BOD_{jk}} V_{jk} + K_2 (CS - C_{DO_{jk}}) V_{jk} \qquad (5.27)$$

for the upper brine layer, and by

$$\Sigma S_{I_{DO}} = - KC_{BOD_{jk}} V_{jk} - BUR_{jb} \qquad (5.28)$$

for the lower brine layer. The relationship for the lake bottom is given by Equation 5.26.

It is well documented in the literature that the solubility of oxygen in water decreases with increasing temperature, increasing concentrations of total dissolved solids and increasing elevations. Data reported by Green (Metcalf and Eddy, Inc., 1972) and formulas such as those developed by Gameson and Robertson (1955) indicate this typical variation of the solubility of oxygen in sea water. Formulas which have been developed for predicting the effects of total dissolved solids on the solubility of oxygen have been formulated for seawater with total dissolved solids concentrations less than 40 g/l. The formula developed by Gameson and Robertson predicts a complete absence of dissolved oxygen when the concentration of total dissolved solids exceeds 180 g/l. However, this prediction did not seem realistic for the Great Salt Lake, and dissolved oxygen saturation values were obtained by laboratory experiments. These experiments were conducted with Great Salt Lake brine at concentrations of total dissolved solids which varied between 50 g/l and 340 g/l. The brine samples were bubble aerated with compressed air and then held at a constant temperature in contact with the atmosphere. Temperatures of 6.0°C and 16.5°C were used in the study. After 24 hours of contact with the atmosphere the oxygen concentration was determined by the azide modification of the Winkler Method in "Standard Methods" (APHA, 1971).

The results of the experiment indicated that the dissolved oxygen saturation concentration remained above zero as the concentration of total dissolved solids approached saturation. The data were fit by regression analysis so that the variation of the saturation concentration of dissolved oxygen could be predicted for various temperatures and salinities. The resulting equation for the saturation concentration of dissolved oxygen as a function of temperature and total dissolved solids and at an elevation comparable to the surface elevation of Great Salt Lake is given by:

$$CS = 7.73 - .0155T - .0311\, C_{TDS} + .353 \times 10^{-4}\, C_{TDS}^2 \qquad (5.29)$$

in which

CS = dissolved oxygen saturation concentration (mg/l)

T = temperature (°C)

C_{TDS} = concentration of total dissolved solids (g/l)

The correlation coefficient (R^2) for the fit of the 6°C and 16.5°C data was 0.994. Figure 5.7 compares the observed and predicted (Equation 5.29) saturation concentration.

Considerable amount of research has been directed toward the determination of the reaeration coefficient, K_2, for various systems. In these studies the reaeration coefficient has been related to the depth and velocity of the fluid. During a study of the Delaware River estuary O'Connor and Dobbins (1958), proposed the following relationship for predicting the reaeration coefficient.

$$K_2 = 12.9 \frac{V^{1/2}}{H^{3/2}} \qquad (5.30)$$

in which

K_2 = reaeration coefficient (day^{-1})

V = velocity (ft/sec)

H = depth (ft)

An empirical equation of the same form was developed by Churchill, Buckingham, and Elmore (1962) for various tributaries of the Tennessee River:

$$K_2 = 11.5 \frac{V^{.969}}{H^{1.673}} \qquad (5.31)$$

All terms in Equation 5.31 are as previously defined. Both of the equations give the value of K_2

at 20°C and yield essentially the same result. The O'Connor and Dobbins equation was chosen for use in this study due to the closer physical similarity between the Delaware River estuary and Great Salt Lake.

Both the reaeration coefficient for dissolved oxygen, K_2, and the first-order decay rate for biochemical oxygen demand, K, are temperature dependent. The equation which was used to adjust these rates for temperatures other than 20°C was derived from the Van't Hoff-Arrhenius equation (Metcalf and Eddy, Inc., 1972) and is given as:

$$k = k_{20}\ \theta^{(T-20)} \qquad \ldots\ldots\ldots\ldots(5.32)$$

in which

k = rate at any temperature

k_{20} = rate at 20°C

θ = temperature correction constant

T = temperature (°C)

A value of $\Theta = 1.024$ was used in the study for correcting the reaeration coefficient. This value was established by Churchill et al. (1962) and same value appears in Metcalf and Eddy, Inc. (1972). The value of Θ applicable to the biochemical oxygen demand was chosen as 1.03 as suggested by O'Connor (1964).

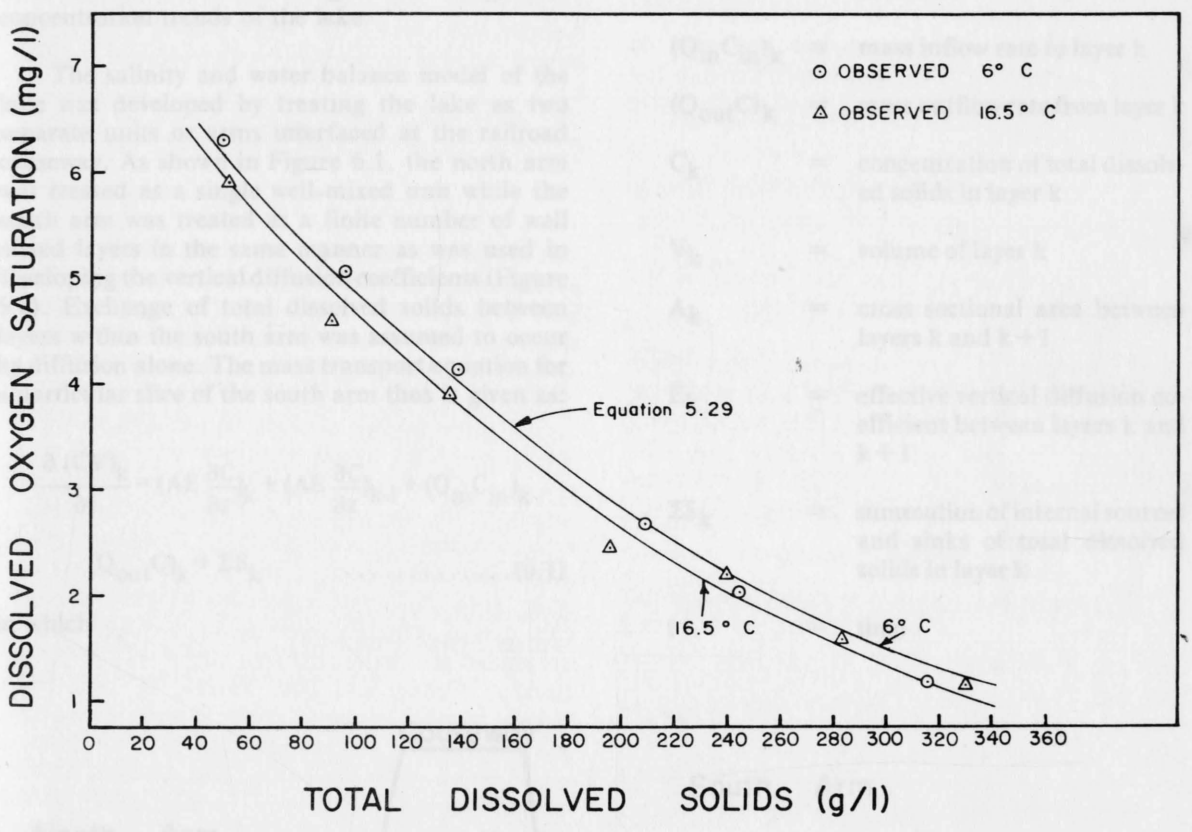

Figure 5.7. Variation of dissolved oxygen saturation with total dissolved solids.

K_2 = reaeration coefficient for DO

CS = saturation concentration of DO

$C_{DO_{i,k}}$ = concentration of DO in node i of layer k

and the rest of the terms are as previously defined.

The summation of sources and sinks terms for the [illegible] comprised of two brine layers [illegible]

[illegible]

for the upper brine layer, and by

$$DO \ldots \qquad (5.28)$$

for the lower brine layer. The relationship for the lake bottom is given by equation 5.26.

It is well documented in the literature that the solubility of oxygen in water decreases with increasing temperature, increasing concentrations of total dissolved solids and increasing elevation. Data reported by Green (Metcalf and Eddy, Inc., 1972) and formulas such as those developed by Gameson and Robertson (1955) indicate this typical variation of the solubility of oxygen in sea water. Formulas which have been developed for predicting the effects of total dissolved solids on the solubility of oxygen have been formulated for streams with total dissolved solids concentrations less than 40 g/l. The formula developed by Gameson and Robertson predicts a complete absence of dissolved oxygen when the concentration of total dissolved solids exceeds 140 g/l. However, this prediction did not seem realistic for the Great Salt Lake, and dissolved oxygen saturation values were obtained by laboratory experiments. [illegible] with Great Salt Lake brine at concentrations of total dissolved solids which ranged between 40 g/l and 340 g/l. The brine samples were initially aerated with compressed air and then held at a constant temperature in contact with the atmosphere. Temperatures of 6.0°C and 16.5°C were used in the study. After 24 hours of contact with the atmosphere the oxygen concentration was determined by the azide modification of the Winkler Method in "Standard Methods" (APHA, 1971).

The results of the experiment indicated that the dissolved oxygen saturation concentration [illegible] almost zero as the concentration of total dissolved solids approached saturation. The data were [illegible] regression analysis so that the variation of [illegible] could be [illegible] The [illegible] concentration of dissolved oxygen as a function of temperature and total dissolved solids and at an elevation corresponding to the surface elevation of [illegible]

[illegible]

in which

CS = dissolved oxygen saturation concentration (mg/l)

T = temperature (°C)

TDS = concentration of total dissolved solids (g/l)

The correlation coefficient (R^2) for the fit of the 6.0 and 16.5°C data was 0.994. Figure 5.7 compares the observed and predicted (Equation 5.29) saturation concentration.

Considerable amounts of research has been directed toward the determination of the reaeration coefficient, K_2, for oxygen systems. In these studies the reaeration coefficient has been related to the depth and velocity of the fluid. During a study of the Delaware River estuary O'Connor and Dobbins (1958) proposed the following relationship for predicting the reaeration coefficient.

$$K_2 = 12.9 \frac{V^{0.5}}{H^{1.5}} \qquad (5.30)$$

in which

K_2 = reaeration coefficient (day^{-1})

[illegible]

An empirical equation of the same form was developed by Churchill, Elmore, and Buckingham (1962) for various tributaries of the Tennessee River:

$$K_2 = 11.6 \frac{V^{0.969}}{H^{1.673}} \qquad (5.31)$$

All terms in Equation 5.31 are as previously defined. Both of the equations give the values of K_2

CHAPTER VI

THE WATER AND SALINITY BALANCE MODEL

A water and salinity balance model of Great Salt Lake was developed initially to provide a means of verifying the vertical diffusion coefficients identified in the study. The model subsequently was used to provide information for the channel-node model and to investigate the long term concentration trends of the lake.

The salinity and water balance model of the lake was developed by treating the lake as two separate units or arms interfaced at the railroad causeway. As shown in Figure 6.1, the north arm was treated as a single well-mixed unit while the south arm was treated as a finite number of well mixed layers in the same manner as was used in developing the vertical diffusion coefficients (Figure 5.3). Exchange of total dissolved solids between layers within the south arm was assumed to occur by diffusion alone. The mass transport equation for a particular slice of the south arm thus is given as:

$$\frac{\partial (CV)_k}{\partial t} = (AE\frac{\partial C}{\partial z})_k + (AE\frac{\partial C}{\partial z})_{k-1} + (Q_{in}C_{in})_k$$

$$- (Q_{out}C)_k + \Sigma S_k \quad \ldots\ldots\ldots\ldots (6.1)$$

in which

$(CV)_k$ = mass of quality constituent in layer k

$(AE\frac{\partial C}{\partial z})_k$ = diffusional mass transport rate between vertical layers k and k+1

$(Q_{in}C_{in})_k$ = mass inflow rate to layer k

$(Q_{out}C)_k$ = mass outflow rate from layer k

C_k = concentration of total dissolved solids in layer k

V_k = volume of layer k

A_k = cross sectional area between layers k and k+1

E_k = effective vertical diffusion coefficient between layers k and k+1

ΣS_k = summation of internal sources and sinks of total dissolved solids in layer k

t = time

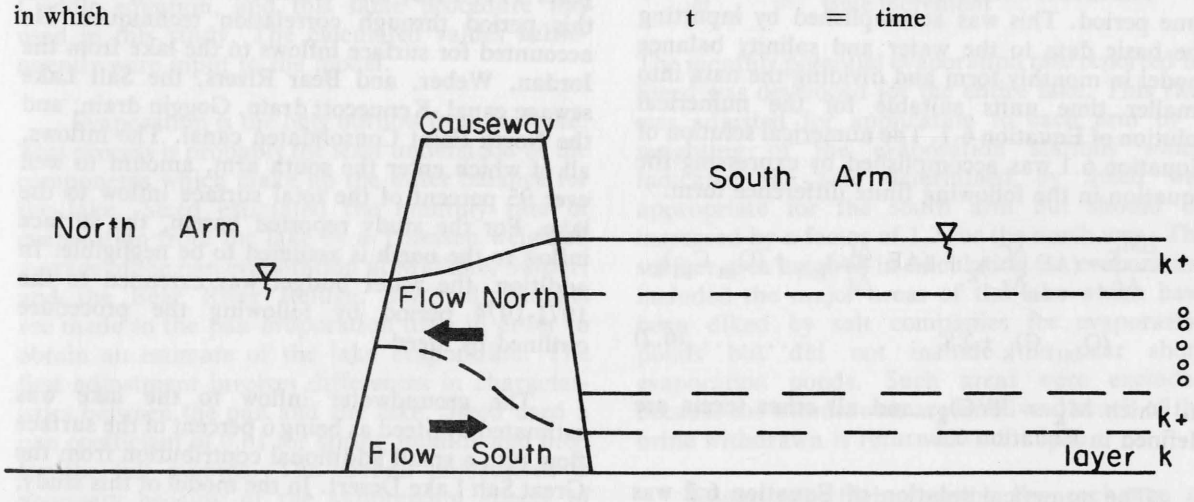

Figure 6.1. Representation of the Great Salt Lake physical system in the water and salinity balance model.

Because the north arm of the lake was assumed to be a single well mixed unit, the vertical diffusion terms of Equation 6.1 were eliminated in applying the equation to this body of water.

The following assumptions were made in applying Equation 6.1 to the calculation of the vertical distribution of salinity within the south arm of the lake:

1. The pycnocline is fixed at an elevation of 4,175 feet.

2. All flows south through the causeway enter the south arm below the pycnocline.

3. Based on velocity profiles presented in Waddell and Bolke (1973), flow north through the causeway fill is evenly distributed with depth above the pycnocline.

4. Based on velocity profiles presented in Waddell and Bolke (1973), flow north through the causeway fill is evenly distributed with depth above the culvert bottom.

5. All inflow to the south arm from streams and groundwater enters only the upper brine layer.

6. Salt dissolving from the bottom of the south arm enters the bottom brine layer.

7. Inflow of total dissolved solids from streams is negligible. The original source of most salts within the Great Salt Lake was the inflowing tributaries. However, within a comparatively short study period of 20 years or less, salt contributions from this source are negligible in terms of the total salt volume within the lake.

The model was designed to simulate a monthly time period. This was accomplished by inputting the basic data to the water and salinity balance model in monthly form and dividing the data into smaller time units suitable for the numerical solution of Equation 6.1. The numerical solution of Equation 6.1 was accomplished by expressing the equation in the following finite difference form:

$$\frac{\Delta M_k}{\Delta t} = \left(AE\frac{\Delta C}{\Delta z}\right)_k + \left(AE\frac{\Delta C}{\Delta z}\right)_{k-1} + (Q_{in}\,C_{in})_k - (Q_{out}\,C)_k + \Sigma S_k \qquad \text{..........(6.2)}$$

in which $M_k = (VC)_k$, and all other terms are defined in Equation 6.1.

The numerical solution of Equation 6.2 was performed by an explicit solution technique which calculated the change of mass within a layer, using the volume and concentration at the beginning of the time step. At the end of the time step the volume was updated and a new concentration calculated. Variations in water volume are assumed to occur for the entire water body of the north arm and for only the top layer of the south arm. The maximum time step for solution stability of Equation 6.2 was estimated from experience using the model, and was found to be:

$$\Delta t \leqslant \frac{(\Delta z)^2}{E} \qquad \text{.................(6.3)}$$

Water Balance

The water balance portion of the model was formulated by accounting for the inflow and outflow to the lake and the exchange of brine between the two arms of the lake through the railroad causeway. The water balance for either arm of the lake for a given time period (Δt) is given by:

$$\text{Change in storage} = (\text{rate of inflow} - \text{rate of outflow})\,\Delta t \qquad \text{............(6.4)}$$

The inflow to either arm of the lake is composed of precipitation, surface and groundwater inflow, and flow through the causeway. The outflow from either arm of the lake is restricted to evaporation and exchange through the causeway.

A water budget analysis of the lake by Steed (1972) provided information on the basic components of the water balance; namely, the rate of precipitation, the surface and groundwater inflow rates, and the rate of evaporation. Steed performed a monthly water budget of the lake covering the years 1944-1970, and estimated missing data for this period through correlation techniques. He accounted for surface inflows to the lake from the Jordan, Weber, and Bear Rivers, the Salt Lake sewage canal, Kennecott drain, Goggin drain, and the North Point Consolidated canal. The inflows, all of which enter the south arm, amount to well over 95 percent of the total surface inflow to the lake. For the study reported herein, the surface inflow to the north is assumed to be negligible. In addition, the water budget was extended to the 1971-1974 period by following the procedure outlined by Steed.

The groundwater inflow to the lake was estimated by Steed as being 6 percent of the surface flow with a small additional contribution from the Great Salt Lake Desert. In the model of this study, Steed's groundwater inflow rates were adopted.

Steed related the 6 percent quantity to contributions principally from the groundwater basins to the east and south of the lake. Since this inflow would enter the south arm and the contribution from the Great Salt Lake Desert is very minor, all the groundwater inflow was assumed to enter only the south arm of the lake.

Steed obtained the monthly rate of precipitation for the lake as a Thiessen weighted average of the precipitation at Corinne, Lake Point, and Farmington. The precipitation input to a particular arm of the lake for a given time increment is calculated in the model as the weighted rate of monthly precipitation times the surface area of the arm at the beginning of the time step. Thus, the precipitation input is given as:

$$P_{in} = P\,A_s\,\Delta t \qquad (6.5)$$

in which

P_{in} = volume of precipitation input to an arm during time Δt

P = monthly precipitation rate

A_s = surface area of arm

Δt = time increment

All of the gaging stations on the major surface inflows to the lake are above major phreatophyte areas bordering the lake. The phreatophyte areas of concern include Bear River Migratory Bird Refuge, Farmington Bay Water Fowl Management Area, and private duck clubs located at the mouth of the Jordan River. Steed calculated evapotranspiration for these areas from the Blaney-Criddle equation, and this same procedure was used in this study. The calculated values subsequently were input to the model.

Evaporation is the only outflow from the lake. This process is probably the least understood of the components which make up the water balance for the lake. Steed estimated the monthly rate of evaporation from the lake by a Thiessen weighted average of the pan evaporation at Midlake, Saltair, and the Bear River Refuge. Two adjustments are made to the pan evaporation data in order to obtain an estimate of the lake evaporation. The first adjustment involves differences in characteristics between the pan and the lake. Steed used a pan coefficient of 0.61 for spring months and 0.66 for the fall months. The second adjustment is necessary because of the suppressing effects of water salinity on evaporation from the lake. An equation describing the effect of salinity on evaporation was developed by Waddell and Bolke (1973). The factor for correcting the evaporation rate is given as:

$$K_E = 1. - 0.778 \times 10^{-3}\, C/\rho \qquad (6.6)$$

in which

K_E = salinity correction factor for evaporation

C = total dissolved solids concentration (g/l)

ρ = density of brine (g/ml)

An empirical relationship between density and concentration of total dissolved solids is given by Waddell and Bolke (1973) as:

$$\rho = 1.00 + C\,(6.3 \times 10^{-4}) \qquad (6.7)$$

On the basis of the above discussion, the general equation for lake evaporation used in the model of this study is as follows:

$$E_{out} = K_E\,E\,A_s\,\Delta t \qquad (6.8)$$

in which

E_{out} = volume of evaporation from an arm during time Δt

E = adjusted (by pan coefficient) monthly evaporation rate

A_s = surface area of arm

Δt = time increment

The monthly potential evaporation rate reported by Steed was developed for the entire lake. This rate was adjusted for application to each arm by a weighting of the evaporation stations which indicated the rate determined by Steed was appropriate for the south arm but should be increased by a factor of 1.2 for the north arm. The surface area involved in calculating the evaporation included the major areas of the lake which have been diked by salt companies for evaporation ponds but did not include the near shore evaporation ponds. Such areas were excluded because the withdrawals are small and much of the brine withdrawn is returned to the lake.

Equations which describe the exchange of brine through the Southern Pacific Transporation Company causeway were developed by Waddell and Bolke (1973). The equations were developed largely from data collected during the 1971-1972 water years and represent empirical relations which predict flow through both culverts and the fill. The culvert flows are given by:

$$Q1C = B \cdot y1 \left[\sqrt{ \left[Y1 - y1 - y2 - CFS \frac{(V2C)^2}{2g}\right] \frac{2g}{(1 + CFS)} + \left(\frac{CFS\,(V2C)^2}{1 + CFS}\right) - \frac{CFS\,(V2C)}{(1 + CFS)} } \right] \quad ..(6.9)$$

and

$$Q2C = B \cdot y2 \left[\sqrt{ \left[Y2 - y2 - y1 \cdot \frac{S1}{S2} - CFS' \frac{(V1C)^2}{2g}\right] \cdot \frac{2g}{(1 + CFS')} } + \left(\frac{CFS'\,(V1C)^2}{1 + CFS'}\right] \cdot \frac{CFS'(V1C)}{(1 + CFS')} \right] \quad .....(6.10)$$

in which

Q1C = south-to-north discharge through culverts (cfs)

Q2C = north-to-south discharge through culverts (cfs)

B = width of culvert (15 feet)

y1 = $-6.30Y2 - 5.84\ (S2-S1) \cdot Y1 + 7.09Y1$

y2 = $6.39Y2 + 5.94\ (S2-S1) \cdot Y1 - 6.23Y1$

ES = altitude of water surface in south part (feet)

EC = altitude of bottom of east or west culvert (feet)

Y1 = ES - EC

Y2 = $Y1 - \Delta H$

CFS = $\{3.55\ [Y1 - (y1 + y2)]/Y1 - Y2)_0 - 1.02$

CFS′ = $\{3.83\ [Y1 - (y1 + y2)]/(Y1 - Y2)\} - 1.19$

V1C = mean velocity of south-to-north flow through culverts (feet/second)

V2C = mean velocity of north-to-south flow through culverts (feet/second)

S1 = specific gravity of brine in south part

S2 = specific gravity of brine in north part

ΔH = difference between altitude (stage) of south and north parts of lake at causeway (feet)

Figure 6.2 illustrates the physical meaning of the various terms involved in the culvert flow equations. Values of Q1C and Q2C are obtained by the simultaneous solution of Equations 6.9 and 6.10.

The equations for flows through the causeway fill are given by Waddell and Bolke (1973) as:

$$Q1F = [6.9835 - 1675.0\ \Delta S + 158.97\ \Delta H + 45535.\ \Delta S^2 - 3773.3\ \Delta S\,\Delta H + 14.010\ \Delta H^2 - 429070.\ \Delta S^3 + 34904.\ \Delta S^2\ \Delta H - 631.20\ \Delta S\ \Delta H^2 + 48.556\ \Delta H^3 + 1302000.\ \Delta S^4 - 105270\ \Delta S^3\ \Delta H - 176.07\ \Delta S\ \Delta H^3 - 5.4593\ \Delta H^4 + 3352.1\ \Delta S^2\ \Delta H^2]\ 69.3963 \quad ....(6.11)$$

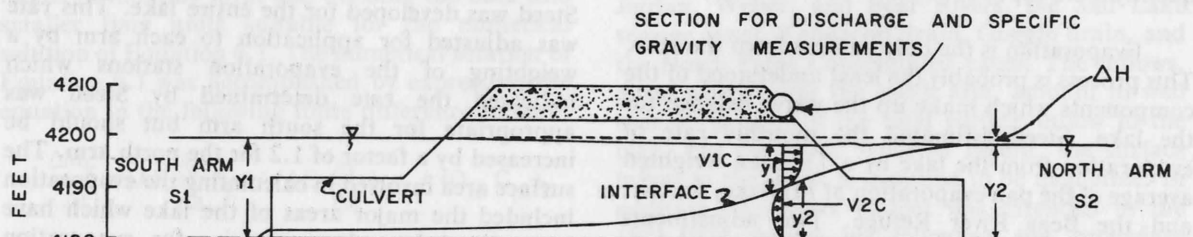

Figure 6.2. Culvert cross section with a representation of the terms involved in the culvert flow equations (modified from Waddell and Bolke, 1973).

and

$$Q2F = [2.1629 + 1290.3\ \Delta S - 113.24\ \Delta H - 19649.\ \Delta S^2 - 912.81\ \Delta S\ \Delta H + 186.17\ \Delta H^2 + 195100.\ \Delta S^3 + 20974.\ \Delta S^2\ \Delta H - 1861.6\ \Delta S\ \Delta H^2 - 18.802\ \Delta H^3 - 629690.\ \Delta S^4 - 66502.\ \Delta S^3\ \Delta H + 308.06\ \Delta S\ \Delta H^3 - 15.187\ \Delta H^4 + 2865.3\ \Delta S^2\ \Delta H^2] \cdot [1. - (4199.5 - ES)/y2F) \cdot 1.312]\ 69.3936 \quad \ldots\ldots(6.12)$$

in which

Q1F = south-to-north discharge through fill (cfs)

Q2F = north-to-south discharge through fill (cfs)

$y2F = 19.307 + 242.23\ \Delta S - 35.429\ \Delta H - 4339.9\ \Delta S^2 + 407.50\ \Delta S\ \Delta H + 14.332\ \Delta H^2 + 19021.\ \Delta S^3 - 1466.8\ \Delta S^2\ \Delta H - 45.647\ \Delta S\ \Delta H^2 - 3.8069\ \Delta H^3$

ΔS = S2-S1

During early operation of the water and salinity balance model an initial volume error was being produced in both arms of the lake at the beginning of each simulation period which was propagated through the entire simulation period (Figure 6.3). The error was traced to the simulated causeway flows and was observed to increase with increasing head difference across the causeway. The volume error was removed by adjusting the head difference across the causeway as follows:

$$\Delta H' = \Delta H - .35\ (\Delta H)^{1.5} \quad \ldots\ldots(6.13)$$

in which

ΔH = head difference across the causeway

$\Delta H'$ = adjusted head difference across the causeway

$\Delta H'$ was used in place of ΔH for calculating the causeway flows in the water and salinity balance model. As shown in Figure 6.3, the inclusion of Equation 6.13 in the model had little effect on the calculation of lake volume or the causeway flows after the first month.

The simulation results for 1974 conditions (Figure 6.3) indicate that during periods of large head differences across the causeway the model has

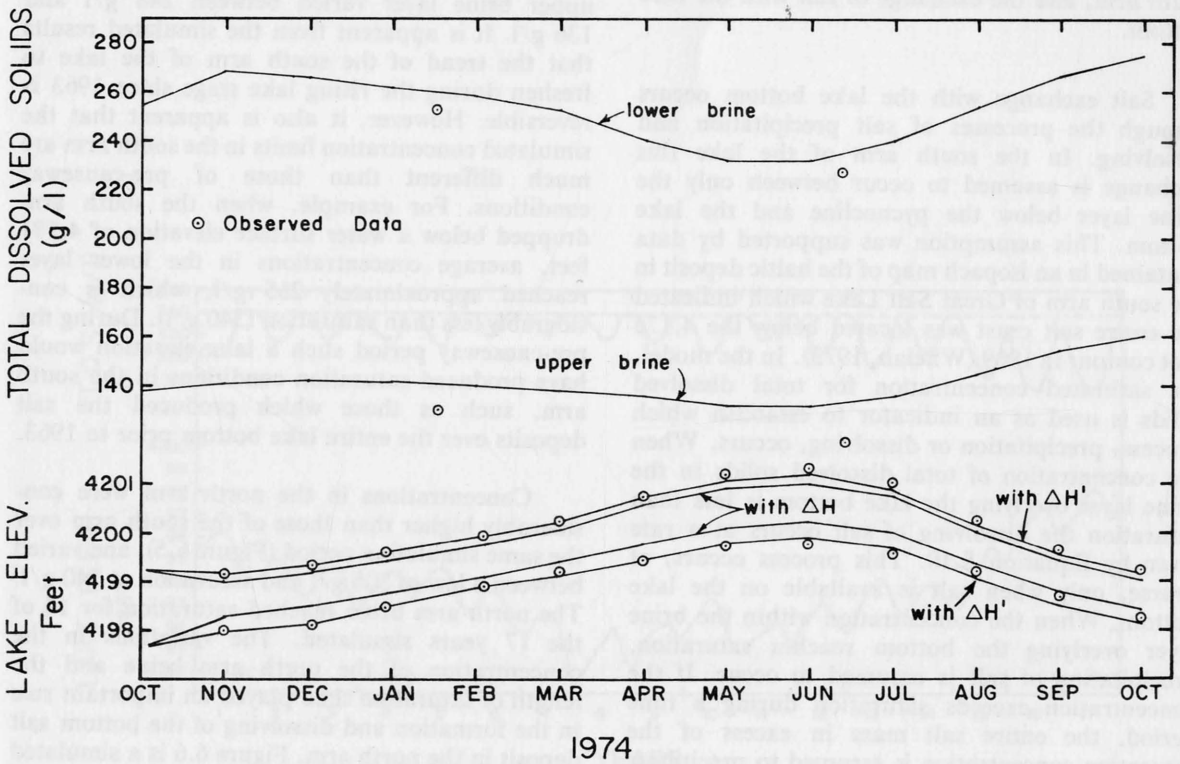

Figure 6.3. Simulations of the 1974 water year showing the improved results obtained by adjusting the head difference across the causeway.

a tendency to calculate higher than observed concentration in the south arm upper brine. This tendency is present only when the head difference across the causeway is greater than the maximum observed head difference during the period in which the data were gathered for the development of the causeway flow equations. As is evident from Figure 5.5 this problem did not occur for low head differences across the causeway.

Salinity Balance

The total salt load in Great Salt Lake consists of the dissolved load in the brine and the precipitated salt on the lake bed. The total salt load for the lake is estimated to be approximately 4.2 million metric tons using the UGMS data on total dissolved solids and the precipitated salt load on the lake bottom as estimated by Hedberg (1970). The annual inflow of total dissolved solids (Hahl and Handy, 1969) and the annual extraction of salt by the salt industries (Madison, 1970) is small compared to the total load in the lake. For this reason, the inflow of total dissolved solids to the lake was assumed to be negligible during the study period and was excluded from the salinity balance. The salt balance for Great Salt Lake thus is a function of the exchange of brine through the causeway, the vertical diffusion of salt within the south arm, and the exchange of salt with the lake bottom.

Salt exchange with the lake bottom occurs through the processes of salt precipitation and dissolving. In the south arm of the lake this exchange is assumed to occur between only the brine layer below the pycnocline and the lake bottom. This assumption was supported by data contained in an isopach map of the haltic deposit in the south arm of Great Salt Lake which indicated the entire salt crust was located below the 4,175 foot contour in 1969 (Whelan, 1973). In the model, the saturated concentration for total dissolved solids is used as an indicator to establish which process, precipitation or dissolving, occurs. When the concentration of total dissolved solids in the brine layer overlying the lake bottom is less than saturation the dissolving of salt occurs at a rate given by Equation 5.10. This process occurs, of course, only when salt is available on the lake bottom. When the concentration within the brine layer overlying the bottom reaches saturation, precipitation of salt is assumed to occur. If the concentration exceeds saturation during a time period, the entire salt mass in excess of the saturation concentration is assumed to precipitate during that time period.

Concentration Trends in Great Salt Lake

The water and salinity balance model was applied to simulate the response of Great Salt Lake over a falling and rising lake stage in order to gain insight into possible future salinity trends of the lake. The important questions which were addressed by the model are as follows:

1. Is the present tendency of the lake to freshen reversible?

2. Will a relationship between stage and concentration be established for the upper brine layer in the south arm?

Beginning with the lake conditions which existed in October, 1972, a decreasing lake stage was simulated by using hydrologic data for the 1954 to 1960 water years. The lake conditions at the end of this seven year simulation period then were used to simulate a ten year period of increasing lake stage using hydrologic data from the 1964 to 1973 water years. The simulated response of the lake under these hydrologic conditions is given in Figure 6.4 for the south arm and Figure 6.5 for the north arm. During the 17 year study period the water surface elevation of the south arm varied between 4,190 and 4,199.75 feet, while the total dissolved solids concentration of the upper brine layer varied between 248 g/l and 136 g/l. It is apparent from the simulated results that the trend of the south arm of the lake to freshen during the rising lake stage since 1963 is reversible. However, it also is apparent that the simulated concentration limits in the south arm are much different than those of pre-causeway conditions. For example, when the south arm dropped below a water surface elevation of 4,191 feet, average concentrations in the lower layer reached approximately 265 g/l, which is considerably less than saturation (340 g/l). During the pre-causeway period such a lake elevation would have produced saturation conditions in the south arm, such as those which produced the salt deposits over the entire lake bottom prior to 1963.

Concentrations in the north arm were considerably higher than those of the south arm over the same simulation period (Figure 6.5), and varied between a low of 305 g/l and saturation at 340 g/l. The north arm brine reached saturation for 14 of the 17 years simulated. The variations in the concentration of the north arm brine and the length of saturation time played an important role in the formation and dissolving of the bottom salt deposit in the north arm. Figure 6.6 is a simulated time plot which shows the variation of the mass of

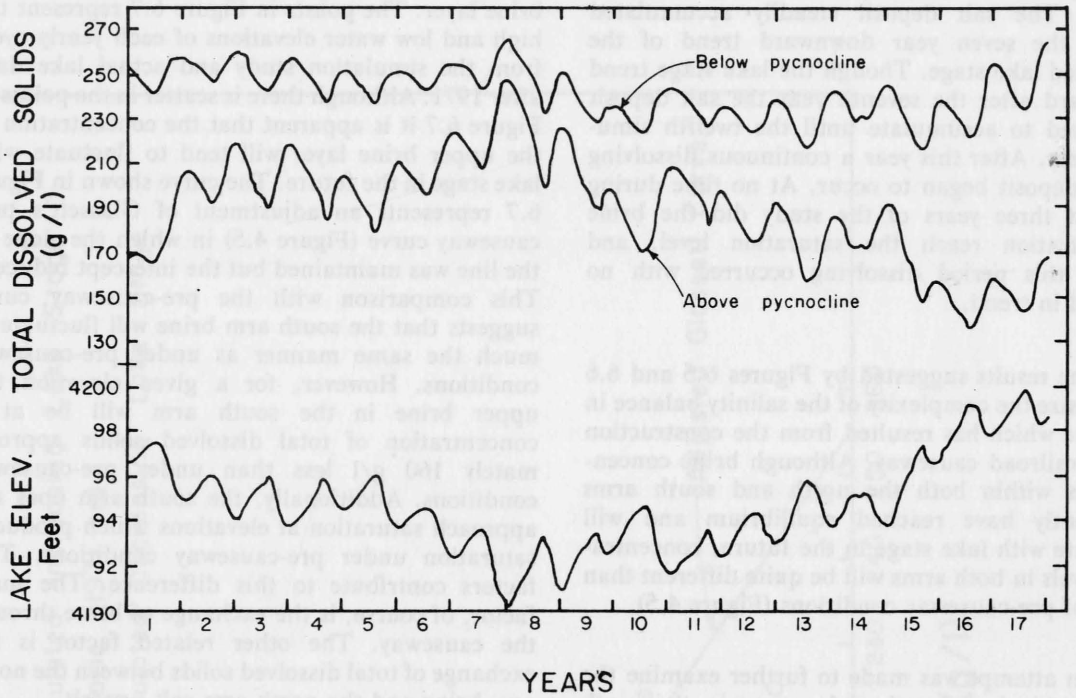

Figure 6.4. Simulated fluctuation of the south arm surface elevation and total dissolved solids concentration of the brine above and below the pycnocline.

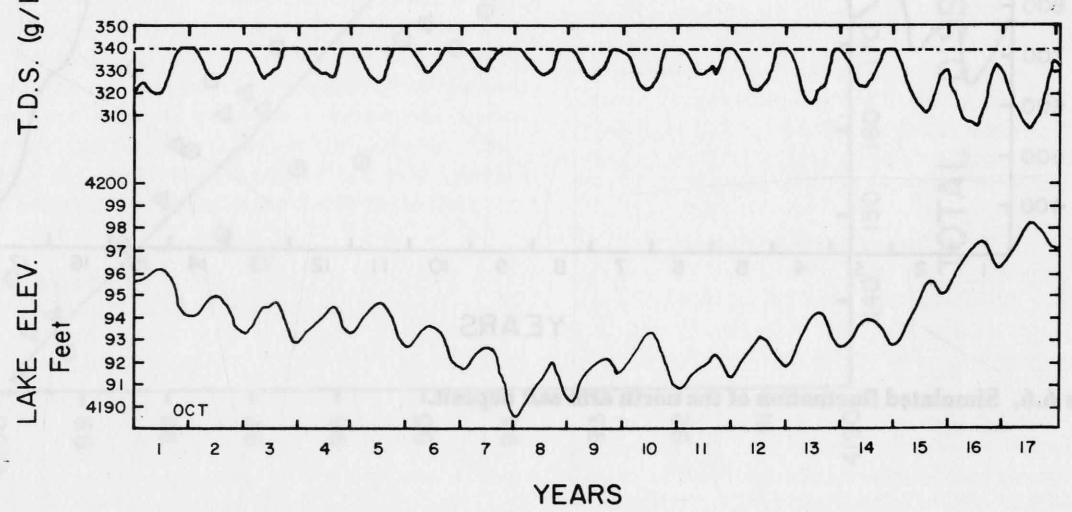

Figure 6.5. Simulated fluctuations of the north arm surface elevation and total dissolved solids concentration of the brine.

salt deposit in the north arm during the study period. The salt deposit steadily accumulated during the seven year downward trend of the simulated lake stage. Though the lake stage trend is upward after the seventh year the salt deposit continued to accumulate until the twelfth simulated year. After this year a continuous dissolving of the deposit began to occur. At no time during the last three years of the study did the brine concentration reach the saturation level, and during this period dissolving occurred with no reversal in trend.

The results suggested by Figures 6.5 and 6.6 emphasize the complexity of the salinity balance in the lake which has resulted from the construction of the railroad causeway. Although brine concentrations within both the north and south arms apparently have reached equilibrium and will fluctuate with lake stage in the future, concentration levels in both arms will be quite different than those of pre-causeway conditions (Figure 4.5).

An attempt was made to further examine the relationship between the lake stage in the south arm and the average concentration of the upper brine layer. The points in Figure 6.7 represent the high and low water elevations of each yearly cycle from the simulation study and actual lake data after 1971. Although there is scatter in the points of Figure 6.7 it is apparent that the concentration of the upper brine layer will tend to fluctuate with lake stage in the future. The curve shown in Figure 6.7 represents an adjustment of Glassett's pre-causeway curve (Figure 4.5) in which the slope of the line was maintained but the intercept reduced. This comparison with the pre-causeway curve suggests that the south arm brine will fluctuate in much the same manner as under pre-causeway conditions. However, for a given elevation the upper brine in the south arm will be at a concentration of total dissolved solids approximately 160 g/l less than under pre-causeway conditions. Additionally, the south arm does not approach saturation at elevations which produced saturation under pre-causeway conditions. Two factors contribute to this difference. The main factor, of course, is the exchange of brine through the causeway. The other related factor is the exchange of total dissolved solids between the north arm brine and the north arm salt deposit.

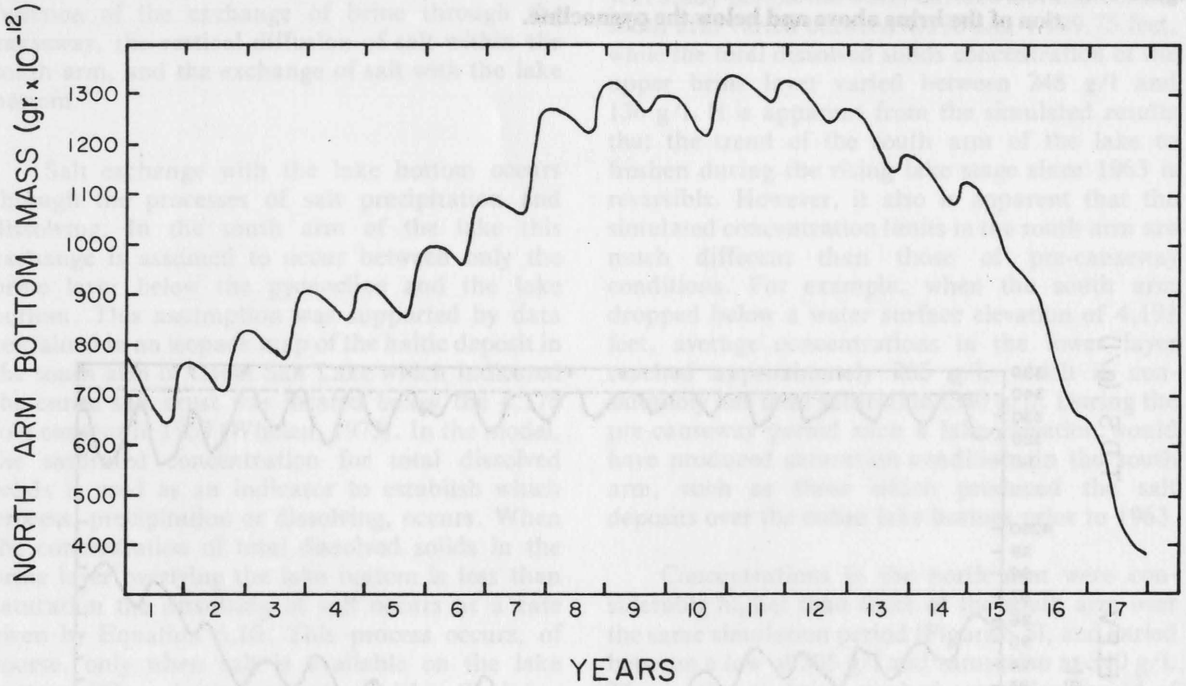

Figure 6.6. Simulated fluctuation of the north arm salt deposit.

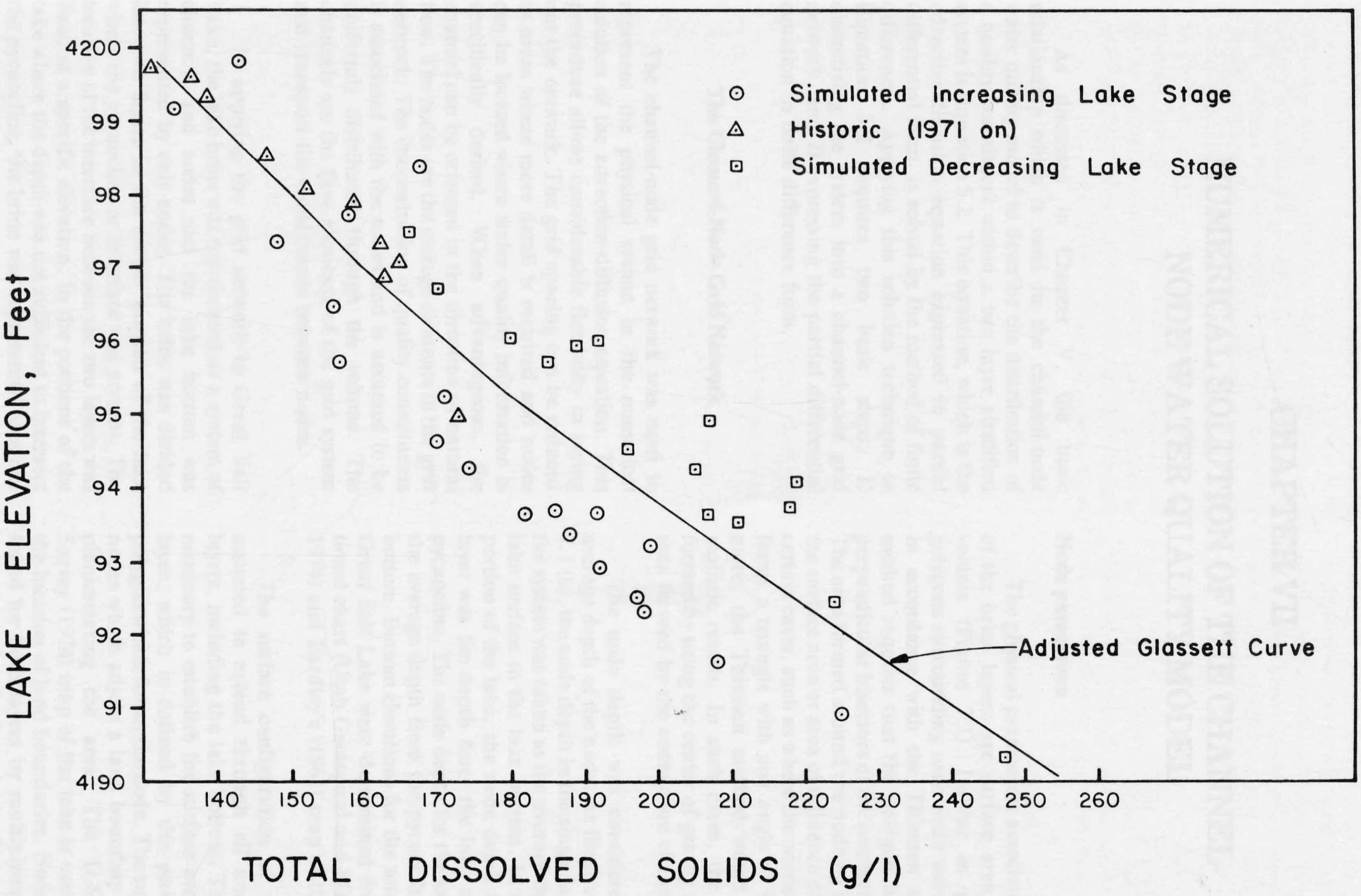

Figure 6.7. Variation of the south arm upper brine total dissolved solids concentration with lake elevation.

salt deposit in the north arm during the study period. The salt deposit steadily accumulated during the seven year downward trend of the simulated lake stage. Though the lake stage trend is upward after the seventh year the salt deposit continued to accumulate until the twelfth simulated year. After this year a continuous dissolving of the deposit began to occur. At no time during the last three years of the study did the brine concentration reach the saturation level, and during this period dissolving occurred with no reversal in trend.

The results suggested by Figures 6.5 and 6.6 emphasize the complexity of the salinity balance in the lake which has resulted from the construction of the railroad causeway. Although brine concentrations within both the north and south arms apparently have reached equilibrium and will fluctuate with lake stage in the future, concentration levels in both arms will be quite different than those of pre-causeway conditions (Figure 4.5).

An attempt was made to further examine the relationship between the lake stage in the south arm and the average concentration of the upper brine layer. The points in Figure 6.7 represent the high and low water elevations of each yearly cycle from the simulation study and actual lake data since 1971. Although there is scatter in the points of Figure 6.7 it is apparent that the concentration of the upper brine layer will tend to fluctuate with lake stage in the future. The curve shown in Figure 6.7 represents an adjustment of Glassett's pre-causeway curve (Figure 4.5) in which the slope of the line was maintained but the intercept reduced. This comparison with the pre-causeway curve suggests that the south arm brine will fluctuate in much the same manner as under pre-causeway conditions. However, for a given elevation the upper brine in the south arm will be at a concentration of total dissolved solids approximately 100 g/l less than under pre-causeway conditions. Additionally, the south arm does not approach saturation at elevations which produced saturation under pre-causeway conditions. Two factors contribute to this difference. The main factor, of course, is the exchange of brine through the causeway. The other related factor is the exchange of total dissolved solids between the north arm brine and the north arm salt deposit.

Figure 6.6. Simulated fluctuation of the north arm salt deposit.

CHAPTER VII

NUMERICAL SOLUTION OF THE CHANNEL-NODE WATER QUALITY MODEL

As discussed in Chapter V, the basic relationship which is used in the channel-node water quality model to describe the distribution of a quality constituent within a two layer stratified system is Equation 5.2. This equation, which is the advective-diffusion equation expressed in partial differential form, is solved by the method of finite differences. Applying this solution technique to Equation 5.2 requires two basic steps: 1) discretizing the system into a channel-node grid network, and 2) expressing the partial differential equation in finite difference form.

The Channel-Node Grid Network

The channel-node grid network was used to represent the physical system in the numerical solution of the advection-diffusion equation. This procedure allows considerable flexibility in laying out the network. The grid spacing can be reduced in areas where more detail is required and nodes can be located where water quality information is specifically desired. When advantageous, the channel can be oriented in the direction of natural flow. The nodes are the storage elements in the grid network. The concentration of quality constituents is associated with the nodes and is assumed to be uniformly distributed through the volume. The channels are the flow elements of the grid system and transport the constituents between nodes.

In applying the grid network to Great Salt Lake, the lake brine was represented as a system of channels and nodes and the lake bottom was represented by only nodes. The brine was divided into two layers in the deeper portion of the lake where the pycnocline or interface was present. The location of the interface between the two layers was fixed at a specific elevation. In the portions of the lake where the depth was not sufficient to intersect the pycnocline, the brine was represented as a one layer system.

Node parameters

The physical parameters associated with nodes of the brine layers are surface area, depth, and volume (Figure 7.1). Insofar as possible, the polygons surrounding each node were constructed in accordance with the Thiessen method. This method requires that the polygon boundaries be perpendicular bisectors of the connection channels. The area formed around the node by the polygon is the surface area or area of influence of the node. In certain cases, such as where the connection channel forms a triangle with one angle of 90 degrees or more, the Thiessen method would not provide realistic results. In such cases, the polygon was formed by using the center of gravity of the surface area formed by the connection channel.

The node depth was considered to be the average depth of the node. As illustrated in Figure 7.1 (b), the node depth in the single layer portion of the system was taken as the average depth from the lake surface to the lake bottom. In the two layer portion of the lake, the node depth for the upper layer was the depth from the lake surface to the pycnocline. The node depth for the lower layer was the average depth from the pycnocline to the lake bottom. Bottom elevations for the south arm of the Great Salt Lake were determined from a navigational chart (Utah Geological and Mineral Survey, 1974) and Eardley's (1961) map of the lake.

The surface configuration of the nodes is assumed to extend through all underlying grid layers, including the lake bottom. Thus, it is only necessary to establish the surface area for the top layer, which is defined by the geometry of the polygon which forms the node. The surface areas of nodes which adjoin a land boundary are found by planimetering the area. The U.S. Geological Survey (1974) map of the lake is used to establish the location of land boundaries. Node volumes are found for both layers by multiplying the average node depth for the layer by surface area. The only node parameter associated with the lake bottom is area.

Channel parameters

Channels are concerned with the movement of the lake brine, and thus do not involve the bottom layer. The physical parameters associated with channels are length, width, depth, and cross-sectional area (Figure 7.2). The length of horizontal channels is simply the distance between two adjacent nodes which are connected by a channel. The horizontal channel width is given by the length of the perpendicular bisector of the channel used in establishing the boundary of the node. When the center of gravity method is used to establish a node boundary, the boundary is not perpendicular to the channel. In these cases, the horizontal channel width is considered to be that component of this line which is perpendicular to the channel. The channel depth is defined as the arithmetic average of the depths of the two nodes it connects. The cross-sectional area of a channel was then found by multiplying the channel depth by the channel width.

Vertical channels exist only when there are two brine layers, and represent the flow path for vertical movement between the two layers. The physical parameters associated with vertical channels are channel length and cross-sectional area. The cross-sectional area of a vertical channel is identical to the surface area of the vertical nodes it connects. The vertical channel length, Δz in Equation 7.2, is the distance between vertical nodes and is calculated as:

$$\Delta z = \tfrac{1}{2}\,(\text{depth of layer 1}) + \tfrac{1}{2}\,(\text{average depth of layer 2}) \qquad (7.1)$$

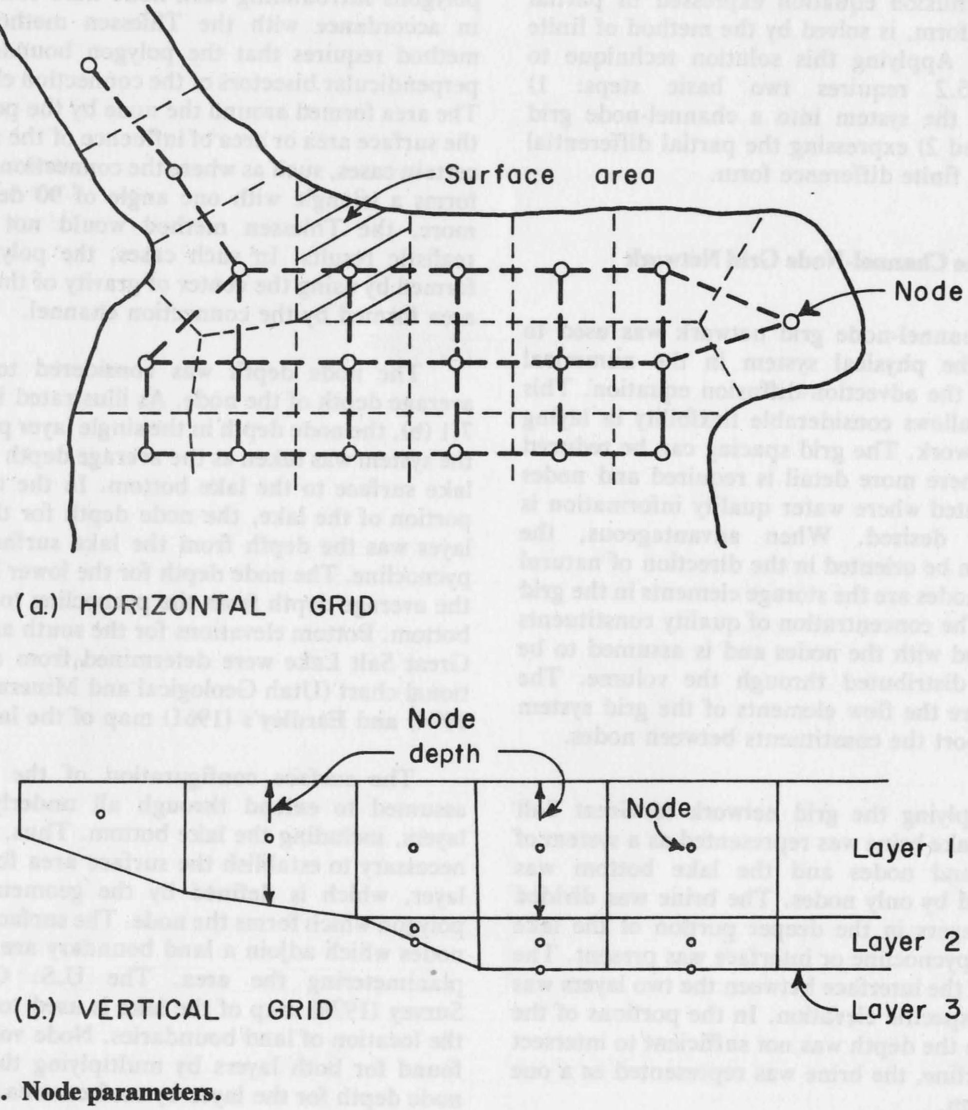

Figure 7.1. Node parameters.

The Finite Difference Equation

The finite difference form of Equation 5.2 applicable to the lake brine layers is

$$\frac{\Delta M_{jk}}{\Delta t} = - \sum_{i=1}^{n} (QC)_{ik} + \sum_{i=1}^{n} (AE \frac{\Delta C}{\Delta l})_{ik} + (AE \frac{\Delta C}{\Delta z})_v + \Sigma S_{jk} \quad \text{. . . . . (7.2)}$$

in which

M_{jk} = mass of quality constituent in node j of brine layer k

The finite difference form of Equation 5.3 applicable to the lake bottom is:

$$\frac{\Delta M_{jb}}{\Delta t} = \Sigma S_{I_{jb}} \quad \text{. . . . . (7.3)}$$

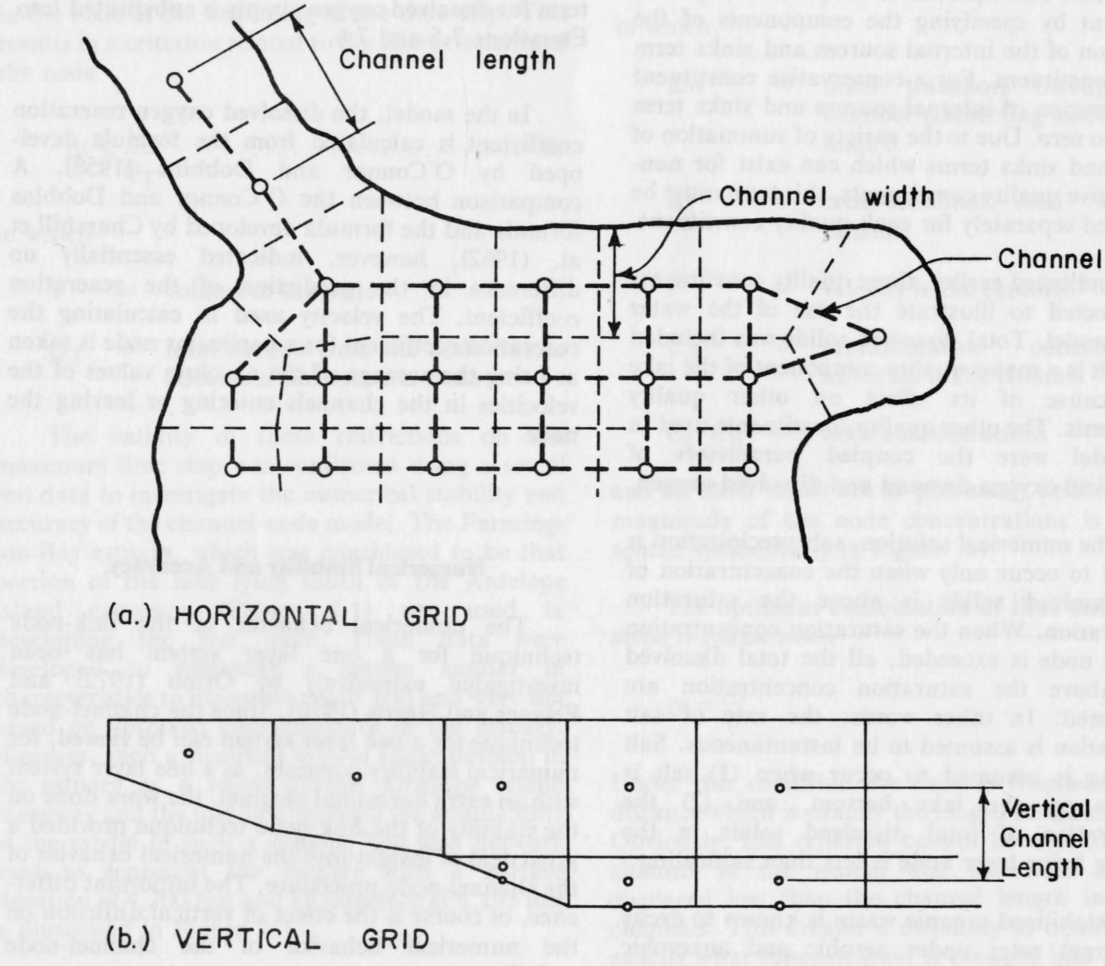

Figure 7.2. Channel parameters.

For a brine layer, the change of mass within a node over a time step is then given by:

$$\Delta M_{jk} = \sum_{i=1}^{n} (QC)_{ik} \Delta t + \sum_{i=1}^{n} (AE \frac{\Delta C}{\Delta 1})_{ik} \Delta t + (AE \frac{\Delta C}{\Delta z})_v \Delta t + \Sigma S \quad \text{. . . . . (7.4)}$$

Similarly, the change of mass for the lake bottom is expressed as:

$$\Delta M_{jb} = \Sigma S_{I_{jb}} \Delta t \quad \text{. . . . . (7.5)}$$

When the summation of external sources and sinks term is included Equation 7.4 becomes

$$\Delta M_{jk} = - \sum_{i=1}^{n} (QC)_{ik} \Delta t + \sum_{i=1}^{n} (AE\frac{\Delta C}{\Delta l})_{ik} \Delta t$$

$$+ (AE\frac{\Delta C}{\Delta z})_v \Delta t + (Q_{in_{jk}} C_{in_{jk}} - Q_{out_{jk}} C_{jk}) \Delta t$$

$$+ \Sigma S_{i_{jk}} \Delta t \quad \ldots\ldots\ldots\ldots\ldots (7.6)$$

The channel node model was designed to investigate the long term (seasonal) trends within the lake on a specific lake surface elevation. Under this assumption, the circulation patterns and velocities, lake inflows, and lake outflows are averaged over the season of interest, and thus remain constant. For a particular season, Equation 7.6 is used with constant coefficients in predicting the distribution of quality constituents by the computer model. The equation is solved in the computer program by using an explicit step forward solution technique.

Equation 7.6 is general in nature and is applicable to both brine layers and to all quality constituents. The equation is adapted to a specific constituent by specifying the components of the summation of the internal sources and sinks term for the constituent. For a conservative constituent the summation of internal sources and sinks term reduces to zero. Due to the variety of summation of sources and sinks terms which can exist for non-conservative quality constituents, this term must be considered separately for each quality constituent.

As indicated earlier, three quality constituents were selected to illustrate the use of the water quality model. Total dissolved solids was included because it is a major quality component of the lake and because of its effect on other quality constituents. The other quality constituents used in the model were the coupled parameters of biochemical oxygen demand and dissolved oxygen.

In the numerical solution, salt precipitation is assumed to occur only when the concentration of total dissolved solids is above the saturation concentration. When the saturation concentration within a node is exceeded, all the total dissolved solids above the saturation concentration are precipitated. In other words, the rate of salt precipitation is assumed to be instantaneous. Salt dissolving is assumed to occur when (1) salt is available on the lake bottom, and (2) the concentration of total dissolved solids in the overlying brine layer node is less than saturation.

Unstabilized organic waste is known to decay at different rates under aerobic and anaerobic conditions. Because of the naturally low concentration of dissolved oxygen in Great Salt Lake, there is the possibility that anaerobic conditions will occur in sections of the lake under various inflow rates of organic wastes. In order to account for this possibility, both the aerobic and anaerobic decay rates are included in the model. When the supply of dissolved oxygen is sufficient to maintain aerobic conditions over a complete time step, the decay rate takes on the value of the aerobic decay rate. In the complete absence of dissolved oxygen, anaerobic conditions exist and the anaerobic decay rate is used. In nodes in which the available dissolved oxygen is not sufficient to maintain aerobic conditions during the entire time step, the decay rate is determined from a straight line interpolation between the aerobic and anaerobic decay rates based on the available dissolved oxygen. This approach eliminates the problem of negative dissolved oxygen concentrations which occur if only the aerobic decay rate were used.

The numerical solution of the summation of sources and sinks term for dissolved oxygen requires no special considerations. The equation representing the summation of sources and sinks term for dissolved oxygen simply is substituted into Equations 7.5 and 7.6.

In the model, the dissolved oxygen reaeration coefficient is calculated from the formula developed by O'Connor and Dobbins (1958). A comparison between the O'Connor and Dobbins formula and the formula developed by Churchill et al. (1962), however, indicated essentially no difference in the prediction of the reaeration coefficient. The velocity used in calculating the reaeration coefficient for a particular node is taken as being the average of the absolute values of the velocities in the channels entering or leaving the node.

Numerical Stability and Accuracy

The numerical behavior of the link-node technique for a one layer system has been investigated extensively by Orlob (1972) and Feigner and Harris (1970). Since the channel-node technique for a two layer system can be viewed, for numerical stability purposes, as a one layer system with an extra horizontal channel, the work done on the stability of the link-node technique provided a great deal of insight into the numerical behavior of the channel-node procedure. The important difference, of course is the effect of vertical diffusion on the numerical behavior of the channel-node technique.

Orlob (1972) reported a criterion for stability of the link-node technique as

$$\Delta t \leqslant \frac{l_i}{v} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.7)$$

in which

Δt = time step

l_i = channel length

v = channel velocity

In the numerical solution, the transfer of quality constituents through a channel occurs only between the two nodes it connects. If the time step exceeds the above condition (Equation 7.7) the actual fluid displacement along the channel is greater than the actual channel length and an unstable condition may result. An additional restriction is placed on the maximum time step in the study. The mass outflow from a node during a time step is not allowed to exceed the mass present in the node at the beginning of the time step. This results in a criterion related to the characteristics of the node

$$\Delta t \leqslant \frac{V}{Q_T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.8)$$

in which

V = volume of the node

Q_T = total outflow from the node due to advection and external sinks

The validity of these restrictions on the maximum time step was confirmed using a set of test data to investigate the numerical stability and accuracy of the channel-node model. The Farmington Bay estuary, which was considered to be that portion of the lake lying south of the Antelope Island causeway (Figure 4.1) was used in developing the test data. These data were developed to represent a system similar in characteristics to the entire south arm and were not based on observed characteristics of the estuary. However, such a stratified system could develop in the estuary as a result of the Antelope Island causeway and the test data indicate the adaptability of the model to such a system. The grid network used to represent the estuary with a surface elevation of 4,200 feet and an interface at 4,195 feet is illustrated in Figure 7.3.

The maximum time step predicted by Equation 7.8 was found to be the limiting time step for the test data. The maximum time step based on the channel flows (Equation 7.7) was found to be approximately three times larger than the maximum allowable time step based on the node volumes (Equation 7.8). When the smaller time step was exceeded numerical instability was produced. This result was not unexpected since both Equations 7.7 and 7.8 produce necessary but not sufficient conditions for numerical stability. It is noted that in some systems the diffusion coefficient is an important stability criterion in determining the maximum time step. However, for the Great Salt Lake system this is not the case because of the low contribution the diffusive process makes to the total transport process.

Figure 7.4 illustrates a typical channel from the channel-node network in which the transport through the channel is given in finite difference form as

$$\Delta M = (AvC_{ik} - EA \frac{C_b - C_a}{\Delta l})\, \Delta t \quad \ldots\ldots\ldots (7.9)$$

in which

ΔM = mass transport through the channel connecting node a and node b

A = cross-sectional area of the channel

v = velocity in the channel

C_{ik} = representative concentration advected in the channel

C_a, C_b = node concentrations

and all other terms are as previously defined. The magnitude of the node concentrations is represented symbolically in Figure 7.4

The optimum combination of time and space steps is found when

$$\Delta t = \frac{\Delta l}{v} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.10)$$

Under this condition the fluid is displaced by a distance which is exactly the length of the channel. Obviously, this criterion cannot be met for each channel in the system and the fluid will be displaced less than the channel length in many channels. This creates a difficulty in determining exactly what concentration is brought into a node during a time step. The simplest assumption is to require the concentration carried in the channel to be the concentration of the node of origin or upstream node. However, Orlob (1972) and Feigner and Harris (1970) found that when the concentration of the upstream node was used the accuracy of the solution was significantly affected by what Orlob termed "numerical mixing." Numerical mixing is simply the numerical propagation of quality perturbations created by not accurately representing the concentration of the quality constituent carried in the channel and was given this name because it exhibited the same numerical characteristics as diffusive transport. The numerical mixing problem was reduced, and thus the solution accuracy increased, in both of the above studies by defining the incoming channel concentration, C_{ik}, as a weighted value of the concentrations in the two nodes of each end of the channel.

Various procedures can be used to compute C_{ik} as a function of the concentrations in the upstream, C_a, and downstream, C_b, nodes. Table 7.1 compares the numerical characteristics of four possible procedures for estimating C_{ik}. Orlob (1972) and Feigner and Harris (1970) found that the quarter point method provided the best combination of numerical stability and accuracy. For the channel shown in Figure 7.4 the quarter point method yields

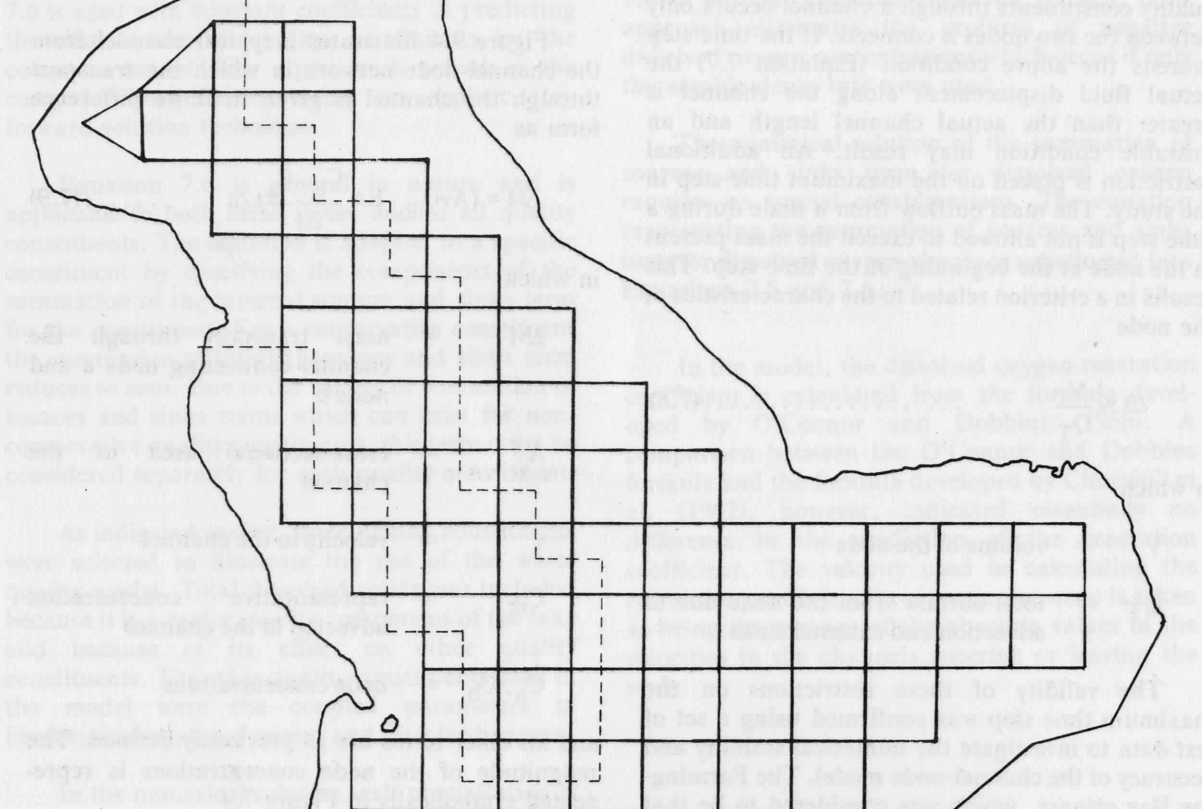

Figure 7.3. Schematic representation of the Farmington Bay Estuary at a surface elevation of 4,200 feet.

$$C_{ik} = \frac{3C_a + C_b}{4} \quad \ldots\ldots\ldots\ldots (7.11)$$

The quarter point method was found to restrict the time step when the downstream concentration was larger than the upstream concentration. This problem was overcome by employing the technique suggested by Feigner and Harris (1970) for the proportional method, namely the upstream advection procedure in which $C_{ik} = C_a$ (Table 7.1). The model allows this method to be selected when the upstream concentration is larger.

The network representing the Farmington Bay estuary was used to test the basic components of the program. The results of a test run used to evaluate the numerical accuracy of the program are presented in Figure 7.5. A concentration of 300 g/l of a conservative constituent was input to the model and assumed to flow through the system at a rate of 2,640 cfs along the path shown by the figure. After a simulation period of 400 hours the concentration within the nodes throughout the flow path approached the concentration of the inflow. These results indicated that the model was performing properly and maintaining numerical accuracy.

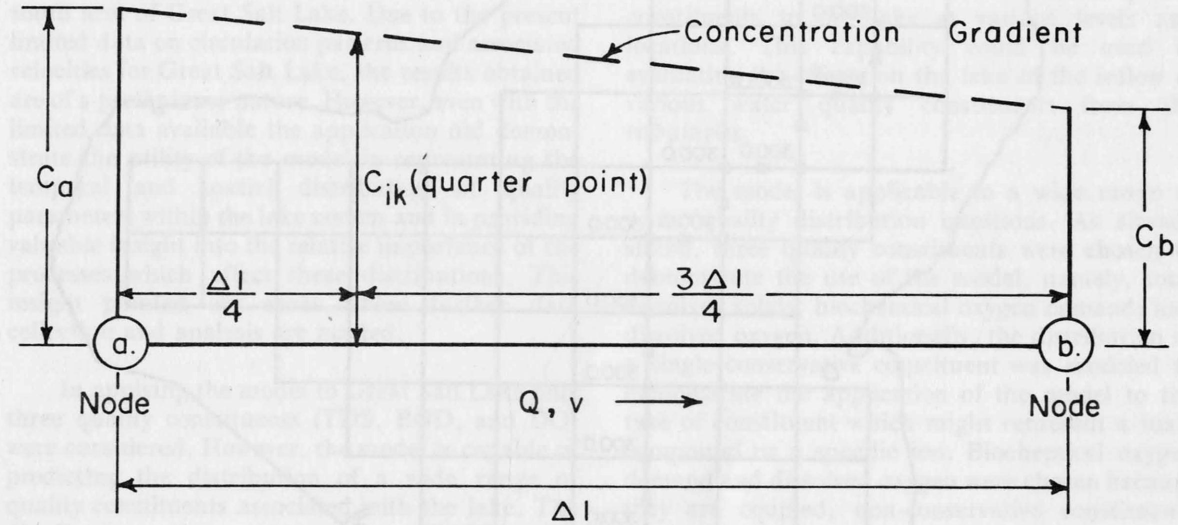

Figure 7.4. Channel elements used in defining C_{ik}.

Table 7.1. Comparison of advection methods (after Reigner and Harris, 1970).

Method	Definition of C	Numerical Mixing	Accuracy	Stability
UPSTREAM	$C_{ik} = C_a$	High	Poor	Excellent
SIMPLE AVERAGE	$C_{ik} = \frac{C_a + C_b}{2}$	Low	Good	Very Poor
QUARTER POINT	$C_{ik} = \frac{3C_a + C_b}{4}$	Moderate	Good	Acceptable
PROPORTIONAL (one-way)	$C_{ik} = \frac{C_a + C_b}{2} + \phi \frac{(C_a - C_b)}{2}$, if $C_a \geqslant C_b$	Moderate	Moderate	Good
	$C_{ik} = C_a$, if $C_a < C_b$			

Note:

$\phi = \frac{v \Delta t}{\Delta l}$

C_a, C_b are as indicated in Figure 7.4.

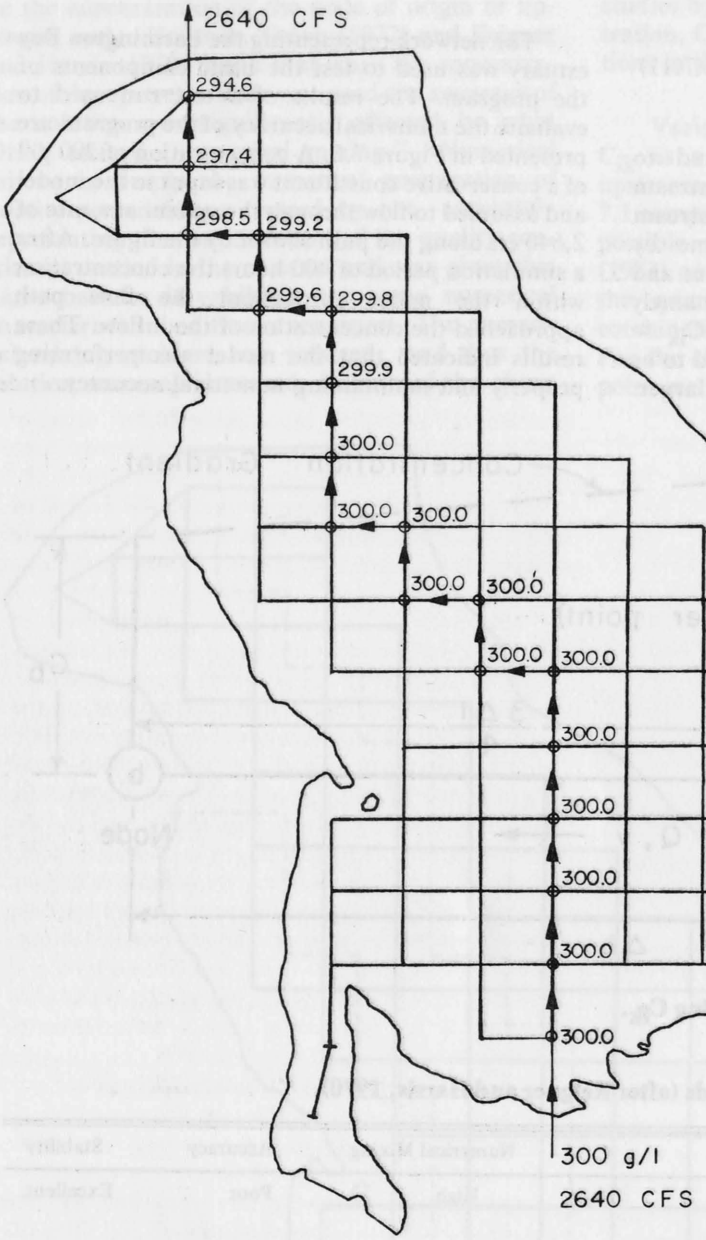

Figure 7.5. Distribution of a conservative constituent along a single path in the Farmington Bay Estuary after 400 hours.

CHAPTER VIII

MODEL APPLICATION

The channel-node model was applied to the south arm of Great Salt Lake. Due to the present limited data on circulation patterns and associated velocities for Great Salt Lake, the results obtained are of a preliminary nature. However, even with the limited data available the application did demonstrate the utility of the model in representing the temporal and spatial distribution of quality parameters within the lake system and in providing valuable insight into the relative importance of the processes which affect these distributions. This insight pointed out areas where further data collection and analysis are needed.

In applying the model to Great Salt Lake only three quality constituents (TDS, BOD, and DO) were considered. However, the model is capable of predicting the distribution of a wide range of quality constituents associated with the lake. The distribution of a conservative constituent is dependent on only the advective and diffusive transport. The modeling of a particular non-conservative constituent is accomplished by the proper definition of the internal sources and sinks. Thus, the model is applicable to:

1. Predicting the distribution of quality constituents presently in the lake.

2. Predicting the distribution of quality constituents introduced into the lake.

3. Accounting for the interactions between quality constituents.

4. Tracing the consequences of alterations to the present physical system on the distribution of quality constituents within the lake.

Because the model is capable of simulating the distribution of both inorganic and organic components within the lake, it will become increasingly more useful for investigating the impacts of various possible management alternatives upon the lake ecosystem. For example, the model is capable of predicting the impacts on the water quality of the lake from the input of specific water quality constituents to the lake at various levels and locations. This capability could be used in evaluating the effects on the lake of the inflow of various water quality constituents from the tributaries.

The model is applicable to a wide range of water quality distribution questions. As already stated, three quality constituents were chosen to demonstrate the use of the model, namely, total dissolved solids, biochemical oxygen demand, and dissolved oxygen. Additionally, the distribution of a single conservative constituent was modeled to demonstrate the application of the model to the type of constituent which might represent a toxic compound or a specific ion. Biochemical oxygen demand and dissolved oxygen were chosen because they are coupled, non-conservative constituents and are important indications of pollution level and the ability of the brine to support a healthy state for important living organisms, such as brine shrimp.

Basic Lake Conditions and Assumptions Used in the Simulation Phase

A surface elevation of 4,200 feet was selected for testing the model. The location of the pycnocline was set at an elevation of 4,175. This surface elevation was selected because it represents a typical elevation during the period when the general circulation pattern shown in Figure 8.1 was observed.

The general long term circulation pattern shown in Figure 8.1 was used in testing the model. The problem in applying this pattern to the south arm of the lake was that information concerning the temporal and spatial variations of circulation velocities were not available. Preliminary information (W. M. Katzenburger, 1974) indicated that point rates of movement vary throughout the year from a high of 1.0 ft/sec to a low of 0.3 ft/sec. In testing the model these surface velocities were assumed to be representative of the average (with depth) velocities for the upper brine layer. Figure

8.1 shows the velocities which were assumed with the various loops of the circulation pattern for the upper brine layer. Note that a velocity of 0.3 ft/sec was associated with the main circulation loop. No information was available on either the circulation pattern or the associated rates of movement for the lower dense brine layer. As shown in Figure 8.2, the long-term circulation pattern of the lower brine layer was assumed to be like that of the upper brine layer but at approximately two-thirds of the velocities of the upper layer.

The ability of the model to simulate long-term seasonal water quality distribution trends was demonstrated by using a three month simulation period. Based on inflow to the lake it appeared that the yearly lake cycle could be divided into four segments corresponding approximately to the seasons of the year. During the season being simulated the inflows and circulation velocities are assumed to be constant and representative of the time period under consideration. It is emphasized that the model is not restricted to simulating a three-month seasonal trend. Rather, the model can be applied to a simulation period of any length for which average lake conditions will produce the desired information on the distribution of water quality constituents.

Other basic data assumptions which were made in simulating the south arm included:

1. The exchange of brine through the railroad causeway fill is evenly distributed along the causeway.

2. Horizontal diffusion coefficients are constant within a layer and do not vary spatially.

3. Vertical diffusion coefficients do not vary spatially.

Figure 8.3 illustrates the grid system used to represent the south arm of the lake and indicates the boundary of the lower brine layer. The grid system used to represent the south arm consisted of 373 nodes with 746 connecting channels for the upper brine layer, while 144 nodes and 254 channels were used to represent the lower brine layer. The considerable flexibility which is possible in laying out the channel-node grid network is evident from Figure 8.3. A grid spacing of one mile was used in the eastern portion of the lake where the inflows occur, and recreational and industrial developments are centered. In the western portion of the lake the grid spacing was increased to two miles.

In an effort to test the reliability of the model the test runs were performed over a period during which inflow and outflow conditions for the south arm could be determined. Based on the following criteria, the months of January, February, and March 1974 were selected as the test simulation period: (1) the average lake surface elevation was 4,200 feet for this period, (2) information was available from UGMS sampling stations on the distribution of total dissolved solids in the lake, (3) data on inflows to the south arm were available, and (4) sufficient information was available to enable an estimate to be made of the exchange of brine through the causeway from the water and salinity balance model. The use of the average data from this period allowed the model to be roughly verified, and thus to demonstrate the capabilities of the model.

Model Verification

The verification run was performed using the inflow and outflow data given in Table 8.1. The causeway flows were determined from the simulation of the 1974 water year using the water and salinity balance model. The exchange of brine through the causeway fill was assumed to be evenly distributed along the length of the causeway.

The initial value of the horizontal diffusion coefficient for the upper layer was assumed to be that reported by the Utah Division of Water Resources (1974), for the horizontal diffusion coefficient at the surface, namely 3.8 ft^2/sec. Because no information was available on this coefficient for the lower brine layer, as an approximation, the same value was assumed. The lack of information on lake circulation patterns made it impossible to verify this assumed value of the horizontal diffusion coefficient for either brine layer.

Table 8.1. Inflow and outflow data used in model verification and demonstration.

Source	Flow (CFS)	TDS Concentration of Inflow (g/l)
Inflow:		
Bear River	2600	20.
North Fork Weber River	260.	5.
South Fork Weber River	520.	5.
Jordan River	415.	10.
Goggin Drain	335	20.
Kennecott Drain	120	20.
Causeway Fill	2200.	312.
Causeway Culverts	187.2	312.
Outflow:		
Causeway Fill	2863.2	–
Causeway Culverts	1294.2	–

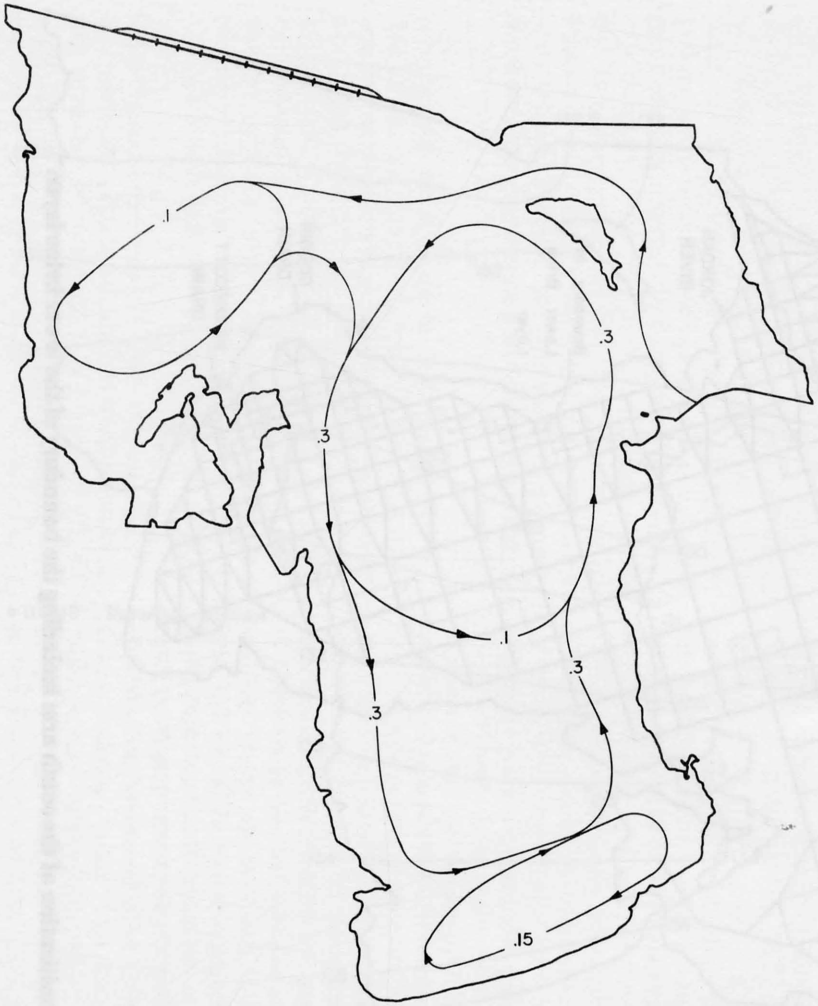

Figure 8.1. Circulation pattern and associated velocities (ft/sec) assumed for the upper brine layer.

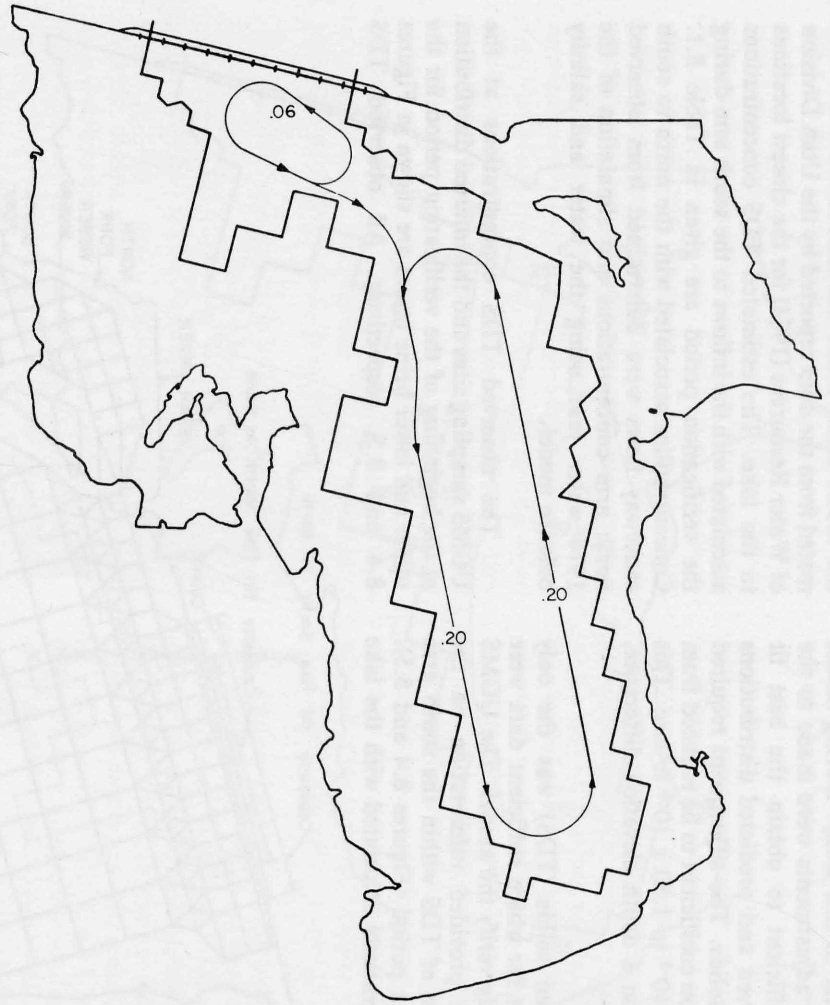

Figure 8.2. Circulation pattern and associated velocities (ft/sec) assumed for the lower brine layer.

The value of the vertical diffusion coefficient was identified earlier in this study. During model verification minor adjustments were made to the value of this coefficient to obtain the best fit between the observed and predicted distributions of total dissolved solids. The adjustment required the vertical diffusion coefficient to be reduced from a value of 1.68×10^{-5} to 1.50×10^{-5} ft²/sec. This value was based on a depth elevation difference, Δz, of 15.5 feet.

Total dissolved solids (TDS) was the only quality constituent for which sufficient data were available to roughly verify the model. The UGMS sampling stations provided information on the spatial distribution of TDS within the south arm for the verification period (Figures 8.4 and 8.5). The TDS concentrations associated with the lake inflows were not available at the points of inflow to the south arm. These concentrations were estimated from the data reported by the Utah Division of Water Resources (1974) for the closest locations to the lake. The estimated TDS concentrations associated with the inflows to the south arm during the verification period are given in Table 8.1. Concentrations associated with the north to south causeway flows were determined from observed north arm concentrations and simulation of the 1974 water year using the water and salinity balance model.

The observed TDS concentrations at the UGMS sampling sites and the inferred distribution at the beginning of the verification period for the upper and lower brine layers are shown in Figures 8.4 and 8.5, respectively. All observed TDS

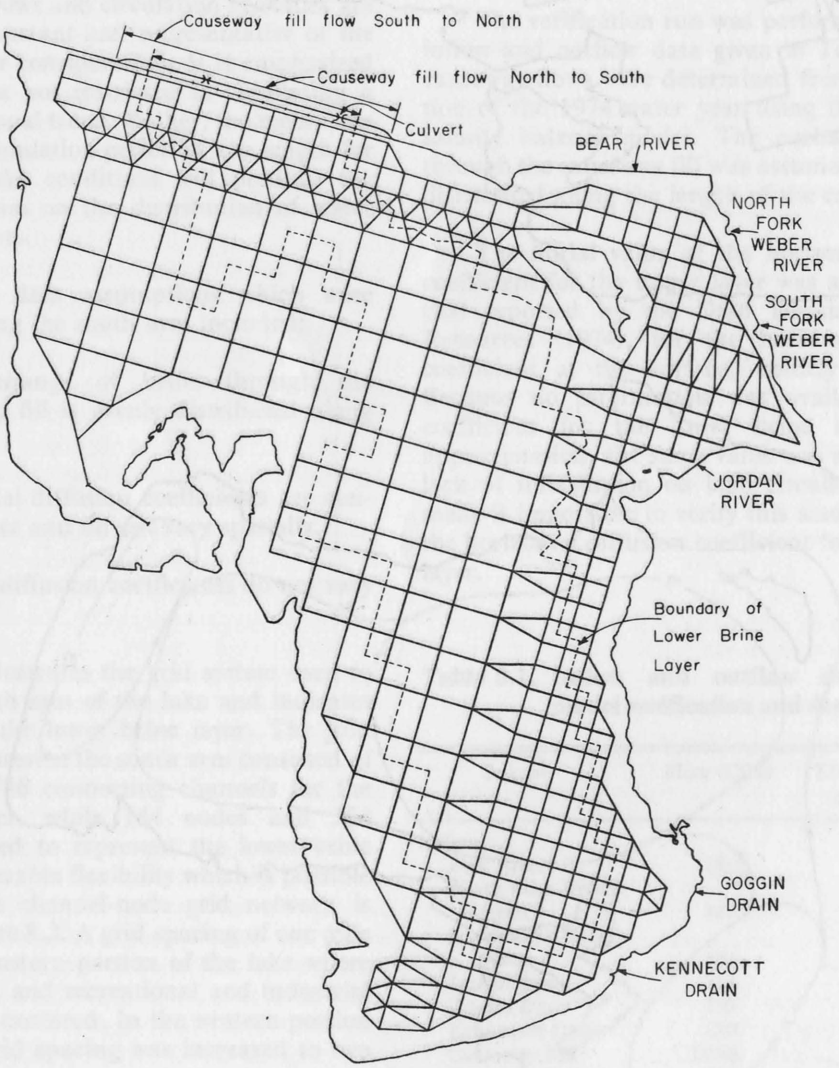

Figure 8.3. Schemitization of the south arm including the boundary of the lower brine layer.

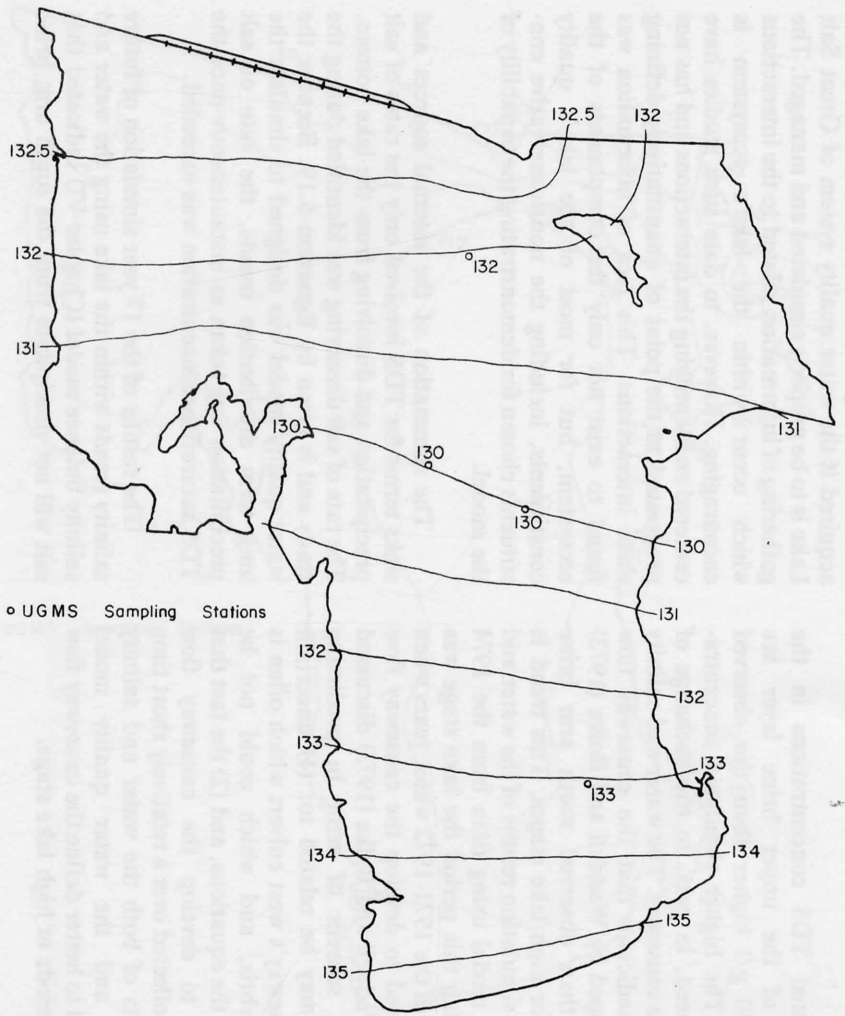

Figure 8.4. Inferred initial TDS (g/l) distribution in the upper brine layer.

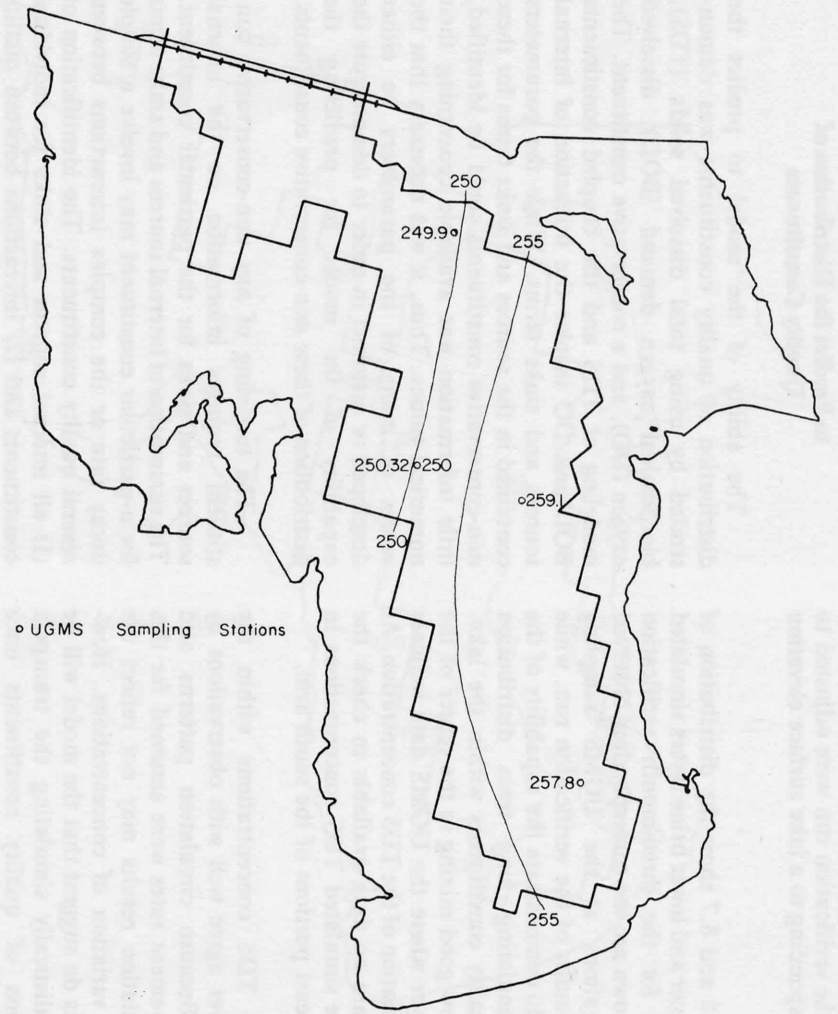

Figure 8.5. Inferred initial TDS (g/l) distribution in the lower brine layer.

concentrations for the upper brine layer which were used to check the verification run were adjusted to a volume corresponding to a lake surface elevation of 4,200 feet.

Figures 8.6 and 8.7 show the distribution of TDS for the upper and lower brine layers simulated by the model for the three-month verification period. Also shown are the corresponding observed TDS concentrations at the UGMS sampling stations. The results of the verification run, while not excellent, do demonstrate the capability of the model for simulating long term distribution patterns of quality constituents within the lake. The results show good mixing in the center of the upper brine layer where the UGMS data indicate little spatial variation of the TDS concentration. At present there are no data available to check the accuracy of the simulated TDS concentrations in the north and east portions of the south arm.

Simulated TDS concentrations within the lower brine layer agree well with observations by the UGMS. Because circulation patterns and associated movement rates were assumed for this layer the simulation results may not reflect the actual spatial variation of concentrations. However, the results do suggest that the model will be capable of realistically simulating the transport and distribution of quality constituents once circulation data are available.

The simulated TDS concentrations in the center portion of the upper brine layer are approximately 10 g/l higher than the observed concentrations. The higher simulated concentrations can be traced, in part, to the exchange of brine through the causeway. The water and salinity balance model indicates that the causeway flow equations developed by Waddell and Bolke (1973) predict higher than observed south arm brine concentrations for high lake stages. This trend is evident from the simulation results of the water and salinity balance model using data from the 1974 water year. During this period the lake stage was higher than that of the 1971-1972 water years when data were gathered to develop the causeway flow equations. As Waddell and Bolke (1973) discussed in their report, sources of error in predicting causeway flows may be related to: (1) uncertain flows in the causeway's west culvert which often is restricted by debris, and which could not be accounted for in the equations, and (2) the fact that the data used to develop the causeway flow equations were collected over a relatively short time span. The results of both the water and salinity balance model and the water quality model indicate the need to better define the causeway flow equations for periods of high lake stage.

Demonstration of the Ability of the Model to Predict the Distribution of Quality Constituents

The ability of the model to predict the distribution of quality constituents was demonstrated by using total dissolved solids (TDS), biochemical oxygen demand (BOD), dissolved oxygen (DO), and a conservative constituent. The modeling of TDS and the coupled constituents BOD and DO involve the utilization of internal sources and sinks terms. While the parameters contained in the sources and sinks terms for these non-conservative constituents could be identified, little information was available concerning their numerical values. Thus, it was necessary that the values of many of the parameters be either developed or assumed in order to demonstrate the capability of the model for predicting the distribution of these non-conservative constituents.

The modeling of any non-conservative constituent requires information on the internal sources and sinks for the particular constituent. The summation of internal sources and sinks terms for a particular constituent may involve a simple decay rate or the complex interactions between several quality constituents. The identification of (1) all internal sources and sinks for individual constituents and (2) interactions between quality constituents represent data which must be acquired if the water quality system of Great Salt Lake is to be properly simulated and managed. The gathering of information related to the interactions which occur within the lake's ecosystem is encouraging. However, to date such studies have centered on identifying the interactions and has not progressed to the point of quantitatively defining these interactions. This lack of information was found to exist not only for components of the ecosystem, but for most of the lake's quality constituents, including the non-conservative constituents chosen for demonstrating the capability of the model.

The summation of the internal sources and sinks terms for TDS involved only the rates of salt precipitation and dissolving from the lake bottom. The rate of salt dissolving was identified during the study and is given by Equation 5.19. Because the water quality model was designed to simulate the long term distribution trends, the rate of salt precipitation was taken as instantaneous once the TDS saturation concentration was exceeded.

The results of the 17 year simulation of future salinity trends within the lake using the water and salinity balance model (Chapter VI) indicated that salt will not precipitate from the south arm brine

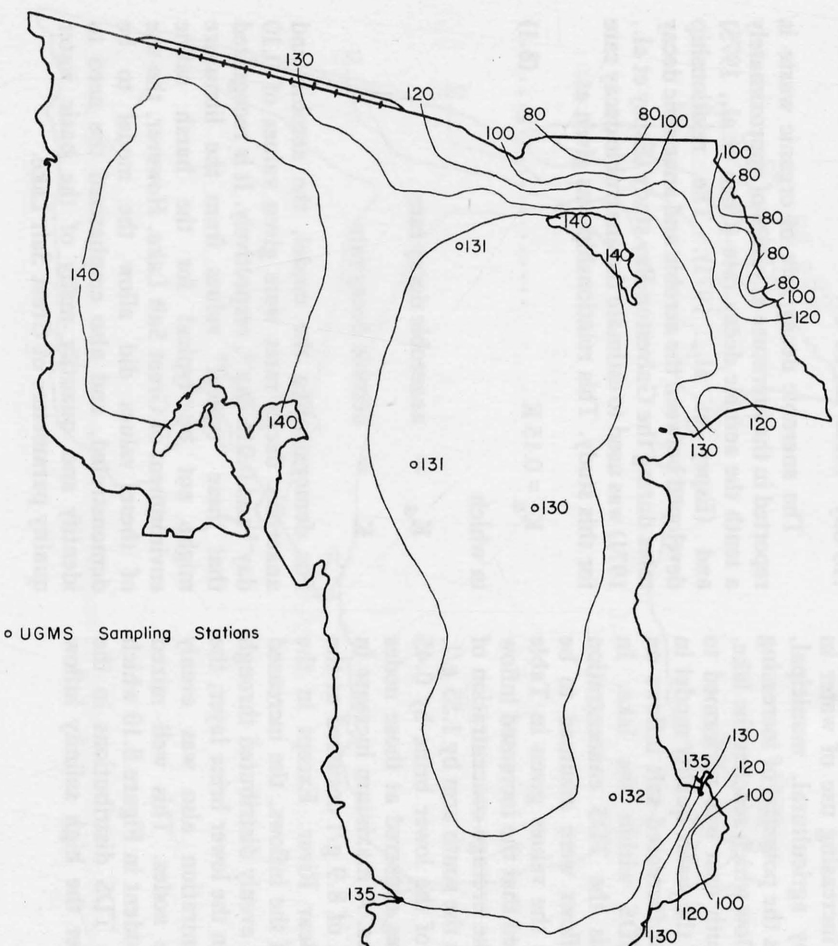

Figure 8.6. Simulated TDS (g/l) distribution in the upper brine layer after three months.

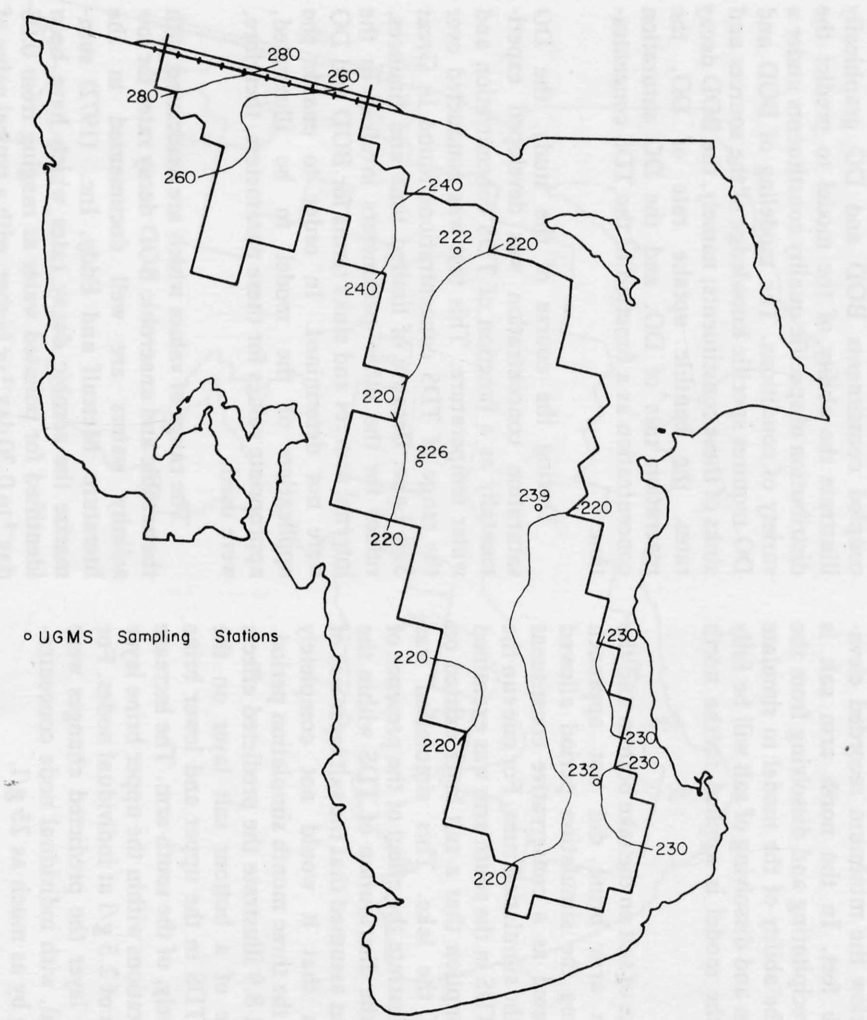

Figure 8.7. Simulated TDS (g/l) distribution in the lower brine layer after three months.

unless the surface elevation of the lake drops substantially below the minimum recorded elevation of 4,196.6 feet. In the north arm salt is continuously precipitating and dissolving from the lake bottom. The ability of the model to simulate the precipitation and dissolving of salt will be fully utilized when the model is applied to the north arm.

The absence of salt on the lake bottom and the fact the south arm brine did not approach saturation during the simulation period allowed TDS to be treated as a conservative constituent during most of the simulation runs. For one run the distribution of TDS in the south arm was examined under the assumption that a salt layer existed on the bottom of the lake. This simulation was performed to illustrate the effect of the presence of a salt layer on the distribution of TDS within the south arm. It was assumed that the salt layer was of sufficient mass that it would not completely dissolve during the three month simulation period. Figures 8.8 and 8.9 illustrate the predicted effects of the presence of a bottom salt layer on the distribution of TDS in the upper and lower brine layers, respecitvely, of the south arm. The increase in TDS concentrations within the upper brine layer was a maximum of 2.5 g/l at individual nodes. For the lower brine layer the predicted changes were more substantial, with individual node concentrations increasing by as much as 25 g/l.

The continuously increasing use of water in the tributary basins by agricultural, municipal, and industrial users has the potential of increasing the TDS load of the inflow which reaches the lake. A simulation of the south arm was performed to demonstrate the use of the water quality model in predicting the effects of increased salt inflows on the distribution of TDS within the lake. In performing the analysis the TDS concentration associated with the inflows were assumed to be increased by ten times the values given in Table 8.1. The results indicated that the increased inflow concentrations raised the average concentration of the upper brine layer in the south arm by 1.55 g/l, and the concentration of the lower brine by 0.45 g/l. The major increases occurred at those nodes which receive the inflows. A maximum increase in the TDS concentration of 8.9 g/l occurred at the inflow point of the Bear River. Except in the immediate proximity of the inflows, the increased TDS concentration was evenly distributed through the upper brine layer. In the lower brine layer, the increased TDS concentration also was evenly distributed among the nodes. This well mixed nature of the brine is evident in Figure 8.10 which presents the simulated TDS distributions in the upper brine layer under the high salinity inflow conditions.

The modeling of the distribution of the coupled constituents BOD and DO graphically illustrate the ability of the model to predict the distribution of specific quality constituents under a variety of conditions. The modeling of BOD and DO requires specific knowledge of the sources and sinks of these constituents; namely, the BOD decay rates, the benthic uptake rate of DO, the reaeration rate of DO, and the DO saturation concentration as a function of the TDS concentration.

During the course of the study, the DO saturation concentration was developed experimentally as a function of TDS concentration and water temperature. This test was conducted over the range of TDS concentrations found in Great Salt Lake. Because of limited time and finances, values for the other parameters involved in the internal sources and sinks terms for BOD and DO were not determined. In order to enable the application of the model to be illustrated, appropriate values for these parameters, therefore, were used.

The range of values which are associated with the aerobic and anaerobic BOD decay rates for low salinity waters are well documented in the literature. Metcalf and Eddy, Inc. (1972) summarize the aerobic decay rates which have been identified for polluted water as ranging from 0.05 day^{-1} to 0.30 day^{-1} or higher, with a typical value of .10 day^{-1} (base 10, 20°C).

The anerobic decay rate of organic waste is reported in the literature at values of approximately a tenth the aerobic decay rate (Chen et al., 1975) and (Espey et al., 1971). The relationship developed between the aerobic and anaerobic decay rates during the Galveston Bay study (Espey et al., 1971) was used to estimate the anaerobic decay rate for this study. This relationship was given as:

$$K_a = 0.15\,K \quad \text{.................. (8.1)}$$

in which

K_a = anaerobic decay rate

K = aerobic decay rate

For demonstrating the model, the aerobic and anaerobic decay rates were given values of 0.10 day^{-1} and 0.015 day^{-1}, respectively. It is recognized that these "typical" values from the literature might not be typical for the harsh saline environment of Great Salt Lake. However, the use of these values did allow the model to be demonstrated, and also emphasized the need to identify and quantify many of the basic water quality parameters of Great Salt Lake.

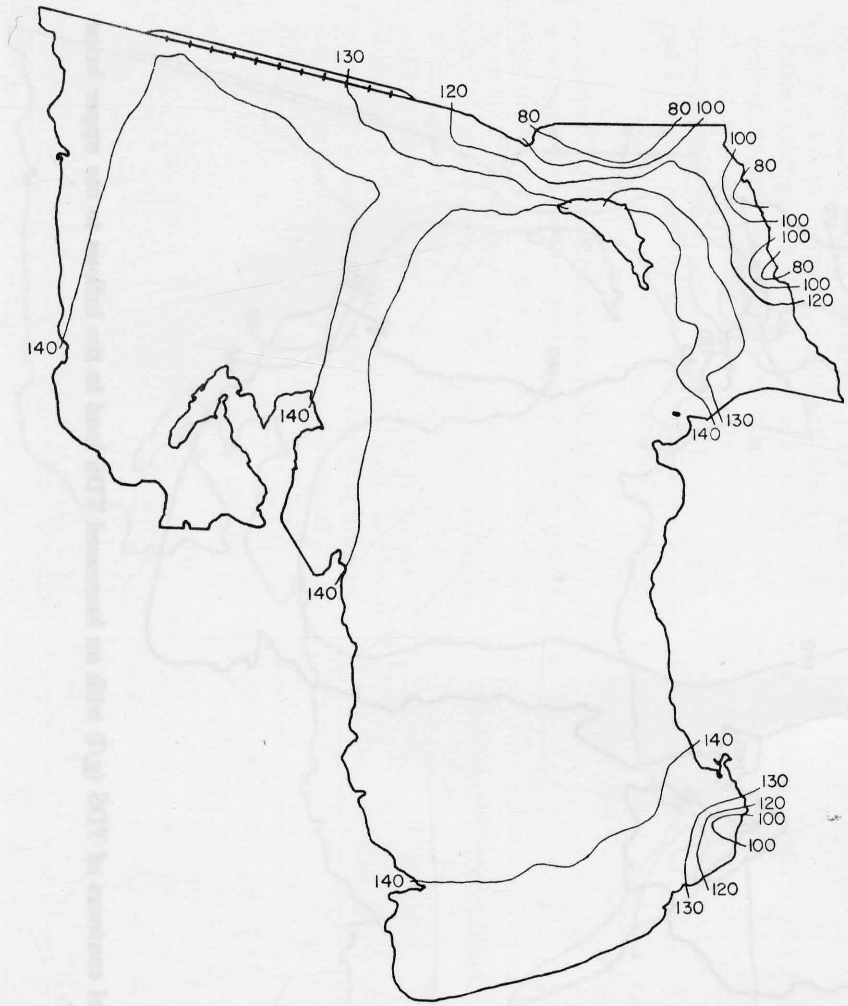

Figure 8.8. Equal contours of TDS (g/l) in the upper brine layer simulated under the assumption a salt deposit existed beneath the lower brine layer.

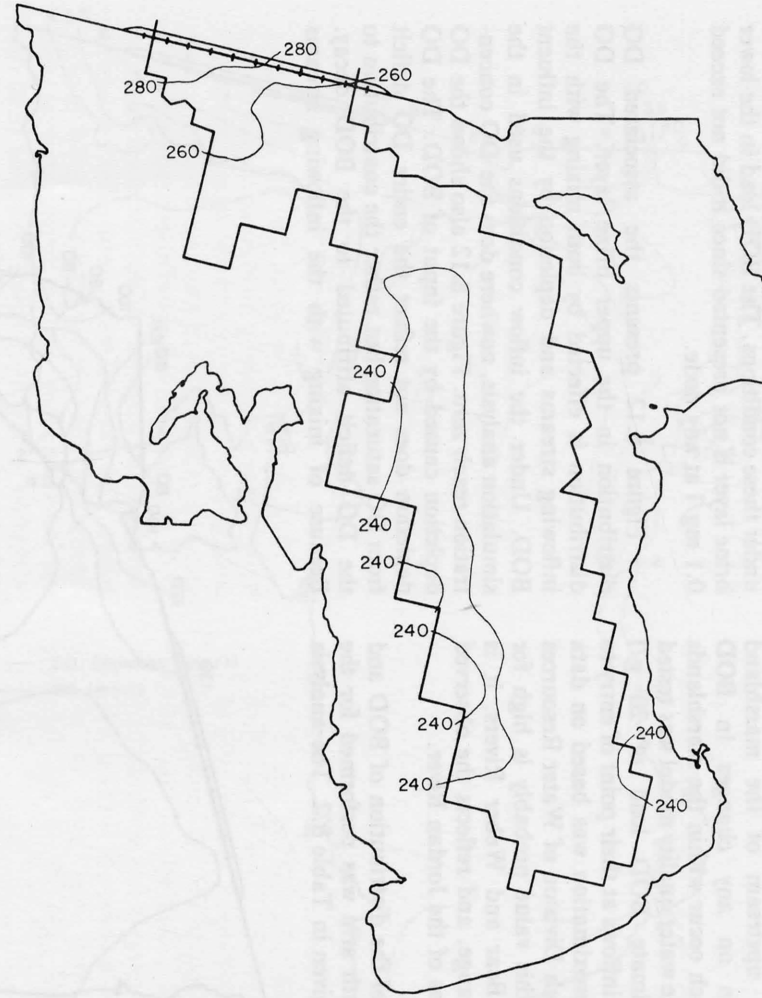

Figure 8.9. Equal contours of TDS (g/l) in the lower brine layer simulated under the assumption a salt deposit existed beneath the lower brine layer.

Data on BOD concentrations of inflowing streams generally are not available at points of entry to the lake. Data presently available are from stations upstream of the lake and, in the case of the major tributaries, upstream of the marshland areas. Information on any changes in BOD concentrations which occur within the marshlands is not available. The water quality model was tested assuming an ultimate BOD load of 20 g/l associated with all inflows at their point of entry to the lake. This approximation was based on data reported by the Utah Division of Water Resources (1974). Although this value probably is high for inflows from the Bear and Weber Rivers, it is within a realistic range, and reflects the observed BOD concentrations of the Jordan River.

A simulation of the distribution of BOD and DO within the south arm was performed for the inflow conditions given in Table 8.2. The analysis utilized the same transport processes, time period, and TDS conditions as were applied during the model verification. Figure 8.11 shows the predicted distribution of BOD within the upper brine layer under these conditions. The BOD load in the lower brine layer is not presented since it did not exceed 0.1 mg/l at any node.

Figure 8.12 presents the associated DO distribution in the upper brine layer. The DO distribution is effected by both mixing with the inflowing streams and depletion by the influent BOD. Under the inflow conditions used in the simulation analysis, nowhere does the DO concentration reach zero. Figure 8.12 also shows the DO depletion caused by the input of BOD. The DO depletion does not reflect the entire DO deficit from DO saturation but rather the contribution to the DO deficit attributed to the BOD decay. Because of mixing with the inflowing streams

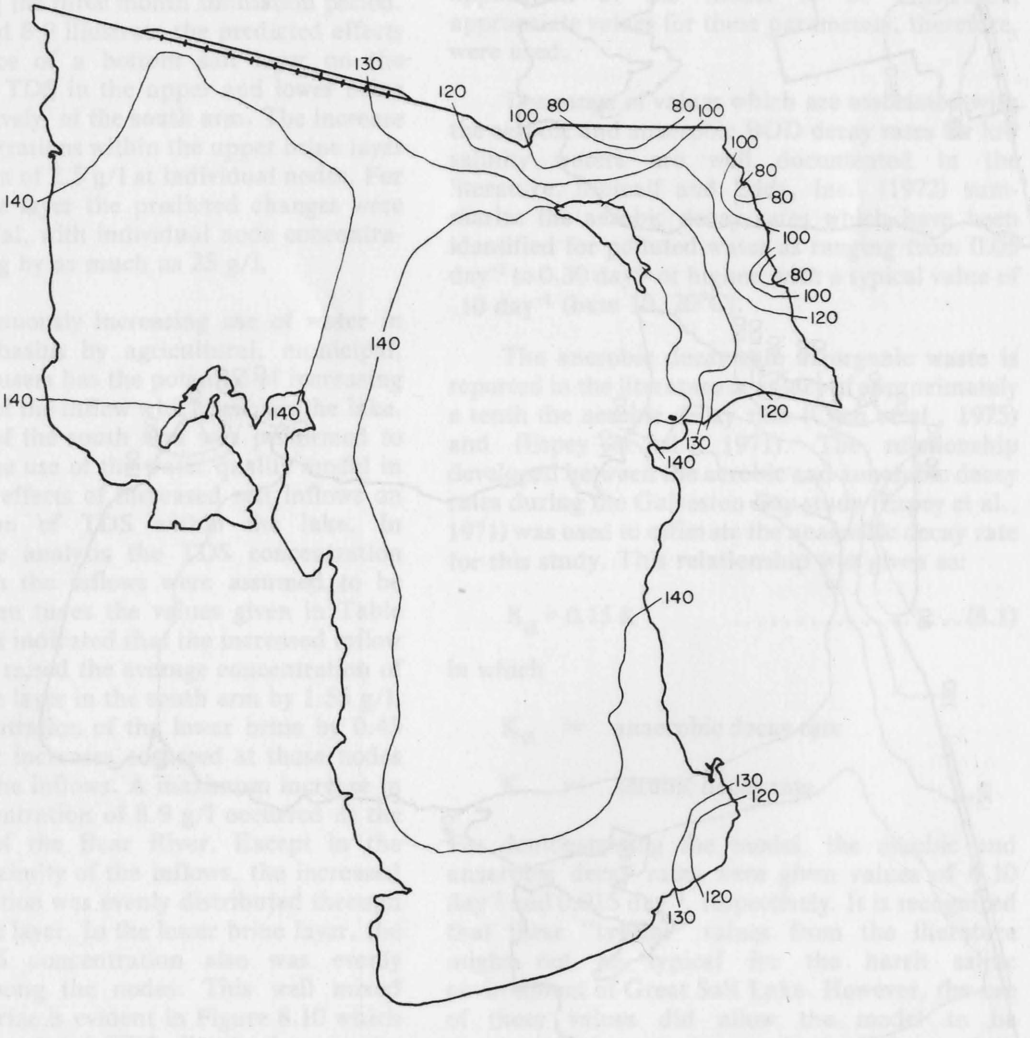

Figure 8.10. Equal contours of TDS (g/l) with an increased TDS load in the inflows to the upper brine layer.

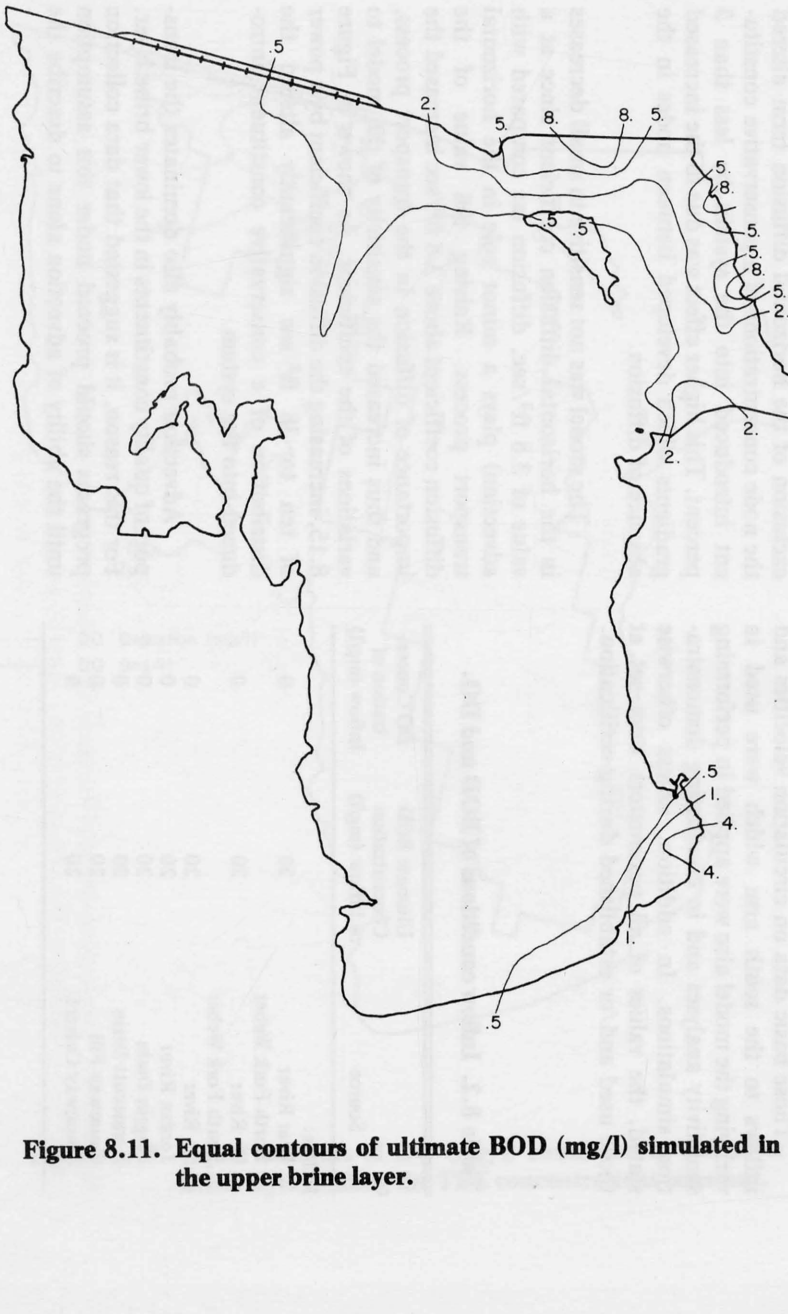

Figure 8.11. Equal contours of ultimate BOD (mg/l) simulated in the upper brine layer.

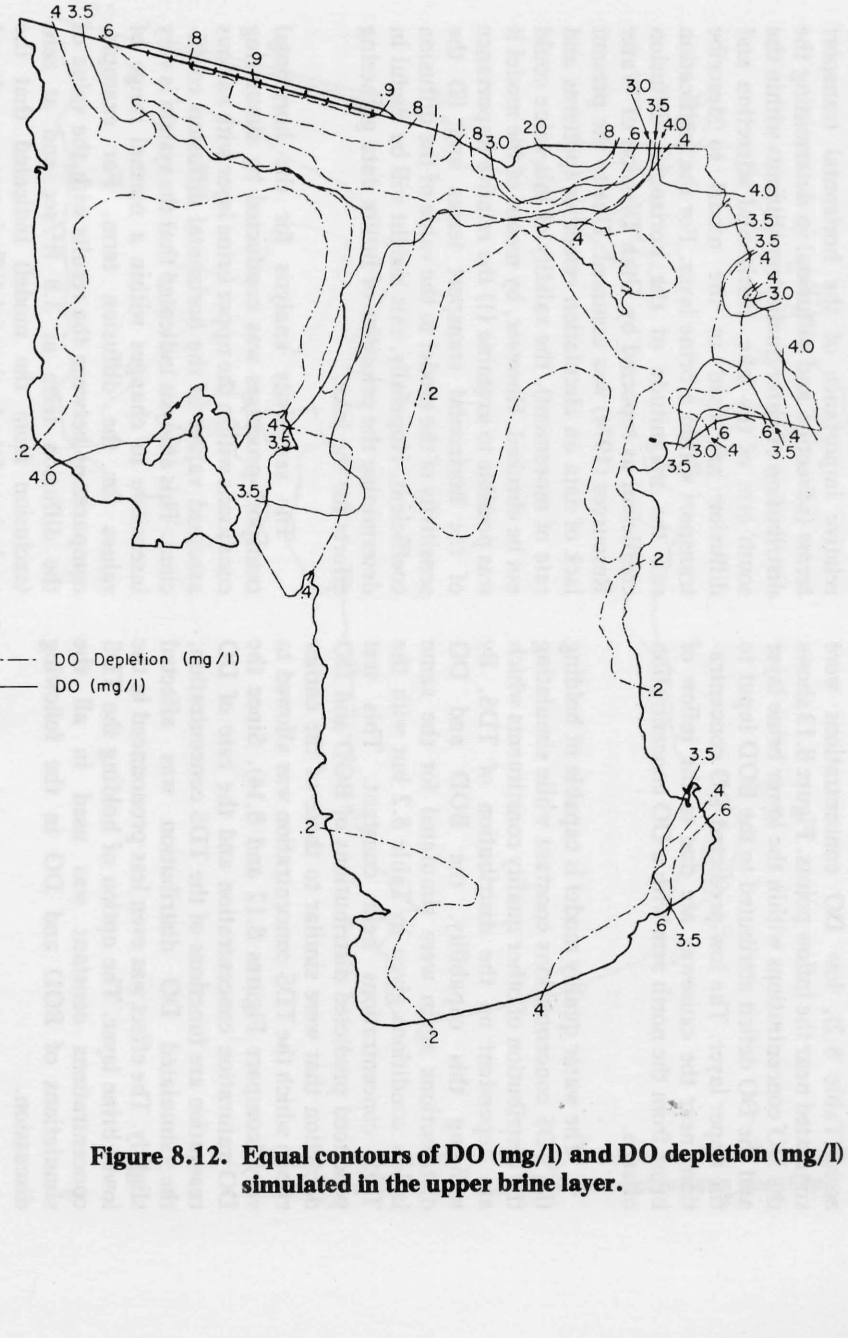

Figure 8.12. Equal contours of DO (mg/l) and DO depletion (mg/l) simulated in the upper brine layer.

which were assumed to have a DO concentration of zero (Table 8.2), low DO concentrations were simulated near the inflow points. Figure 8.13 shows the DO concentrations within the lower brine layer and the DO deficit attributed to the BOD input to the upper layer. The low predicted DO concentrations near the causeway are due to the inflow of brine from the north arm with a DO concentration of zero.

The water quality model is capable of holding the TDS concentrations constant while simulating the distribution of other quality constituents which are dependent on the distribution of TDS. By utilizing this capability, the BOD and DO distributions again were simulated for the same inflow conditions given in Table 8.2 but with the TDS concentrations held constant. This test produced predicted distributions of BOD and DO depletion that were similar to those of the earlier run in which the TDS concentration was allowed to vary (compare Figures 8.12 and 8.14). Since the DO saturation concentration and the rate of DO reaeration are functions of the TDS concentration, the simulated DO distribution was affected slightly. The effect was even less pronounced in the lower brine layer. The option of holding the TDS concentrations constant was used in all the simulations of BOD and DO in the following discussion.

Model Sensitivity Studies

Those basic data on circulation velocities and inflows to the south arm which were used in verifying the model also were applied in performing sensitivity analyses and in conducting demonstration simulations. In addition, unless otherwise stated, the values of all parameters were set at those used and/or established during verification.

Table 8.2. Inflow conditions of BOD and DO.

Source	Ultimate BOD Concentration of Inflow (mg/l)	DO Concentration of Inflow (mg/l)
Inflow:		
Bear River	20	0
North Fork Weber River	20	0
South Fork Weber River	20	0
Jordan River	20	0
Goggin Drain	20	0
Kennecott Drain	20	0
Causeway Fill	20	0
Causeway Culvert	20	0

The sensitivity studies provided a test of the relative importance of the horizontal transport terms (advection and diffusion) in determining the distribution of water quality constituents within the south arm of the lake. Horizontal advection and diffusion are used in the model to describe transport within a brine layer. For the verification run the magnitude of the horizontal diffusion coefficient as reported by Utah Division of Water Resources (1974) was assumed. Due to the present lack of data on circulation velocities (patterns and rate of movement), the validity of this value could not be checked. However, by means of the model it was possible to examine (1) the relative importance of the horizontal transport terms and (2) the sensitivity of the model to the value of the diffusion coefficient. Hopefully, this insight will be useful in determining the priorities of future data gathering efforts for the lake.

The sensitivity analysis for the horizontal transport processes was conducted by simulating conditions within the upper brine layer with various assumed values of the horizontal diffusion coefficient. This analysis indicated that the system is very insensitive to changes within a normal range of values for the diffusion term. For example, comparisons between the results with the value of the diffusion term at 3.8 ft^2/sec and at zero (exclusion from the model) indicated that the exclusion of the horizontal diffusion process altered the simulated TDS concentrations associated with the nodes by less than 0.5 percent or 0.4 g/l. The exclusion of the horizontal diffusion term altered the node concentrations of a conservative constituent introduced into the system by less than 3 percent. This higher effect was due to the increased gradients which developed between nodes in the absence of diffusion.

The model was not sensitive to small decreases in the horizontal diffusion coefficient since at a value of 3.8 ft^2/sec, diffusion (as compared with advection) plays a minor role in the horizontal transport process. Raising the value of the diffusion coefficient above 3.8 ft^2/sec increased the importance of diffusion in the transport process, and thus increased the sensitivity of the model to variations of the coefficient. As shown in Figure 8.15, increasing the diffusion coefficient by a power of ten to 38 ft^2/sec significantly altered the distribution of a conservative constituent introduced into the system.

Advection probably also dominates the transport of quality constituents in the lower brine layer. For this reason, it is suggested that data collection programs should proceed under this assumption until the ability of advection alone to describe the

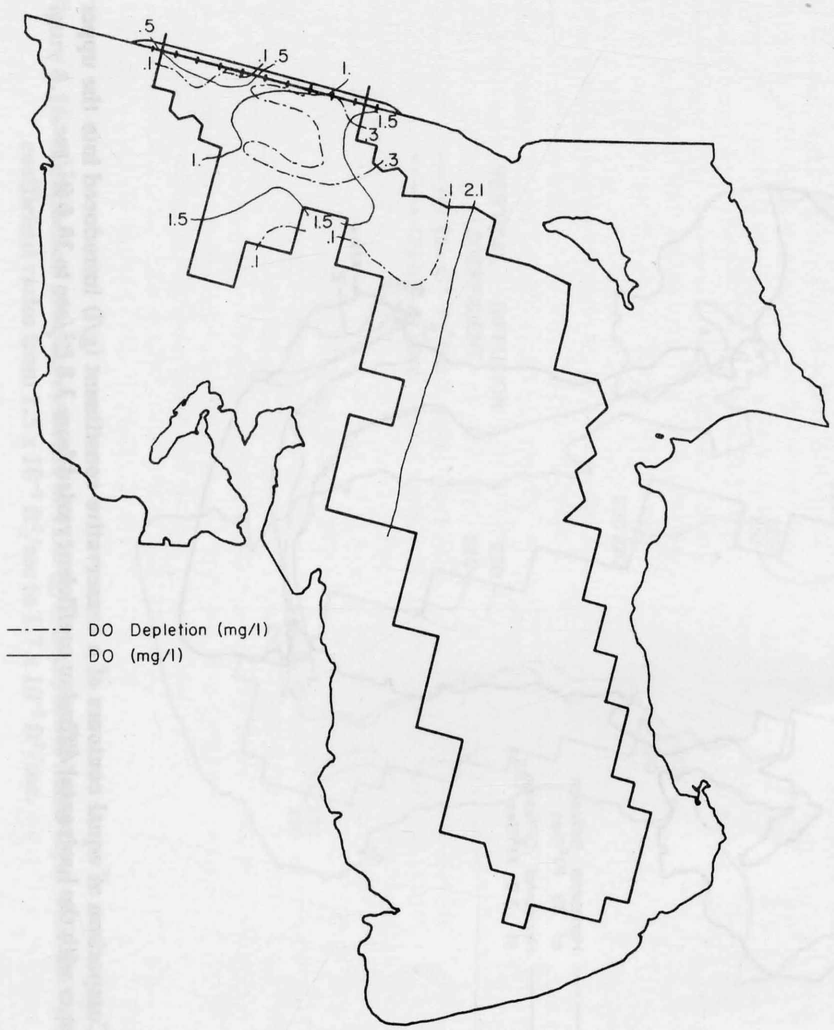

Figure 8.13. Equal contours of DO (mg/l) simulated in the lower brine layer holding the TDS concentrations constant.

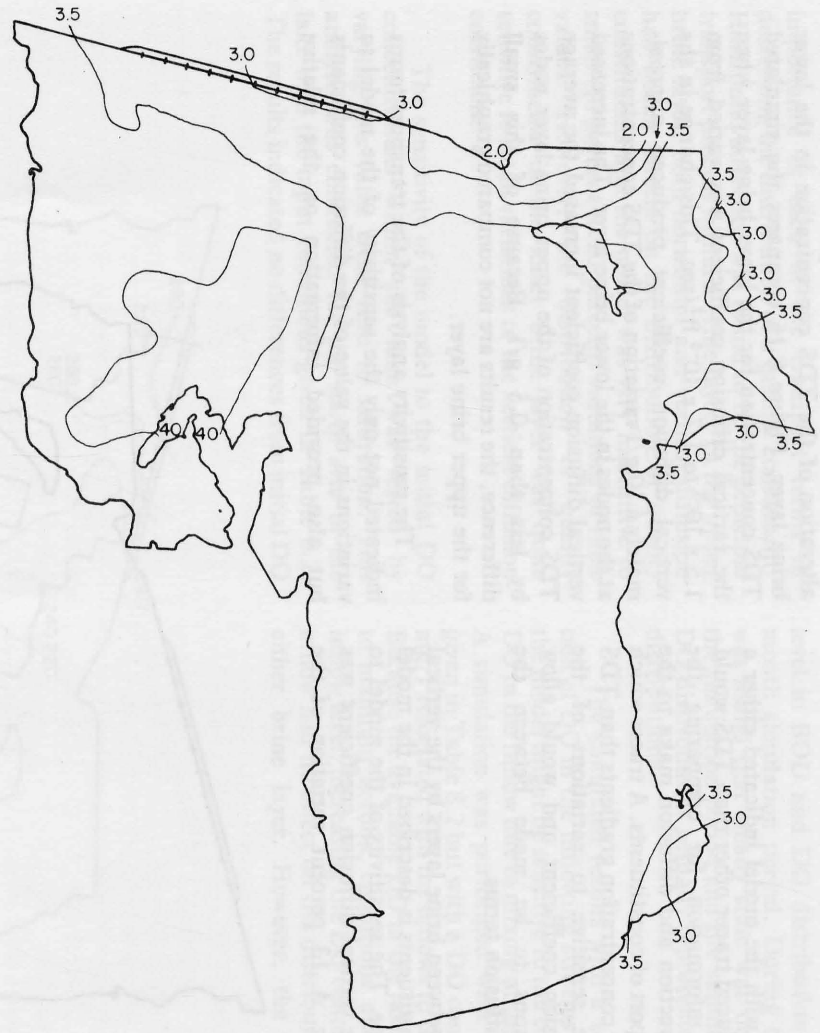

Figure 8.14. Equal contours of DO (mg/l) simulated in the upper brine layer holding the TDS concentrations constant.

distribution of constituents in the lower brine layer can be tested.

Experience with the model indicated either a natural or introduced tracer other than TDS would provide better information for comparing the contribution advection and diffusion make to the horizontal transport of constituents. A tracer which developed larger concentration gradients than TDS would be more sensitive to variations of the horizontal diffusion coefficient and would allow better comparisons to be made between the advection and diffusion terms.

Transport between brine layers by the vertical movement of constituents is described in the model by diffusion alone. The sensitivity of the model to variations in the vertical diffusion coefficient was quite interesting. A 13 percent variation of the vertical diffusion coefficient produced a marked alteration of the TDS concentration in the lower brine layer. Figure 8.16 compares the simulated TDS concentration for the lower brine layer when the vertical diffusion coefficient was varied from 1.5×10^{-5} to 1.7×10^{-5} ft^2/sec. This change in the vertical diffusion coefficient produced approximately a 10 g/l variation of the TDS concentrations at the nodes in the lower brine layer. The increased vertical diffusion coefficient increased the average TDS concentration of the upper brine layer nodes by less than 0.5 g/l. Because of this small difference, the results are not compared graphically for the upper brine layer.

The sensitivity analysis of the transport terms indicated not only the sensitivity of the model to variations in the value of the diffusion coefficients but also provided information on the relative

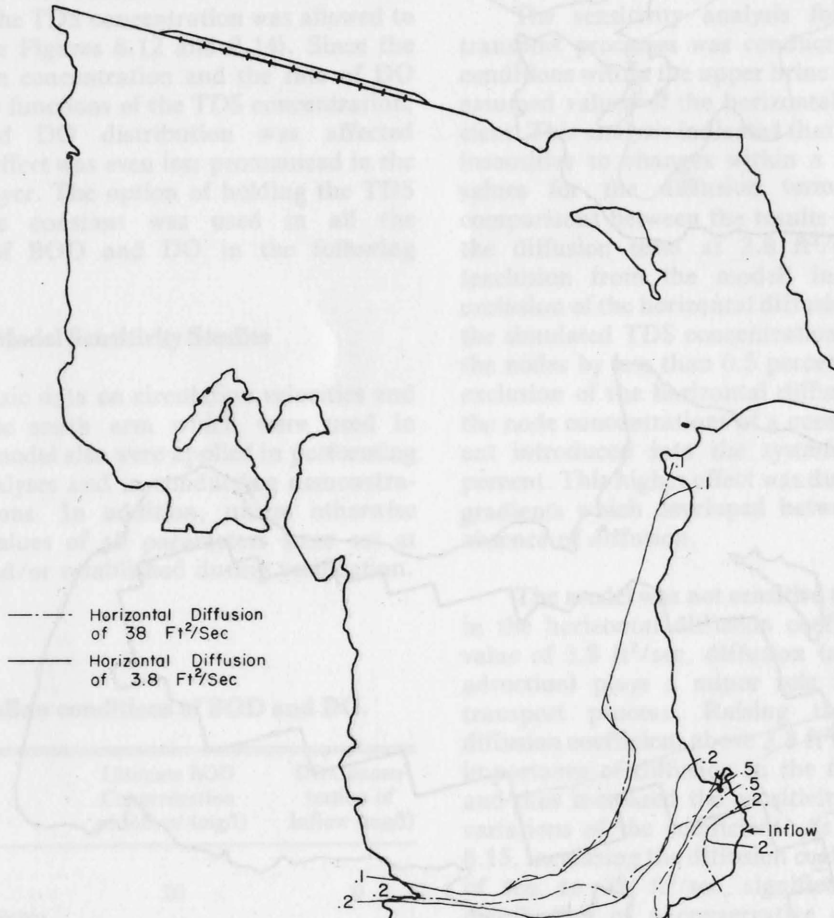

Figure 8.15. Comparison of equal contours of a conservative constituent (g/l) introduced into the upper layer with the horizontal diffusion coefficient varied from 3.8 ft^2/sec to 38.0 ft^2/sec.

importance of each of the transport terms in describing the distribution of a quality constituent. Horizontal advection was found to be the principal transport process within a brine layer. In the upper brine layer, both horizontal and vertical diffusion had minor effects on the distribution of quality constituents and the model was very insensitive to small (10 percent to 20 percent) variations of their values. However, the distribution of quality constituents in the lower brine layer was quite sensitive to small variations of the vertical diffusion coefficient.

The sensitivity of the model to the initial DO concentrations within the lake was tested by varying this value from zero to saturation. This analysis was conducted for the south arm of the lake with the input conditions given in Table 8.2. The results indicated no differences from initial DO level in BOD and DO distribution for the three month simulation period. During this analysis it was found that steady state was obtained during the simulation period and the simulated BOD and DO distributions actually represented steady state distributions.

The simulated results with a zero concentration of DO in the inflowing streams indicated that the model might be sensitive to the concentration of DO in the inflow due to mixing at the inflow points. A simulation was performed with the conditions given in Table 8.2 but with a DO concentration of 5 mg/l associated with the inflows to the upper layer. Because the available DO in the lake was sufficient to maintain aerobic conditions under either DO inflow level, increasing the DO concentration of the inflow had no effect on the distribution of BOD in either brine layer. However, the increased DO

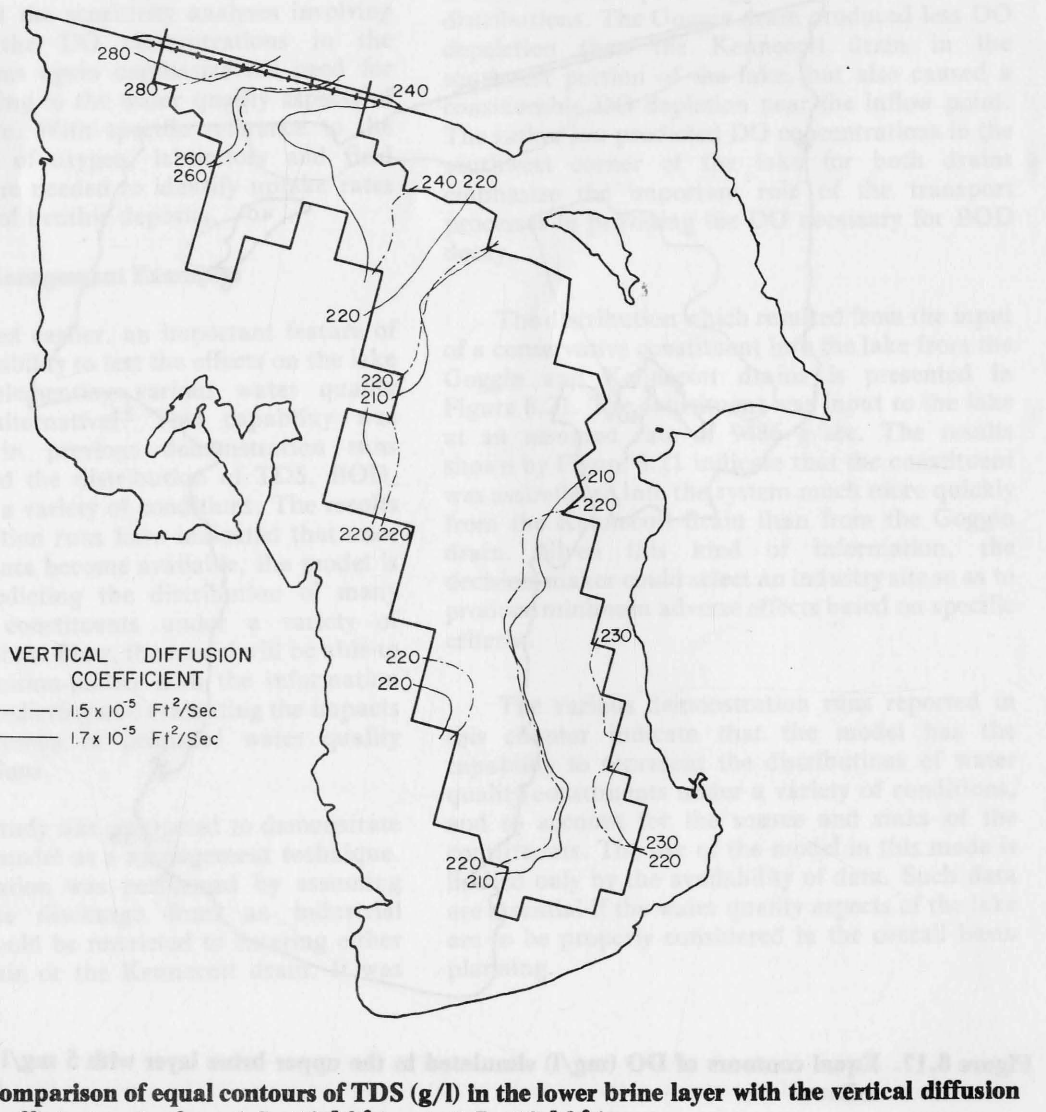

Figure 8.16. Comparison of equal contours of TDS (g/l) in the lower brine layer with the vertical diffusion coefficient varies from 1.5 x 10^{-5} ft^2/sec to 1.7 x 10^{-5} ft^2/sec.

concentration in the inflow streams did significantly alter the distribution of DO near the inflow points to the lake in the upper brine layer. This increase is evident when Figure 8.17 is compared with Figure 8.14. The increased DO concentration of the inflow had little effect on the lower brine layer, with a maximum increase of 0.1 mg/l produced at any node.

The simulated DO distribution in the lower brine layer using the conditions given in Table 8.2 did not produce the absence of DO below the pycnocline reported by Lin et al. (1972) (see Figure 8.15). If their observations are correct, there is probably some mechanism utilizing the available DO in addition to the inflow of BOD. A possible sink for the available DO in the lower lake levels would be the uptake of DO by benthic deposits. A study was conducted to examine the possible effects of a benthic layer of organic material on the distribution of dissolved oxygen within the waters of the lake. The lack of data required that an assumption be made of the benthic uptake rate of oxygen. Some benthic uptake rates reported from laboratory measurements are 2.0 gm/day/m^2 (O'Connor, 1966), 2.2 gm/day/m^2 (Knowles et al., 1962), and 1.7 gm/day/m^2 (Hanes and Irvine, 1968). The above benthic uptake rates were reported at a temperature of 20°C. Using the conditions outlined in Table 8.2 an initial simulation was performed with a benthic demand on the available DO of 2.0 gm/day/m^2. This demand was placed on the nodes of both layers which were in contact with the lake bottom. As shown in Figure 8.18 the benthic uptake rate placed a significant strain on the available DO in both brine layers. The available DO was completely depleted in the lower brine layer and, as shown in Figure 8.18, at several points in the upper brine layer.

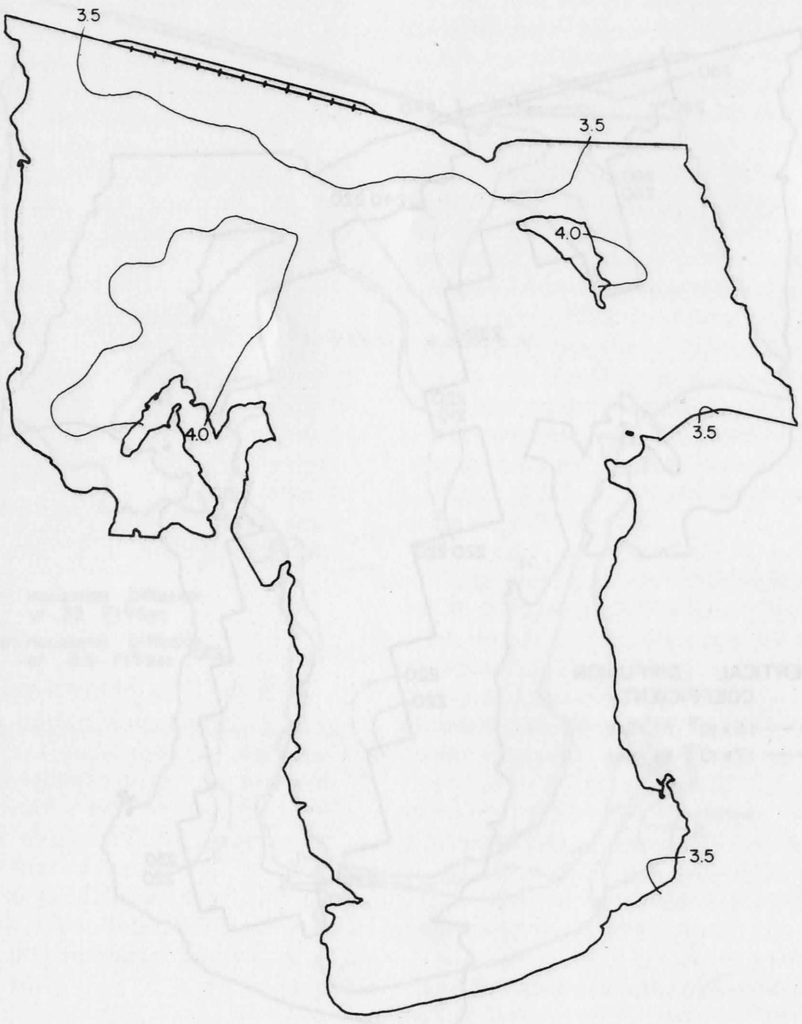

Figure 8.17. Equal contours of DO (mg/l) simulated in the upper brine layer with 5 mg/l of DO in the inflows.

The DO concentration observed in the lake by Lin et al. (1972) indicated an absence of oxygen below the pycnocline but the authors did not report areas of zero DO concentrations above the pycnocline. Therefore, simulations were performed with lower benthic uptake rates than 2.0 gm/day/m^2. A benthic uptake rate of 0.5 g/day/m^2 produced the same absence of DO within the lower brine layer, but brought the level of DO within the upper brine layer more in accordance with the values observed by Lin et al. (1972) (see Figure 8.19). Additonally, these results indicate the DO distribution within the lake is sensitive to variations of the benthic uptake rate.

The above results suggest that the benthic uptake of oxygen may be a major factor in determining the distribution of dissolved oxygen within the lake. The results of the simulation runs which incorporated the effects of the benthic uptake rate and the sensitivity analyses involving variations of the DO concentrations in the inflowing streams again emphasize the need for basic data relating to the water quality aspects of Great Salt Lake. With specific reference to the benthic uptake of oxygen, laboratory and field investigations are needed to identify uptake rates and the extent of benthic deposits.

Management Examples

As indicated earlier, an important feature of the model is its ability to test the effects on the lake system of implementing various water quality management alternatives. This capability was demonstrated in previous demonstration runs which simulated the distribution of TDS, BOD, and DO under a variety of conditions. The results of these simulation runs have indicated that once the necessary data become available, the model is capable of predicting the distribution of many water quality constituents under a variety of possible conditions. Thus, the model will be able to provide the decision-maker with the information necessary for predicting and evaluating the impacts on the lake system of proposed water quality management plans.

A simple study was conducted to demonstrate the use of the model as a management technique. The demonstration was performed by assuming that the waste discharge from an industrial development could be restricted to entering either the Goggin drain or the Kennecott drain. It was further assumed that the industry would increase the BOD load input to the lake and would introduce a conservative constituent into the lake, such as a specific chemical compound. Simulations under these constituents were performed so that the resulting constituent distributions could be examined.

The industry in the example was assumed to produce a BOD inflow to the lake of 4743 g/sec. All other input conditions assumed for the study are given in Table 8.2. Figure 8.20 presents the predicted DO distributions resulting from the inflow of the assumed BOD load at (a) the Goggin drain and (b) the Kennecott drain. Only the southern portion of the south arm is shown by Figure 8.20 since this is the area of greatest impact. A comparison of Figure 8.20 (a) and (b) indicates that the input of the BOD load to the lake at each of the two points produced distinctly different DO distributions. The Goggin drain produced less DO depeletion than the Kennecott drain in the southwest portion of the lake, but also caused a considerable DO depletion near the inflow point. The rather low predicted DO concentrations in the southwest corner of the lake for both drains emphasize the important role of the transport processes in providing the DO necessary for BOD decay.

The distribution which resulted from the input of a conservative constituent into the lake from the Goggin and Kennecott drains is presented in Figure 8.21. The constituent was input to the lake at an assumed rate of 9486 g/sec. The results shown by Figure 8.21 indicate that the constituent was assimilated into the system much more quickly from the Kennecott drain than from the Goggin drain. Given this kind of information, the decision-maker could select an industry site so as to produce minimum adverse effects based on specific criteria.

The various demonstration runs reported in this chapter indicate that the model has the capability to represent the distributions of water quality constituents under a variety of conditions, and to account for the source and sinks of the constituents. The use of the model in this mode is limited only by the availability of data. Such data are essential if the water quality aspects of the lake are to be properly considered in the overall basin planning.

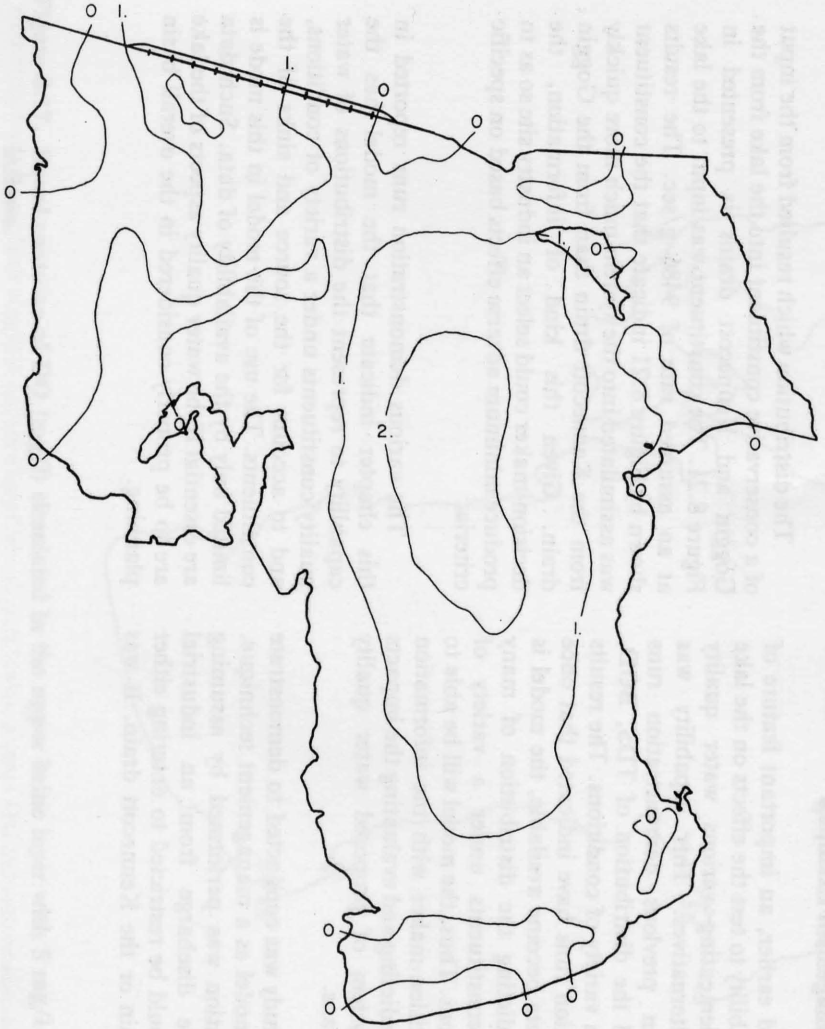

Figure 8.18. Equal contours of DO (mg/l) simulated in the upper brine layer with a benthic uptake rate of 2.0 g/day/sec^3.

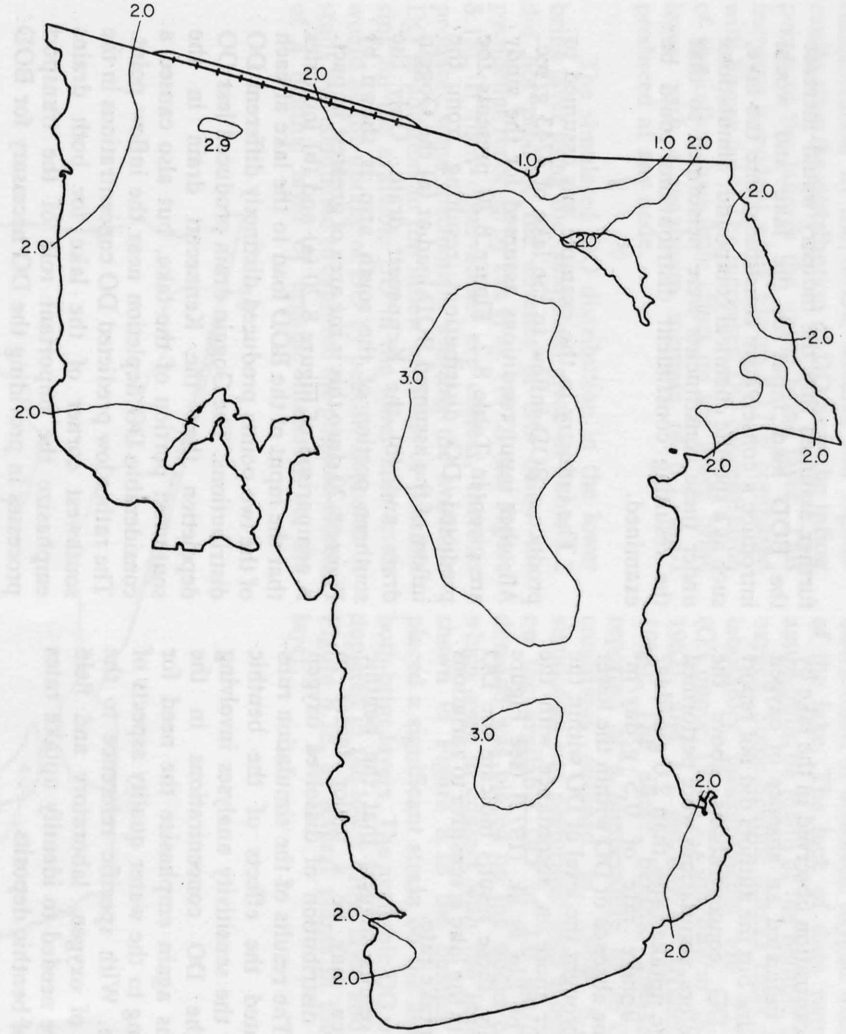

Figure 8.19. Equal contours of DO (mg/l) simulated in the upper brine layer with a benthic uptake rate of .5 g/day/sec^2.

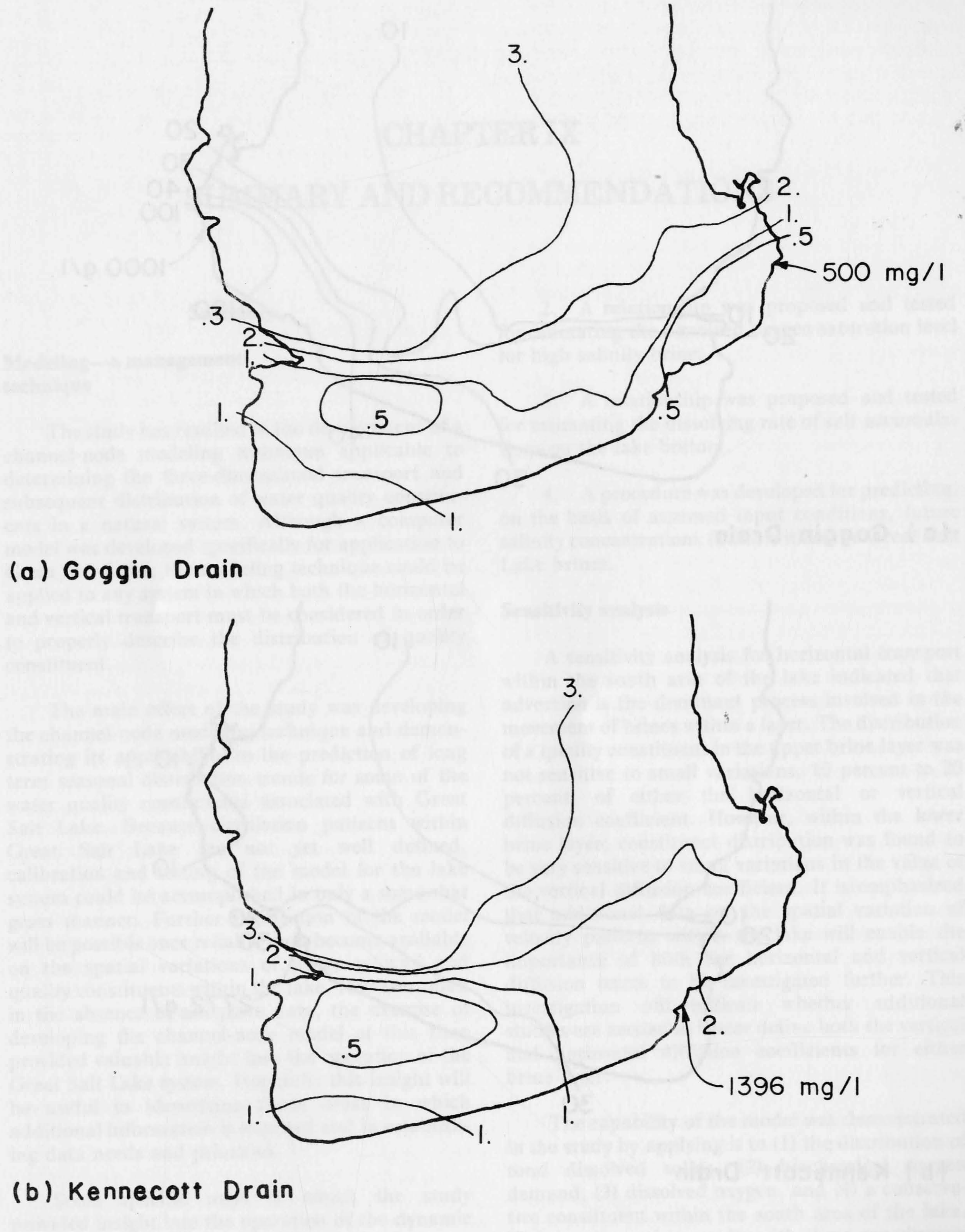

Figure 8.20. Equal contours of DO (mg/l) simulated for inflow from the Goggin drain and the Kennecott drain.

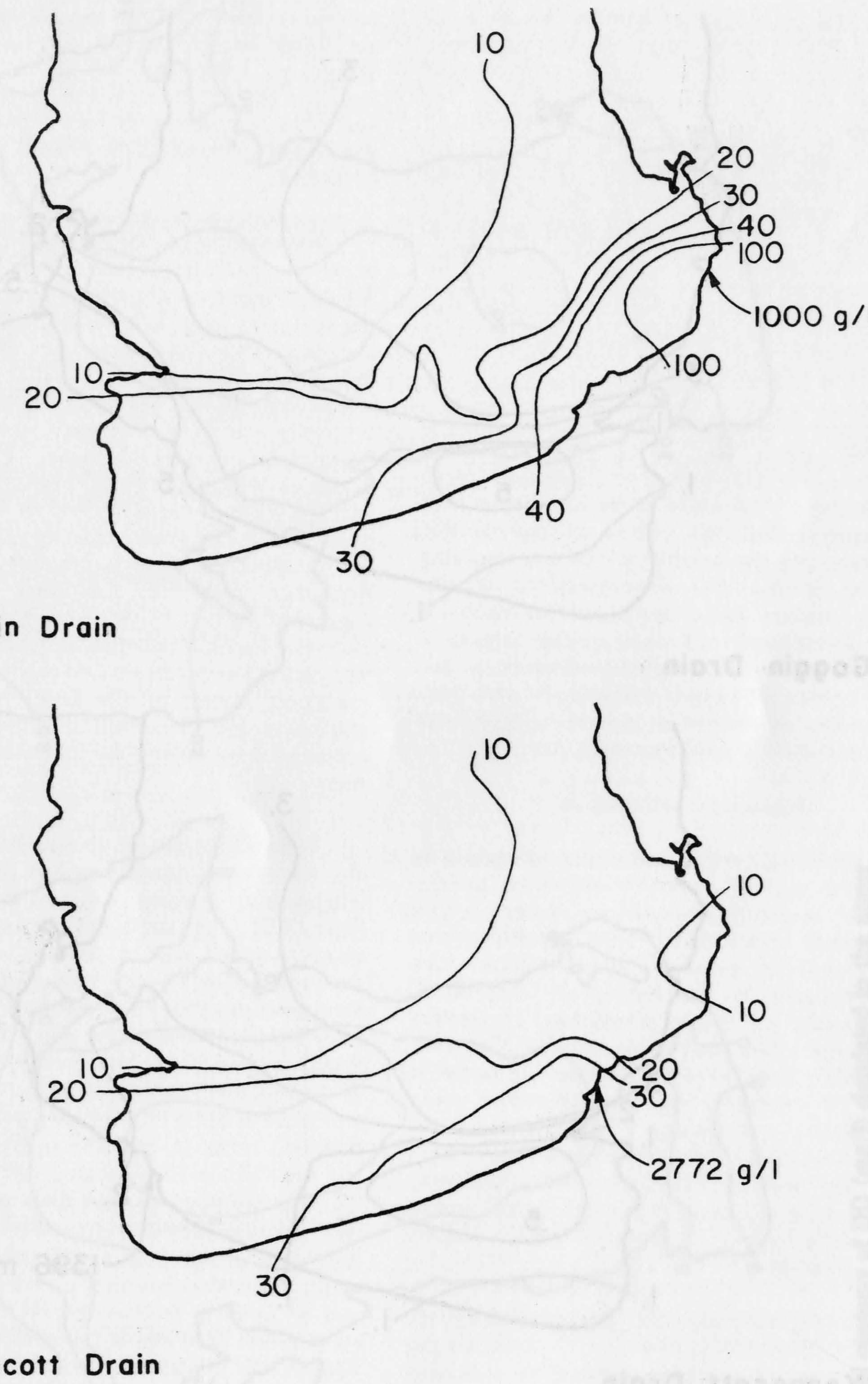

Figure 8.21. Equal contours of a conservative constituent simulated for inflow from the Goggin drain and the Kennecott drain.

CHAPTER IX

SUMMARY AND RECOMMENDATIONS

Summary

Modeling—a management technique

The study has resulted in the development of a channel-node modeling technique applicable to determining the three-dimensional transport and subsequent distribution of water quality constituents in a natural system. Although a computer model was developed specifically for application to Great Salt Lake, the modeling technique could be applied to any system in which both the horizontal and vertical transport must be considered in order to properly describe the distribution of quality constituent.

The main effort of the study was developing the channel-node modeling technique and demonstrating its applicability to the prediction of long term seasonal distribution trends for some of the water quality constituents associated with Great Salt Lake. Because circulation patterns within Great Salt Lake are not yet well defined, calibration and testing of the model for the lake system could be accomplished in only a somewhat gross manner. Further verification of the model will be possible once reliable data become available on the spatial variations of water velocity and quality constituents within the lake. However, even in the absence of adequate data, the exercise of developing the channel-node model at this time provided valuable insight into the operation of the Great Salt Lake system. Hopefully this insight will be useful in identifying those areas in which additional information is required and in establishing data needs and priorities.

Some specific ways in which the study provided insight into the operation of the dynamic system of Great Salt Lake are listed as follows:

1. A procedure was developed for determining the vertical diffusion coefficients from observed concentration profiles for total dissolved solids (TDS).

2. A relationship was proposed and tested for estimating the dissolved oxygen saturation level for high salinity brines.

3. A relationship was proposed and tested for estimating the dissolving rate of salt accumulations on the lake bottom.

4. A procedure was developed for predicting, on the basis of assumed input conditions, future salinity concentrations (TDS) within the Great Salt Lake brines.

Sensitivity analysis

A sensitivity analysis for horizontal transport within the south arm of the lake indicated that advection is the dominant process involved in the movement of brines within a layer. The distribution of a quality constituent in the upper brine layer was not sensitive to small variations, 10 percent to 20 percent, of either the horizontal or vertical diffusion coefficient. However, within the lower brine layer, constituent distribution was found to be very sensitive to small variations in the value of the vertical diffusion coefficient. It is emphasized that additional data on the spatial variation of velocity patterns within the lake will enable the importance of both the horizontal and vertical diffusion terms to be investigated further. This investigation will indicate whether additional studies are needed to better define both the vertical and horizontal diffusion coefficients for either brine layer.

The capability of the model was demonstrated in the study by applying it to (1) the distribution of total dissolved solids, (2) biochemical oxygen demand, (3) dissolved oxygen, and (4) a conservative constituent within the south area of the lake. The demonstration results with these constituents indicate that the model is a valuable management tool for examining the impacts of various possible management alternatives on individual water quality constituents and their interactions within the lake. A capability to predict management impacts in advance provides an opportunity for possible adverse effects on the system to be averted or minimized. This kind of management technique is especially important for Great Salt Lake, because as Stephens and Gillespie (1972) point out, the simple nature of the lake ecosystem makes it very susceptible to changes brought about by man.

Recommendations for Data Collection and Research

An important result of this study was the identification of areas where data gathering projects and specific studies should be undertaken.

Data needs

Several important data gaps relating to basic physical information became apparent during the model development process. The results suggested for example, that the causeway flow equations developed by Waddell and Bolke (1973), while giving good results at low lake stages, might not accurately predict causeway flows when south arm surface elevations are greater than 4,200 feet. The present flow equations were based on data which were gathered over a short time span and Waddell and Bolke themselves suggested that additional data be gathered in order to refine the equations. The present high lake stage would afford an ideal opportunity to obtain the needed data to improve the equations. The lake stage is continuously changing and this same opportunity might not be available again for some time.

The water quality model emphasized the need to obtain data pertaining to both the quality and quantity of flow at points of inflow to the lake. In most cases these data are difficult to obtain because the flows pass through marshlands bordering the lake. The outflow from the marshlands is generally diffused rather than confined to well defined channels. However, for management purposes, it is important to have information on changes which occur within the marshlands on both the quality and quantity of flows which enter the lake.

Important areas of data need as identified by the study are summarized as follows:

1. Systematic monitoring of the distribution of important water quality constituents within the lake.

2. Systematic monitoring of water quantity and quality inflows to the marshlands bordering the lake and to the lake itself.

3. Sampling of the lake brines with emphasis on improved delineation of the pycnocline and the vertical variations of salinity (TDS) below the pycnocline.

4. Sampling of the north arm in order to define temporal variations in the mass of precipitated salt.

5. A sampling program to provide improved definition of lake circulation patterns and water movement velocities within the lake as functions of time and space.

6. A program to provide improved definition of the lake bottom elevation contours.

7. Water quality and quantity data relating to flow through the Antelope Island and the Union Pacific causeways within the lake (both culvert and porous media flow).

Research needs

Effective management of any system requires that the system by sufficiently well understood to enable realistic predictions to be made of the consequences of proposed management changes. In this report, the study clearly identified some areas of inadequate system understanding from the viewpoint of effective management. Increased knowledge of the system is possible through research studies which are directed toward those areas of specific need, and some of these are discussed in the following paragraphs.

The modeling of the coupled constituents biochemical oxygen demand (BOD) and dissolved oxygen (DO) required that the values be estimated or assumed for all parameters involved in the summation of the internal sources and sinks term, except the dissolved oxygen saturation concentration. This same lack of basic information applies to the parameters in the internal sources and sinks terms for most lake constituents, including complex quality constituents such as coliform bacteria, algae, brine shrimp, and brine fly larvae.

The unique characteristics and harsh saline environment of the lake require that parameters which normally could be established from literature be re-examined under the specific conditions of the lake. An example of this need is the variation of the dissolved oxygen saturation level with TDS concentration for the lake. The dissolved oxygen saturation level has been established in detail for waters with total dissolved solids concentrations of less than 40 g/l. The occurrence of salinity concentration levels in this range are common in lakes, rivers, estuaries, and oceans. However, because of the unique nature of the lake, with salinity concentrations commonly exceeding 300 g/l, it was necessary to establish by laboratory experiment a relationship between dissolved oxygen saturation level and salinity concentrations in the high range. Many of the characteristics and parameters pertaining to other quality constituents could similarly be established by laboratory experiments rather than through investigations directly on the lake. Additional understanding through studies of this nature is required not only for comprehensive modeling of the lake system, but also for planning activities involving components of the total system, such as individual quality constituents.

It is encouraging to note that government agencies and private organizations are becoming increasingly more cognizant of the unique nature of Great Salt Lake and of the need to obtain additional information on many aspects of this system. For example, on October 15, 1975, a meeting was held in Salt Lake City between the National Oceanic and Atmospheric Administration (NOAA), members of the Great Salt Lake Division Board, and people from Utah State University involved in studying the lake. During this meeting, NOAA expressed interest in providing assistance in outlining a procedure for gathering data and for defining processes relating to transport within the lake. NOAA has gained extensive experience with this type of study on large lakes, such as Lake Ontario, and is in a position to provide valuable suggestions regarding a similar project for Great Salt Lake. On a note of caution, in order to effectively utilize the compatibilities of all groups which could become involved in data collection and research programs for Great Salt Lake, a well directed and coordinated research strategy is essential.

Some important areas of research need, as identified by this study, are summarized as follows. Because research studies usually imply data collection activities, some overlap occurs between the following list and the "data needs" identified in the previous section of this report.

1. Refinement of the equations of flow through causeways (refer to item 7 under "data needs").

2. A definition of changes in water quantities and qualities in the marshlands bordering the lake.

3. A determination of the interactions between both the living and nonliving components of the lake ecosystem.

4. Studies of the growth and decay rates of organisms in the lake.

5. Studies to determine the lethal concentrations of various chemicals for the organisms in the lake.

6. An examination of the effects of variations in the concentration of total dissolved solids on the growth, reproduction, and the utilization of food by the organic components of the lake system.

7. Studies involving quantifications of the parameters contained in the sources and sinks terms for various lake quality constituents, such as salinity (total dissolved solids), dissolved oxygen, and coliform bacteria.

8. An examination of the importance of specific transport processes involved at various depths within the lake. Advection, in particular, appears to be the dominant transport process in the upper portion of the lake (refer to item 5 under "data needs").

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APPENDIXES

APPENDIX A

CHANNEL-NODE WATER QUALITY MODEL

The channel-node water quality model consists of two programs; the data file program and the channel-node program. The data file program creates a data file of basic information related to the physical characteristics of the channels and nodes. This information is stored and serves as input to the channel-node program. The channel-node program performs the actual simulation of the distribution of quality constituents within the lake. Both the data file program and the channel-node program were programmed using Fortran IV and executed on a UNIVAC 1108 computer.

Data File Program

The data file program was designed to take basic information related to the characteristics of the channels and nodes and convert them to simplified form for storage and use in the channel-node program. Data are input to the program in the units of feet and miles. All data stored in the data file are converted to the length units of feet.

The channel parameters IENDL(I) and IENDH(I) represent the node numbers associated with the nodes which the channel connects. For bookkeeping purposes IENDL(I) is assigned the node number with the lower numerical value. A test was incorporated into the program to insure that IENDL(I) is less than IENDH(I). If this criteria is not met, an error message results which indicates the channel where the error occurred.

The channel parameter L2CA(I) and the node parameter L2NA(I) are used to indicate if the channel or node is located in the one or two layer portion of the lake. When these parameters have a value of zero, it indicates the channel or node is located in the single layer portion of the lake. These parameters are assigned a value of one when the channel or node is located in the portion of the lake where two layers exist. These parameters are assigned a one or zero in the data file rather than the yes or no which appears in the sample output. The sample output indicates which data are stored in the data file. Only the parameters indicated as "transferred" are stored. The locations where "no channel" or "no node" appear indicates the absence of values in the data file.

Table A-1. Parameters output on the data file.

INPUT DATA LAYOUT

	Col.		Identifier
Card 1	1-5	NR	Card input devise code
	6-10	NP	Output devise code for print
	11-15	NT	Output devise code for tape file

FORMAT (16I5)

	Col.		Identifier
Card 2	1-5	NN1	Number of nodes in upper layer
	6-10	NC1	Number of channels in upper layer
	11-15	NN2	Number of nodes in lower layer
	16-30	NC2	Number of channels in lower layer

FORMAT (16I5)

	Col.		Identifier
Card 3	1-5	DTINF	Depth to pycnocline (feet)

FORMAT (16F5.0)

Card 4 is repeated for NC1 channels varying I

	Col.		Identifier
Card 4	1-5	J	Channel number
	6-10	IENDL(I)	Lower of the two node numbers associated with the nodes the channel connects
	11-15	IENDH(I)	Higher of the two node numbers associated with the nodes the channel connects
	16-20	W(I)	Channel width (miles)
	21-25	CLTH(I)	Channel length (miles)
	26-30	L2CA(I)	0 - no channel exists in lower layer 1 - channel exists for both upper and lower layer

FORMAT (3I5, 2F5.0, I5)

Card 5 is repeated for NN1 nodes varying I.

	Col.		Identifier
Card 5	1-5	J	Node number
	6-10	L2NA(I)	0 - no node exists in lower brine 1 - node exists for both upper and lower brine
	11-15	ASURF(I)	Surface area of node (miles^2)
	16-20	TDN	Average depth of lake over the area of inflowing of the node (feet)

FORMAT(2I5, 2F5.0)

Table A-1. Parameters Output on the Data File.

The following is a list of the channel and node parameters output on the data file:

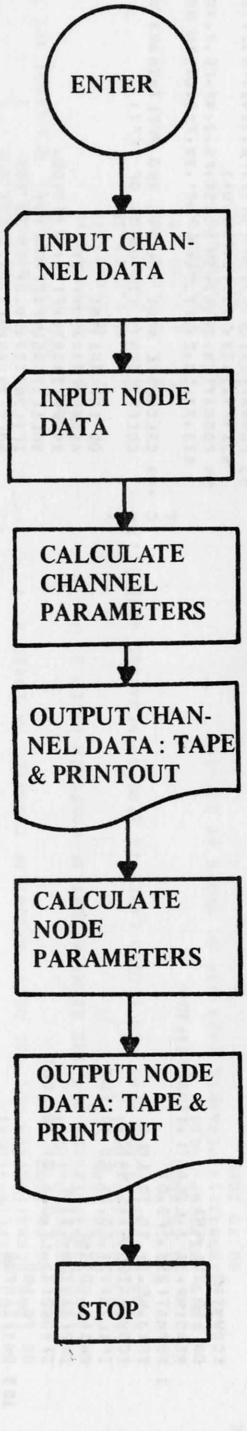
Channels:

Identifier	
L2CA(I)	Same as input
DC1(I)	Depth of channel in upper layer (feet)
DC2(I)	Depth of channel in lower layer (feet)
IENDL(I)	Same as input
IENDH(I)	Same as input
DIFUC1(I)	Cross sectional area of horizontal channel divided by the channel length for the upper layer (feet)
DIFUC2(I)	Cross sectional area of horizontal channel divided by the channel length for the lower layer (feet)
QCOEF1(I)	Cross sectional area of horizontal channel in upper layer (feet^2)
QCOEF2(I)	Cross sectional area of horizontal channel in lower layer (feet^2)

Nodes:

Identifier	
L2NA(I)	Same as input
DN1(I)	Depth of node in upper layer (feet)
DN2(I)	Depth of node in lower layer (feet)
ASURF(I)	Surface area of node (feet^2)
VOL1(I)	Volume of node in upper layer (feet^3)
VOL2(I)	Volume of node in lower layer (feet^3)
VDIFUC(I)	Surface area of node divided by the vertical channel length (feet)

DATA FILE PROGRAM



DATA FILE PROGRAM LISTING

```
C *** PROGRAM TO REDUCE AND SUMMARIZE BASIC GRID DATA
      DIMENSION ASURF(380),CLTH(750),DC1(750),DC2(750),DIFUC1(750),
     1DIFUC2(750),DN1(380),DN2(380),IENDL(750),IENDH(750),L2CA(750),
     2L2NA(380),QCOEF1(750),QCOEF2(750),VDIFUC(750),VOL1(380),VOL2(380),
     3W(750),ASURFM(380)
      READ(5,1) NR,NP,NT
      READ(NR,1) NN1,NC1,NN2,NC2
    1 FORMAT(16I5)
      READ(NR,2) DTINF
    2 FORMAT(16F5.0)
C
C *** CHANNEL DATA
C
      ICOUNT=0
      DO 100 I=1,NC1
      READ(NR,5) J,IENDL(I),IENDH(I),W(I),CLTH(I),L2CA(I)
    5 FORMAT(3I5,2F5.0,I5)
      IF(J.NE.I) GO TO 1009
      ICOUNT=ICOUNT+L2CA(I)
  100 IF(IENDL(I).GE.IENDH(I)) GO TO 1001
      IF(ICOUNT.NE.NC2) GO TO 1003
C
C *** NODE DATA
C
      ICOUNT=0
      DO 102 I=1,NN1
      READ(NR,3) J,L2NA(I),ASURF(I),TDN
    3 FORMAT(2I5,2F5.0)
      IF(J.NE.I) GO TO 1011
      ICOUNT=ICOUNT+L2NA(I)
      IF(L2NA(I).EQ.0) GO TO 103
      DN1(I)=DTINF
      DN2(I)=TDN-DTINF
      IF(DN2(I).LE.0.) GO TO 1007
      GO TO 102
  103 DN1(I)=TDN
  102 CONTINUE
      IF(ICOUNT.NE.NN2) GO TO 1005
C
C *** CALCULATETHE AVG DEPTH OF EACH CHANNEL,THE PRELIMINARY HORIZONTAL
C     DIFFUSOON COEFFICIENTS,AND FLOW COEFFICIENTS(IN UNITS OF FEET)
C
      DO 104 I=1,NC1
      IL=IENDL(I)
      IH=IENDH(I)
      DC1(I)=(DN1(IL)+DN1(IH))/2.
      DIFUC1(I)=W(I)*DC1(I)/CLTH(I)
      QCOEF1(I)=W(I)*DC1(I)*5280.
      IF(L2CA(I).EQ.0) GO TO 104
      IF(L2NA(IL).NE.1.OR.L2NA(IH).NE.1) GO TO 1013
      DC2(I)=(DN2(IL)+DN2(IH))/2.
      DIFUC2(I)=W(I)*DC2(I)/CLTH(I)
      QCOEF2(I)=W(I)*DC2(I)*5280.
  104 CONTINUE
C
C *** OUTPUT CHANNEL DATA
C
C *** OUTPUT ON TAPE
      WRITE(NT) (L2CA(I),I=1,NC1)
      WRITE(NP,51)
   51 FORMAT(52X,12HCHANNEL DATA //)
      WRITE(NP,252)
  252 FORMAT(10X,7H***T***,23X,'****************************************** TRANSF
     $ERED *************************************')
      WRITE(NP,52)
   52 FORMAT(1X,'CHANNEL  LAYER 2  CHANNEL    CHANNEL    CHANNEL DEPTH  C
     $HANNEL DEPTH  LOW    HIGH  DIFUC1  DIFUC2       QCOFF1       QCOEF2',/,
     $1X, ' NUMBER    ASSOC.  WIDTH,MI  LENGTH,MI  LAYER 1,FEET   LAYER 2
     $,FEET   NODE  NODE  FEET     FEET        FEET**2     FEET**2'/)
      DO 106 I=1,NC1
      IF(L2CA(I).EQ.0) GO TO 105
      WRITE(NP,53) I,W(I),CLTH(I),DC1(I),DC2(I),IENDL(I),IENDH(I),DIFUC1
     $(I),DIFUC2(I),QCOEF1(I),QCOEF2(I)
      WRITE(NT) DC1(I),DC2(I),IENDL(I),IENDH(I),DIFUC1(I),DIFUC2(I),
     $QCOEF1(I),QCOEF2(I)
      GO TO 106
  105 WRITE(NP,54) I,W(I),CLTH(I),DC1(I),IENDL(I),IENDH(I),DIFUC1(I),
     $QCOEF1(I)
      WRITE(NT) DC1(I),IENDL(I),IENDH(I),DIFUC1(I),QCOEF1(I)
  106 CONTINUE
   53 FORMAT(2X,I4,6X,3HYES,5X,F6.2,4X,F6.2,7X,F6.2,9X,F6.2,6X,I3,3X,I3,
     $2X,F7.2,1X,F7.2,2(F11.0))
   54 FORMAT(2X,I4,6X,3H NO,5X,F6.2,4X,F6.2,7X,F6.2,8X,10HNO CHANNEL,3X,
     $I3,3X,I3,2X,F7.2,4X,'NC',2X,F11.0,11H NO CHANNEL )
C
C *** CALCULATE NODE VOLUMES AND PRELIMINARY VERTICAL DIFFUSION
C     COEFFICIENTS (IN UNITS OF FEET)
C
      DO 107 I=1,NN1
      ASURFM(I)=ASURF(I)
      ASURF(I)=ASURF(I)*27878400.
      VOL1(I)=ASURF(I)*DN1(I)
      IF(L2NA(I).EQ.0) GO TO 107
      VOL2(I)=ASURF(I)*DN2(I)
      VDIFUC(I)=ASURF(I)/((DN1(I)+DN2(I))/2.)
  107 CONTINUE
C
C *** OUTPUT NODE DATA
C
C *** OUTPUT ON TAPE
      WRITE(NT) (L2NA(I),I=1,NN1)
      WRITE(NP,55)
   55 FORMAT(1H1,45X,10H NODE DATA //)
      WRITE(NP,256)
  256 FORMAT(9X,7H***T***,40X,'************************* TRANSFERED * ******
     $***************')
      WRITE(NP,56)
   56 FORMAT(1X,' NODE    LAYER 2  NODE DEPTH  NODE DEPTH  SURFACE AREA
     $SURFACE AREA   NODE VOLUME     NODE VOLUME       VDIFUC,FT',/,1X,'NUM
     $BER  ASSOC.   LAYER 1,FT  LAYER 2,FT     MILES**2         FEET**2
     $LAYER 1,FT**3  LAYER 2,FT**3'/)
```

```
      DO 108 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 109
      WRITE(NP,57) I,DN1(I),DN2(I),ASURFM(I),ASURF(I),VOL1(I),VOL2(I),
     $VDIFUC(I)
      WRITE(NT) DN1(I),DN2(I),ASURF(I),VOL1(I),VOL2(I),VDIFUC(I)
      GO TO 108
  109 WRITE(NP,58) I,DN1(I),ASURFM(I),ASURF(I),VOL1(I)
      WRITE(NT) DN1(I),ASURF(I),VOL1(I)
  108 CONTINUE
   57 FORMAT(3X,I3,5X,3HYES,2(7X,F5.2),7X,F6.2,5X,F12.0,2X,F13.0,2X,
     $F13.0,2X,F11.0)
   58 FORMAT(3X,I3,5X,3H NO,7X,F5.2,5X,7HNO NODE,7X,F6.2,5X,F12.0,2X,
     $F13.0,8X,7HNO NODE,6X,7HNO NODE )
      GO TO 1000
 1001 WRITE(NP,1002) I
 1002 FORMAT(1X,9H IEND I= ,I5)
      GO TO 1000
 1003 WRITE(NP,1004)
 1004 FORMAT(1X,44H NOT THE RIGHT AMOUNT OF CHANNELS IN LAYER 2  )
      GO TO 1000
 1005 WRITE(NP,1006)
 1006 FORMAT(1X,41H NOT THE RIGHT AMOUNT OF NODES IN LAYER 2  )
      GO TO 1000
 1007 WRITE(NP,1008) I
 1008 FORMAT(1X,50H DEPTH IN SECOND LAYER IS ZERO OR NEGATIVE WITH I=,I4
     $)
      GO TO 1000
 1009 WRITE(NP,1010)I
 1010 FORMAT(1X,'CHANNEL DATA OUT OF ORDER AT I=',I4)
      GO TO 1000
 1011 WRITE(NP,1012) I
 1012 FORMAT(1X'NODE DATA OUT OF ORDER AT I=',I4)
      GO TO 1000
 1013 WRITE(NP,1014) I
 1014 FORMAT(1X,'AT I=',I5,' A NODE FOR CHANNEL I IS NOT INCLUDED IN LAY
     $ER 2')
 1000 STOP
      END
```

SAMPLE INPUT

```
CARD 1
   5    6    9
CARD 2
  373  746  144  254
CARD 3
  25.
CARD 4
    1    1     2.7302.000     0
    2    2    31.0001.000     0
    3    3    41.0001.000     0
    4    4    51.0001.000     1
    5    5    61.0001.000     1
    6    6    71.0001.000     1
    7    7    81.0001.000     1
    8    8    91.0001.000     1
    9    9   101.0001.000     1
   10   10   111.0001.000     1
      ... REPEAT UNTIL NC1 CARDS ARE INPUT ...
CARD 5
    1    0 2.8710.10
    2    0 1.0821.75
    3    0 1.0024.35
    4    1 1.0026.55
    5    1 1.0028.65
    6    1 1.0029.95
    7    1 1.0030.42
    8    1 1.0030.67
    9    1 1.0030.70
   10    1 1.0030.46
      ... REPEAT UNTIL NN1 CARDS ARE INPUT ...
```

SAMPLE OUTPUT

CHANNEL DATA

CHANNEL NUMBER	***T*** LAYER 2 ASSOC.	CHANNEL WIDTH,MI	CHANNEL LENGTH,MI	CHANNEL DEPTH LAYER 1,FEET	CHANNEL DEPTH LAYER 2,FEET	LOW NODE	HIGH NODE	DIFUC1 FEET	DIFUC2 FEET	QCOEF1 FEET**2	QCOFF2 FEET**2
				************************************* TRANSFERED	***********************************						
1	NO	.73	2.00	15.92	NO CHANNEL	1	2	5.81	NC	61381.	NC CHANNEL
2	NO	1.00	1.00	23.05	NO CHANNEL	2	3	23.05	NC	121704.	NO CHANNEL
3	NO	1.00	1.00	24.67	NC CHANNEL	3	4	24.67	NC	130284.	NO CHANNEL
4	YES	1.00	1.00	25.00	2.60	4	5	25.00	2.60	132000.	13728.
5	YES	1.00	1.00	25.00	4.30	5	6	25.00	4.30	132000.	22704.
6	YES	1.00	1.00	25.00	5.19	6	7	25.00	5.19	132000.	27377.
7	YES	1.00	1.00	25.00	5.55	7	8	25.00	5.55	132000.	29270.
8	YES	1.00	1.00	25.00	5.69	8	9	25.00	5.69	132000.	30017.
9	YES	1.00	1.00	25.00	5.58	9	10	25.00	5.58	132000.	29452.
10	YES	1.00	1.00	25.00	5.20	10	11	25.00	5.26	132000.	27773.

:

REPEAT FOR NC1 CHANNELS

NODE DATA

NODE NUMBER	***T*** LAYER 2 ASSOC.	NODE DEPTH LAYER 1,FT	NODE DEPTH LAYER 2,FT	SURFACE AREA MILES**2	SURFACE AREA FEET**2	NODE VOLUME LAYER 1,FT**3	NODE VOLUME LAYER 2,FT**3	VDIFUC,FT
					************************ TRANSFERED	************************		
1	NO	10.10	NO NODE	2.87	80011008.	808111176.	NO NODE	NO NODE
2	NO	21.75	NO NODE	1.08	30108672.	654863608.	NO NODE	NO NODE
3	NO	24.35	NO NODE	1.00	27878400.	678839632.	NO NODE	NO NODE
4	YES	25.00	1.55	1.00	27878400.	696960000.	43211518.	2100068.
5	YES	25.00	7.65	1.00	27878400.	696960000.	101756152.	1946136.
6	YES	25.00	4.95	1.00	27878400.	696960000.	137993080.	1861663.
7	YES	25.00	5.42	1.00	27878400.	696960000.	151100930.	1832839.
8	YES	25.00	5.67	1.00	27878400.	696960000.	158070570.	1817959.
9	YES	25.00	5.70	1.00	27878400.	696960000.	158060380.	1816182.
10	YES	25.00	5.49	1.00	27878400.	696960000.	152218064.	1830492.

:

REPEAT FOR NN1 NODES

Channel-Node Program

The channel-node program performs the actual simulation of the distribution of quality constituents within the lake. The program is organized as a main driver and a series of subroutines which perform specific functions. The main driver of the program serves as the coordinator of the subroutines, initializes the various parameters, and performs calculations common to all the quality constituents. Thus, the calculation of advection, diffusion, and the summation of external sources and sinks during each time step is performed in the main driver.

The input of data is performed by the NCD subroutine. Data are input to the program from the data file created by the data file program and card input. The card input is designed with several options so that data can be efficiently input. The use of the parameters IQ1 and IQ2 allows the operator to choose to input channel velocities (ft/sec) or channel flows (cfs) for either layer. The direction of flow within a channel is determined from the positive or negative sign associated with the channel velocity or channel flow. The flow is input as positive when it flows from the low node to the high node it connects or from IENDL(I) to IENDH(I). Flow in the reverse direction is assigned a negative value.

The parameters IDC1(I), IDC2(I), and IDC3(I) allow the operator to choose a single initial value of constituent concentration which will be assigned to all nodes of a specific layer or to input a specific initial concentration for each node of a layer. The use of these parameters allows this option to be applied to each constituent for each layer.

In a system such as Great Salt Lake, the number of channels and nodes within the lower brine layer is significantly lower than the number of channels and nodes within the upper brine layer. In order to reduce the input, the program was designed so that data related to channel flows and initial node concentrations are only input for the channels and nodes which exist in the lower brine layer. Such data are input in increasing order of channel numbers or node numbers skipping the nodes or channels which do not exist in the lower layer.

The output from the channel-node program can be varied. The program contains a parameter, ISKIP, which provides an option to suppress the output of information concerning channel flows and the initial constituent concentrations at each node. When this option allows the output of these initial conditions it requires a line for each channel and each node of the upper layer plus a line for each lake bottom node. When the lake bottom concentrations are not required, the program contains an additional parameter, IBB, which allows the output of the lake bottom concentrations to be skipped.

The remainder of the output from the channel-node program consists of the simulated node concentrations. Each time the output is requested a line of output is required for each upper layer node. Each line contains the concentrations for each constituent at nodes in the upper and lower layers. The lake bottom concentrations are output separately and require one line for each node. The IBB option can be used to suppress this output.

The simulated node concentrations are output at the end of the simulation period. This corresponds to the program completing the simulation for NTS time steps. The parameter NPOUT can be used to output the simulated node concentrations at intermediate time steps. For example, if NTS was 300 the node concentrations could be output at half the total simulation period by setting NPOUT at 150. Similarly, NPOUT would be set at 100 to obtain the node concentrations after each 100 time steps.

The computer time required to perform a simulation for a particular constituent varies with the complexity of the subroutine which accounts for the internal sources and sinks of the constituent. With a grid network composed of 746 channels and 373 nodes in the upper layer and 254 channels and 144 nodes in the lower layer, the channel-node program required 54 seconds of computer use time to simulate the distribution of a conservative constituent over 720 time steps. The computer use time was increased to 166 seconds when the program was used to simultaneously simulate the distribution of a conservative constituent and the non-conservative coupled constituents biochemical oxygen demand and dissolved oxygen.

INPUT DATA LAYOUT

	Col.	Identifier	
Card 1	1-5	NR	Card input devise code
	6-10	NP	Output devise code for print
	11-15	NRT	Output devise code for tape file
		FORMAT(16I5)	
Card 2	1-5	NN1	Number of nodes in upper brine layer
	6-10	NC1	Number of channels in upper brine layer
	11-15	NN2	Number of nodes in lower brine layer
	16-20	NC2	Number of channels in lower brine layer
	21-25	NCONST	Number of quality constituents modeled
	26-30	NIF1	Number of inflows to upper brine layer
	31-35	NIF2	Number of inflows to lower brine layer
	36-40	NOF1	Number of outflows from upper brine layer
	41-45	NOF2	Number of outflows from lower brine layer
	46-50	NTS	Number of time step
	51-55	NPOUT	Number of time steps between output of node concentrations
	56-60	NTDS	Number associated with the quality constituent TDS
	61-65	NLN	Number of first quality constituent to be simulated (included so that the TDS concentration could be held constant)
		FORMAT (16I5)	
Card 3	1-5	ISKIP	0 - skip output of initial conditions 1 - output initial conditions
	6-10	IBB	0 - skip output of concentration at lake botton grid points 1 - output lake botton grid points
	11-15	IQ1	0 - input channel velocities for upper brine 1 input channel flows for upper layer
	16-20	IQ2	(same as IQ1 for lower brine layer)
		FORMAT (16I5)	
Card 4	1-10	DELT	Time step (hours)
	11-20	FRAC	Upstream factor (Table 7. 1)
	21-30	CFM	Conversion from cubic feet to liters
	31-40	VS	BOD settling velocity (ft/sec)
	41-50	BUR	Benthic uptake rate of DO (grams/meter^2/day)
	51-60	E1C	Horizontal diffusion coefficient for layer 1 (ft^2/sec)
	61-70	E2C	Horizontal diffusion coefficient for layer 2 (ft^2/sec)
	71-80	EVC	Vertical diffusion coefficient (ft^2/sec)
	1-10	TEMP	Temperature of brine (^{o}C)
	11-20	THETA	Temperature correction factor for BOD decay
		FORMAT (8F10. 0)	
Card 5	1-10	RDIS	TDS dissolving constant (Days^{-1})
		FORMAT (8F10. 0)	
Card 6	1-4	NAMEC(1)	Identifier for constituent 1
	.	.	.
	.	.	.
	.	.	.
		NAMEC(NCONST)	Identifier for constituent NCONST
		FORMAT (20A4)	
Card 7	1-4	AHEAD(1)	
	.	.	
	.	.	Output heading
	.	.	
	17-20	AHEAD(5)	
		FORMAT (20A4)	
Card 8	1-4	BHEAD(1)	
	.	.	
	.	.	Output heading
	.	.	
	17-20	BHEAD(5)	
		FORMAT (20A4)	
Card	1-4	CHEAD(1)	Output heading
	5-8	CHEAD(2)	
		FORMAT (20A4)	
Card 10	1-10	AD	Aerobic BOD decay rate for brine (day^{-1})
	11-20	AM	Anaerobic BOD decay rate for brine (day^{-1})
	21-30	ADB	Aerobic BOD decay rate for benthic deposits (day^{-1})
	31-40	AMB	Anaerobic BOD decay rate for benthic deposits (day^{-1})
	41-50	AR	Constants involved in calculating reaeration coefficient (see Equation 5. 30)
	51-60	P1	
	61-70	P2	
		FORMAT (8F10. 0)	
Card 11	1-5	ICALL(1)	
	.	.	Indicate subroutine to be called to calculated the internal sources and sinks of constituent 1
	.	.	
	.	.	
	.	ICALL(NCONST)	same for constituent NCONST
		For a conservative constituent set ICALL = 0	
		FORMAT (16I5)	
Card 12	If IQ1 0		
	1-5	V1(1)	Velocity in channel 1 of upper layer (ft/sec)
	.	.	
	.	.	
	.	.	
		V1(NC1)	Velocity in channel NC1 of upper layer
		FORMAT (16I5)	
	If IQ1 1		
	1-10	Q1(1)	Flow in channel 1 of upper layer (cfs)
	.	.	
	.	.	
	.	.	
		Q1(NC1)	Flow in channel NC1 of upper layer
		FORMAT (8F10. 0)	
Card 13	If IQ2 = 0		
	1-5	AV2(1)	Channel velocity for first channel in lower layer (ft/sec)
	.	.	
	.	.	
	.	.	
		AV2(NC2)	Channel velocity for last channel in lower layer
		FORMAT (16F5. 0)	
	If IQ2 = 1		
	1-10	AQ2(1)	Flow in first channel in lower layer (cfs)

Card	Col.	Identifier	
Card 13 Cont	.	.	
	.	.	
		AQ2(NC2)	Flow in last channel in lower layer (cfs)
		FORMAT (8F10.0)	
Card 14	1-5	IDC1(1)	0 - the initial concentration of constituent 1 in all the upper brine layer nodes is to be set at a constant value
	.	.	1 - the inital concentration of constituent 1 is to be read for each upper brine layer node
		IDC1(NCONST)	same as above for constituent NCONST
		FORMAT (16I5)	
Card 15	1-5	IDC2(1)	same as IDC1(1) but for the lower layer nodes
	.	.	
		IDC2(NCONST)	same as above for constituent NCONST
		FORMAT (16I5)	
Card 16	1-5	IDC3(1)	same as IDC1(1) but for the lake bottom nodes
	.	.	
		IDC3(NCONST)	same as above for constituents NCONST
		FORMAT (16I5)	
Card 17	1-5	CI1(1)	Initial concentration of quality constituent 1 for nodes in upper layer. Used when IDC1(1) = 0 (g/l)
	.	.	
		CI1(NCONST)	same as CI1(1) for constituent NCONST
		FORMAT (16F5.0)	
Card 18	1-5	CI2(1)	Same as CI1 (1) but for the lower layer nodes (g/l)
	.		
		CI2(NCONST)	Same as CI2(1) but for constituent NCONST
		FORMAT (16F5.0)	
Card 19	1-5	CI3(1)	Same as CI1(1) but for the lake bottom nodes (g/ft^2)
	.	.	
		CI3(NCONST)	Same as CI=(1) but for constituent NCONST
		FORMAT (16F5.0)	

Repeat for N = 1, NCONST
Option: If IDC1(N) = 0 SKIP 20

Card	Col.	Identifier	
Card 20	1-5	C1(N, 1)	Initial concentration of quality out constituent N for node 1 in upper layer (g/l)
	.	.	
		C1(N, NN1)	Same as C1(N, 1) but for node NN1
		FORMAT (16F5.0)	

Repeat for N = 1, NCONST
Option: If IQC2(N) = 0 SKIP 21

Card	Col.	Identifier	
Card 21	.	AC2(N, 1)	Initial concentration of quality constituent N for first node in lower layer (g/l)
	.	.	
		AC2(N, NN2)	Same as C2 (N, 1) but for last node in lower layer.
		FORMAT (16F5.0)	

Repeat for N = 1, NCONST
Option: If IDC3(N) = 0 SKIP 22

Card	Col.	Identifier	
Card 22	1-5	C3(N, 1)	Initial concentration of quality constituent N for node 1 on lake bottom (g/ft^2)
	.	.	
		C3(N, NN1)	Same as C3(N, 1) but for node NN1
		FORMAT (16F5.0)	

Option: If NIF1 = 0 SKIP 23
Repeat for I = 1, NIF1

Card	Col.	Identifier	
Card 23	1-5	J	Upper layer node receiving inflow
	6-10	QIN1(J)	Inflow rate (cfs)
	11-15	CIN1(1, J)	Concentration of constituent 1 associated with the inflow (g/l)
	.	.	
		CIN1(NCONST, J)	Concentration of constituent NCONST associated with the inflow
		FORMAT (16F5.0)	

Option: If NIF2 = 0 SKIP 24
Repeat for I = 1, NIF2

Card	Col.	Identifier	
Card 24	1-5	J	Lower layer node receiving inflow
	6-10	QIN2(J)	Inflow rate (cfs)
	11-15	CIN2(1, J)	Concentration of constituent 1 associated with the inflow (g/l)
	.	.	
		CIN2(NCONST, J)	Concentration of constituent NCONST associated with the inflow
		FORMAT (16F5.0)	

Option: If NOF1 = 0 SKIP 25
Repeat for I = 1, NOF1

Card	Col.	Identifier	
Card 25	1-5	J	Upper layer node from which outflow occurs
	6-10	QOUT(J)	Outflow rate (cfs)
		FORMAT (16F5.0)	

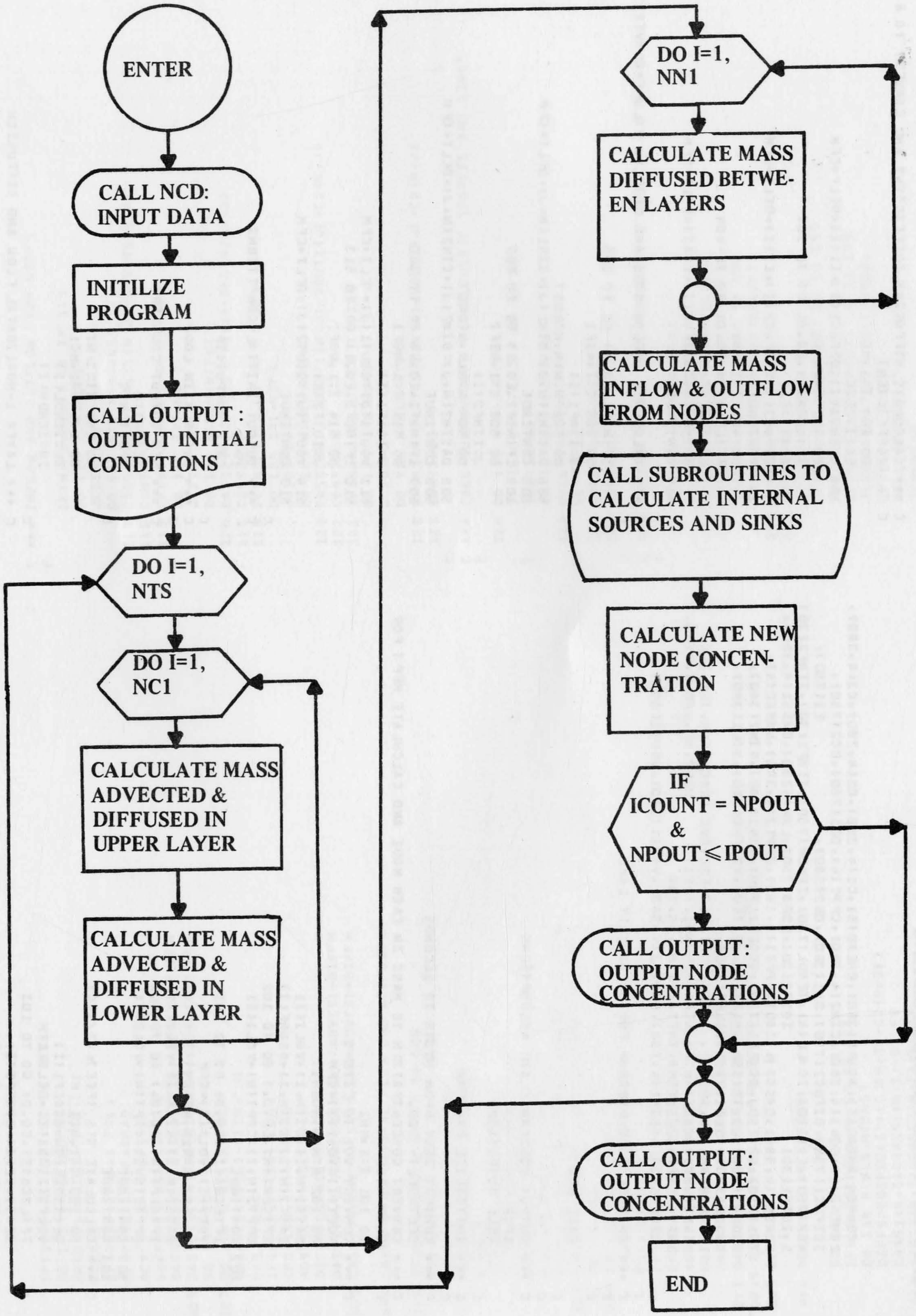
Option: If NOF2 = 0 SKIP 26
Repeat for I = 1, NOF2

Card	Col.	Identifier	
Card 26	1-5	J	Lower layer node from which outflow occurs
		QOUT2(J)	Outflow rate (cfs)
		FORMAT (16F5.0)	
Card 27	1-5	CPPT(1)	Saturation concentration of constituent 1. Use zero if not applicable.
	.	.	
		CPPT(NCONST)	Same as CPPT(1) but for constituent NCONST
		FORMAT (16F5.0)	

Table A-2. Principal variables in the channel-node water quality model.

Variable	Description
ASURF(I)	Surface area of node I
C1(N, I)	Concentration of constituent N in node I of the upper layer
C2(N, I)	Concentration of constituent N in node I of the lower layer
C3(N, I)	Concentration of constituent N associated with node I of the lake bottom
CIN1(N, I)	Concentration of constituent N in the inflow to node I of the upper layer
CIN2(N, I)	Concentration of constituent N in the inflow to node I of the lower layer
CLTH(I)	Length of channel I
CPPT(N)	Saturation concentration for constituent N
DASS1(N, I)	Mass of constituent N in node I of the upper layer
DASS2(N, I)	Mass of constituent N in node I of the lower layer
DASS3(N, I)	Mass of constituent N associated with node I of the lake bottom
DC1(I)	Depth of channel I of the upper layer
DC2(I)	Depth of channel I of the lower layer
DIFUC1(I)	Cross sectional area divided by the channel length for Channel I of the upper layer
DIFUC2(I)	Cross sectional area divided by the channel length for channel I of the lower layer
DN1(I)	Depth of node I of the upper layer
DN2(I)	Depth of node I of the lower layer
DPPT1(N, I)	Mass of constituent N which will create saturation in node I of the upper layer
DPPT2(N, I)	Mass of constituent N which will create saturation in node I of the lower layer
IENDL(I)	Lower node number of the two nodes channel I connects
IENDH(I)	Higher node number of the two nodes channel I connects
IINF1(I)	Indicates node I of the upper layer receives inflow
IINF2(I)	Indicates node I of the lower layer receives inflow
IOTF1(I)	Indicates there is an outflow from node I of the upper layer
IOTF2(I)	Indicates there is an outflow from node I of the lower layer
L2CA(I)	Indicates if the channel exists in both brine layers
L2NA(I)	Indicates if the node exists in both brine layers
NAMEC(N)	Alphameric identifier for constituent N
Q1(I)	Flow rate in channel I of the upper layer
Q2(I)	Flow rate in channel I of the lower layer
QCOEF1(I)	Cross sectional area of channel I of the upper layer
QCOEF2(I)	Cross sectional area of channel I of the lower layer
QIN1(I)	Inflow to node I of the upper layer
QIN2(I)	Inflow to node I of the lower layer
QOUT1(I)	Outflow from node I of the upper layer
QOUT2(I)	Outflow from node I of the lower layer
V1(I)	Velocity of flow in channel I of the upper layer
V2(I)	Velocity of flow in channel I of the lower layer
VDIFUC(I)	Cross sectional area divided by the channel length for vertical channel I
VOL1(I)	Volume of node I of the upper layer
VOL2(I)	Volume of node I of the lower layer
VOLF1(I)	Volume of flow in channel I of the upper layer
VOLF2(I)	Volume of flow in channel I of the lower layer
W(I)	Width of channel I

CHANNEL-NODE PROGRAM



CHANNEL—NODE PROGRAM LISTING

```
      COMMON AHEAD(5),ASURF(380),BHEAD(5),C1(4,380),C2(4,380),C3(4,380),
     2CHEAD(5),CIN1(4,380),CIN2(4,380),CPPT(4),DC1(750),DC2(750),
     3DIFUC1(750),DIFUC2(750),DN1(380),DN2(380),                E1(750),
     4E2(750),EV(380),ICALL(4),IENDL(750),IENDH(750),IINF1(30),IINF2(30)
     5,IOTF1(30),                 IOTF2(30),L2CA(750),L2NA(380),DASS1(4,380),
     6DASS2(4,380),DASS3(4,380),DPPT1(4,380),DPPT2(4,380),NAMEC(4),
     7Q1(750),Q2(750),QCOEF1(750),QCOEF2(750),QIN1(380),QIN2(380),
     8QOUT1(380),QOUT2(380),V1(750),V2(750),VDIFUC(380),VOL1(380),
     9VOL2(380),VOLF1(750),VOLF2(750),
     1AD,ADB,AM,AMB,AP,BUR,    CFM,DELT,E1C,E2C,EVC,FRAC,IBUR,IE1,IE2,
     2ISKIP,NC1,NCONST,NIF1,NIF2,NLN,NN1,NOF1,        NOF2,NP,NPOUT,NTDS,
     3NTS,P1,P2,ROIS,TEMP,THETA,TTIME,VS,IBB
      DIMENSION DASIN1(4,380),DASIN2(4,380),VOUT1(380),VOUT2(380)
C
C *** CHANNEL NODE PROGRAM FOR GREAT SALT LAKE
C
C
      CALL NCD
C
C
C *** OUTPUT CONSTANTS AND ASSUMPTIONS
      IP=2
      CALL OUTPUT(IP)
C
C *** INITIALIZE PROGRAM
C
C *** CONVERT DELT FROM HOURS TO SECONDS
      DELT=DELT*3600.
C *** CONVERT CONCENTRATION TO MASS IN EACH NODE AND CALCULATE MPPT FOR
C     EACH NODE
      DO 101 I=1,NN1
C *** CONVERT VOL TO LITERS
      VOL1(I)=VOL1(I)*CFM
      DO 102 N=NLN,NCONST
      DASS1(N,I)=C1(N,I)*VOL1(I)
      DASS3(N,I)=C3(N,I)*ASURF(I)
      IF(CPPT(N).LE.0.) GO TO 102
      DPPT1(N,I)=CPPT(N)*VOL1(I)
  102 CONTINUE
      IF(L2NA(I).EQ.0) GO TO 101
      VOL2(I)=VOL2(I)*CFM
      DO 502 N=NLN,NCONST
      DASS2(N,I)=C2(N,I)*VOL2(I)
      IF(CPPT(N).LE.0.) GO TO 502
      DPPT2(N,I)=CPPT(N)*VOL2(I)
  502 CONTINUE
  101 CONTINUE
C *** CALCULATE Q'S (FEET**3/SEC)
      DO 103 I=1,NC1
      Q1(I)=V1(I)*QCOEF1(I)
      VOLF1(I)=Q1(I)*DELT*CFM
      IF(L2CA(I).EQ.0) GO TO 103
      Q2(I)=V2(I)*QCOEF2(I)
      VOLF2(I)=Q2(I)*DELT*CFM
  103 CONTINUE
C *** CALCULATE DIFFUSION COEFFICIENT AND CONVERT TO A TOTAL DIFFUSION
C     COEFFICIENT
      DO 104 I=1,NC1
      E1(I)=E1C
  104 DIFUC1(I)=DIFUC1(I)*E1(I)*DELT*CFM
      DO 307 I=1,NC1
      IF(L2CA(I).EQ.0) GO TO 307
      E2(I)=E2C
      DIFUC2(I)=DIFUC2(I)*E2(I)*DELT*CFM
  307 CONTINUE
      DO 404 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 404
      EV(I)=EVC
      VDIFUC(I)=VDIFUC(I)*EV(I)*DELT*CFM
  404 CONTINUE
C
C *** CALCULATE INFLOW MASS AND OUTFLOW VOLUME*CONVERSION FACTOR
C
      IF(NIF1.EQ.0) GO TO 105
      DO 505 I=1,NIF1
      J=IINF1(I)
      DO 506 N=NLN,NCONST
  506 DASIN1(N,J)=QIN1(J)*CIN1(N,J)*DELT*CFM
  505 CONTINUE
  105 IF(NIF2.EQ.0) GO TO 507
      DO 508 I=1,NIF2
      J=IINF2(I)
      DO 509 N=NLN,NCONST
  509 DASIN2(N,J)=QIN2(J)*CIN2(N,J)*DELT*CFM
  508 CONTINUE
  507 IF(NOF1.EQ.0) GO TO 510
      DO 511 I=1,NOF1
      J=IOTF1(I)
  511 VOUT1(J)=QOUT1(J)*DELT*CFM
  510 IF(NOF2.EQ.0) GO TO 513
      DO 514 I=1,NOF2
      J=IOTF2(I)
  514 VOUT2(J)=QOUT2(J)*DELT*CFM
  513 CONTINUE
C
C *** OUTPUT INITIAL CONDITIONS
      IP=0
      CALL OUTPUT(IP)
C
C *** ENTER MAIN LOOP
C
C *** SET OUTPUT COUNTERS
      ICOUNT=0
      IPOUT=NTS
C
      DO 199 IT=1,NTS
      DO 106 I=1,NC1
      IL=IENDL(I)
      IH=IENDH(I)
C
C *** LAYER 1-HORIZONTAL FLOW AND DIFFUSION
C
```

```
      IF(Q1(I).LT.0.) GO TO 107
      DO 109 N=NLN,NCONST
      GRAD=C1(N,IL)-C1(N,IH)
      F=FRAC
      IF(GRAD.LT.0.) F=1.
      CP=C1(N,IH)+F*GRAD
      ADVECT=CP*VOLF1(I)
      DIFFH=DIFUC1(I)*GRAD
      DASS1(N,IL)=DASS1(N,IL)-ADVECT-DIFFH
  109 DASS1(N,IH)=DASS1(N,IH)+ADVECT+DIFFH
      GO TO 210
  107 DO 108 N=NLN,NCONST
      GRAD=C1(N,IL)-C1(N,IH)
      F=1.-FRAC
      IF(GRAD.LT.0.) F=0.
      CP=C1(N,IH)+F*GRAD
      ADVECT=CP*VOLF1(I)
      DIFFH=DIFUC1(I)*GRAD
      DASS1(N,IL)=DASS1(N,IL)-ADVECT-DIFFH
  108 DASS1(N,IH)=DASS1(N,IH)+ADVECT+DIFFH
C
C *** LAYER 2-HORIZONTAL FLOW AND DIFFUSION
C
  210 IF(L2CA(I).EQ.0) GO TO 106
      IF(Q2(I).LT.0.) GO TO 110
      DO 112 N=NLN,NCONST
      GRAD=C2(N,IL)-C2(N,IH)
      F=FRAC
      IF(GRAD.LT.0.) F=1.
      CP=C2(N,IH)+F*GRAD
      ADVECT=CP*VOLF2(I)
      DIFFH=DIFUC2(I)*GRAD
      DASS2(N,IL)=DASS2(N,IL)-ADVECT-DIFFH
  112 DASS2(N,IH)=DASS2(N,IH)+ADVECT+DIFFH
      GO TO 106
  110 DO 111 N=NLN,NCONST
      GRAD=C2(N,IL)-C2(N,IH)
      F=1.-FRAC
      IF(GRAD.LT.0.) F=0.
      CP=C2(N,IH)+F*GRAD
      ADVECT=CP*VOLF2(I)
      DIFFH=DIFUC2(I)*GRAD
      DASS2(N,IL)=DASS2(N,IL)-ADVECT-DIFFH
  111 DASS2(N,IH)=DASS2(N,IH)+ADVECT+DIFFH
CFOR,S GSLPRG,BODDO,CSLPRG,BODDO,GSLPRG,BODDO
  106 CONTINUE
C
C *** VERTICAL DIFFUSION
C
      DO 113 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 113
      DO 114 N=NLN,NCONST
      DIFFV=VDIFUC(I)*(C1(N,I)-C2(N,I))
      DASS1(N,I)=DASS1(N,I)-DIFFV
  114 DASS2(N,I)=DASS2(N,I)+DIFFV
  113 CONTINUE
C
```

```
C *** INFLOW AND OUTFLOW FROM NODES
C
      IF(NIF1.EQ.0) GO TO 115
      DO 116 I=1,NIF1
      J=IINF1(I)
      DO 117 N=NLN,NCONST
  117 DASS1(N,J)=DASS1(N,J)+DASIN1(N,J)
  116 CONTINUE
  115 IF(NIF2.EQ.0) GO TO 118
      DO 119 I=1,NIF2
      J=IINF2(I)
      DO 120 N=NLN,NCONST
  120 DASS2(N,J)=DASS2(N,J)+DASIN2(N,J)
  119 CONTINUE
  118 IF(NOF1.EQ.0) GO TO 121
      DO 122 I=1,NOF1
      J=IOTF1(I)
      DO 123 N=NLN,NCONST
  123 DASS1(N,J)=DASS1(N,J)-VOUT1(J)*C1(N,J)
  122 CONTINUE
  121 IF(NOF2.EQ.0) GO TO 314
      DO 125 I=1,NOF2
      J=IOTF2(I)
      DO 126 N=NLN,NCONST
  126 DASS2(N,J)=DASS2(N,J)-VOUT2(J)*C2(N,J)
  125 CONTINUE
C
C *** CALL SUBROUTINES TO CALCULATE SOURCES AND SINKS
C
  314 DO 127 N=NLN,NCONST
      IF(ICALL(N).EQ.0) GO TO 127
      ILL=ICALL(N)
      GO TO (128,129),ILL
  128 CALL SALT(N)
      GO TO 127
  129 CALL BODDO(N,IT)
  127 CONTINUE
C
C *** CALCULATE NEW NODE CONCENTRATIONS
C
      DO 190 N=NLN,NCONST
      DO 191 I=1,NN1
      C1(N,I)=DASS1(N,I)/VOL1(I)
      C3(N,I)=DASS3(N,I)/ASURF(I)
      IF(L2NA(I).EQ.0) GO TO 191
      C2(N,I)=DASS2(N,I)/VOL2(I)
  191 CONTINUE
  190 CONTINUE
      ICOUNT=ICOUNT+1
      IF(ICOUNT.NE.NFOUT) GO TO 199
      IPOUT=IPOUT-ICOUNT
      IF(NPOUT.GT.IPOUT) GO TO 199
      TTIME=FLOAT(IT)*DELT/3600.
      IP=1
      CALL OUTPUT(IP)
      ICOUNT=0
  199 CONTINUE
```

```
      TTIME=FLOAT(NTS)*DELT/3600.
      IP=1
      CALL OUTPUT(IP)
      STOP
      END
      SUBROUTINE NCD
      COMMON AHEAD(5),ASURF(380),BHEAD(5),C1(4,380),C2(4,380),C3(4,380),
     2CHEAD(5),CIN1(4,380),CIN2(4,380),CPPT(4),DC1(750),DC2(750),
     3DIFUC1(750),DIFUC2(750),DN1(380),DN2(380),              E1(750),
     4E2(750),EV(380),ICALL(4),IENDL(750),IENDH(750),IINF1(30),IINF2(30)
     5,IOTF1(30),        IOTF2(30),L2CA(750),L2NA(380),DASS1(4,380),
     6DASS2(4,380),DASS3(4,380),DPPT1(4,380),DPPT2(4,380),NAMEC(4),
     7Q1(750),Q2(750),QCOEF1(750),QCOEF2(750),QIN1(380),QIN2(380),
     8QOUT1(380),QOUT2(380),V1(750),V2(750),VDIFUC(380),VOL1(380),
     9VOL2(380),VOLF1(750),VOLF2(750),
     1AD,ADB,AM,AMB,AR,BUR,    CFM,DELT,E1C,E2C,EVC,FRAC,IBUR,IE1,IE2,
     2ISKIP,NC1,NCONST,NIF1,NIF2,NLN,NN1,NOF1,       NOF2,NP,NPOUT,NTDS,
     3NTS,P1,P2,RDIS,TEMP,THETA,TTIME,VS,IBB
      DIMENSION AV2(750),AC2(4,380),CI1(4),CI2(4),CI3(4),IDC1(4),IDC2(4)
     2,IDC3(4)
C
C *** SUBROUTINE TO INPUT DATA
C
      READ(5,1) NR,NP,NRT
      READ(NR,1) NN1,NC1,NN2,NC2,NCONST,NIF1,NIF2,NOF1,NOF2,NTS,NPOUT,
     $NTDS,NLN
      READ(NR,1) ISKIP,IBB,IQ1,IQ2
    1 FORMAT(16I5)
      READ(NR,9) DELT,FRAC,CFM,VS,BUR,E1C,E2C,EVC,TEMP,THETA
      READ(NR,7) RDIS
    7 FORMAT(8E10.0)
    9 FORMAT(8F10.0)
      READ(NR,6) (NAMEC(I),I=1,NCONST)
      READ(NR,6) (AHEAD(M),M=1,5)
      READ(NR,6) (BHEAD(M),M=1,5)
      READ(NR,6) (CHEAD(M),M=1,2)
    6 FORMAT(20A4)
      READ(NR,9) AD,AM,ADB,AMB,AR,P1,P2
      READ(NR,1) (ICALL(N),N=1,NCONST)
      READ(NRT) (L2CA(I),I=1,NC1)
      DO 103 I=1,NC1
      IF(L2CA(I).EQ.0) GO TO 203
      READ(NRT) DC1(I),DC2(I),IENDL(I),IENDH(I),DIFUC1(I),DIFUC2(T),
     $QCOEF1(I),QCOEF2(I)
      GO TO 103
  203 READ(NRT) DC1(I),IENDL(I),IENDH(I),DIFUC1(I),QCOEF1(I)
  103 CONTINUE
      READ(NRT) (L2NA(I),I=1,NN1)
      DO 104 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 204
      READ(NRT) DN1(I),DN2(I),ASURF(I),VOL1(I),VOL2(I),VDIFUC(I)
      GO TO 104
  204 READ(NRT) DN1(I),ASURF(I),VOL1(I)
  104 CONTINUE
C *** INPUT VELOCITIFS(FT/SEC) OR FLOW (FT**3/SEC)
      IF(IQ1.EQ.0) GO TO 251
      READ(NR,9) (Q1(I),I=1,NC1)
      DO 252 I=1,NC1
  252 V1(I)=Q1(I)/QCOEF1(I)
      GO TO 253
  251 READ(NR,5) (V1(I),I=1,NC1)
  253 IF(IQ2.EQ.0) GO TO 254
      READ(NR,9) (AV2(I),I=1,NC2)
      IC=0
      DO 255 I=1,NC1
      IF(L2CA(I).EQ.0) GO TO 255
      IC=IC+1
      Q2(I)=AV2(IC)
      V2(I)=Q2(I)/QCOEF2(I)
  255 CONTINUE
      GO TO 256
  254 READ(NR,5) (AV2(I),I=1,NC2)
      IC=0
      DO 205 I=1,NC1
      IF(L2CA(I).EQ.0) GO TO 205
      IC=IC+1
      V2(I)=AV2(IC)
  205 CONTINUE
C *** INPUT INITIAL CONCENTRATIONS AT EACH NODE (G/LITER)
  256 READ(NR,1) (IDC1(N),N=1,NCONST)
      READ(NR,1) (IDC2(N),N=1,NCONST)
      READ(NR,1) (IDC3(N),N=1,NCONST)
      READ(NR,9) (CI1(N),N=1,NCONST)
      READ(NR,9) (CI2(N),N=1,NCONST)
      READ(NR,9) (CI3(N),N=1,NCONST)
      DO 105 N=1,NCONST
      IF(IDC1(N).GT.0) GO TO 207
      DO 208 I=1,NN1
  208 C1(N,I)=CI1(N)
      GO TO 105
  207 READ(NR,5) (C1(N,I),I=1,NN1)
  105 CONTINUE
      DO 106 N=1,NCONST
      IF(IDC2(N).GT.0) GO TO 209
      DO 210 I=1,NN1
  210 C2(N,I)=CI2(N)
      GO TO 106
  209 READ(NR,5) (AC2(N,I),I=1,NN2)
      IC=0
      DO 206 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 206
      IC=IC+1
      C2(N,I)=AC2(N,IC)
  206 CONTINUE
  106 CONTINUE
C *** READ INITIAL MASS ON LAKE BOTTOM (GRAMS/FOOT**2)
      DO 107 N=1,NCONST
      IF(IDC3(N).GT.0) GO TO 211
      DO 212 I=1,NN1
  212 C3(N,I)=CI3(N)
      GO TO 107
  211 READ(NR,5) (C3(N,I),I=1,NN1)
  107 CONTINUE
C
```

```
C *** INPUT INFLOW AND OUTFLOW DATA
C
      IF(NIF1.EQ.0) GO TO 112
      DO 111 I=1,NIF1
      READ(NR,8) J,QIN1(J),(CIN1(N,J),N=1,NCONST)
  111 IINF1(I)=J
    8 FORMAT(I5,15F5.0)
  112 IF(NIF2.EQ.0) GO TO 114
      DO 113 I=1,NIF2
      READ(NR,8) J,QIN2(J),(CIN2(N,J),N=1,NCONST)
  113 IINF2(I)=J
  114 IF(NOF1.EQ.0) GO TO 116
      DO 115 I=1,NOF1
      READ(NR,8) J,QOUT1(J)
  115 IOTF1(I)=J
  116 IF(NOF2.EQ.0) GO TO 109
      DO 117 I=1,NOF2
      READ(NR,8) J,QOUT2(J)
  117 IOTF2(I)=J
C *** READ SATURATION CONCENTRATION OF EACH CONSTITUENT
  118 READ(NR,5) (CPPT(N),N=1,NCONST)
    5 FORMAT(16F5.0)
      RETURN
      END
      SUBROUTINE SALT(N)
      COMMON AHEAD(5),ASURF(380),BHEAD(5),C1(4,380),C2(4,380),C3(4,380),
     2CHEAD(5),CIN1(4,380),CIN2(4,380),CPPT(4),DC1(750),DC2(750),
     3DIFUC1(750),DIFUC2(750),DN1(380),DN2(380),              E1(750),
     4E2(750),EV(380),ICALL(4),IENDL(750),IENDH(750),IINF1(30),IINF2(30)
     5,IOTF1(30),           IOTF2(30),L2CA(750),L2NA(380),DASS1(4,380),
     6DASS2(4,380),DASS3(4,380),DPPT1(4,380),DPPT2(4,380),NAMEC(4),
     7Q1(750),Q2(750),QCOEF1(750),QCOEF2(750),QIN1(380),QIN2(380),
     8QOUT1(380),QOUT2(380),V1(750),V2(750),VDIFUC(380),VOL1(380),
     9VOL2(380),VOLF1(750),VOLF2(750),
     1AD,ADB,AM,AMB,AR,BUR,    CFM,DELT,E1C,E2C,EVC,FRAC,IBUR,IE1,IE2,
     2ISKIP,NC1,NCONST,NIF1,NIF2,NLN,NN1,NOF1,         NOF2,NP,NPOUT,NTDS,
     3NTS,P1,P2,RDIS,TEMP,THETA,TTIME,VS,IBB
C
C *** SUBROUTINE TO PRECIPITATE AND DISSOLVE SALT
C
C *** REDISSOLVE SALT
      DO 101 I=1,NN1
      IF(DASS3(N,I).LE.0.) GO TO 101
      IF(L2NA(I).EQ.0) GO TO 102
      IF(DASS2(N,I).GE.DPPT2(N,I)) GO TO 101
      DR=RDIS*(CPPT(N)-C2(N,I))*VOL2(I)*DELT/86400.
      DASS2(N,I)=DASS2(N,I)+DR
      DASS3(N,I)=DASS3(N,I)-DR
      GO TO 101
  102 IF(DASS1(N,I).GE.DPPT1(N,I)) GO TO 101
      DR=RDIS*(CPPT(N)-C1(N,I))*VOL1(I)*DELT/86400.
      DASS1(N,I)=DASS1(N,I)+DR
      DASS3(N,I)=DASS3(N,I)-DR
  101 CONTINUE
C *** PRECIPITATE SALT
      DO 103 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 104
      IF(DASS1(N,I).LE.DPPT1(N,I)) GO TO 105
      DASS2(N,I)=DASS2(N,I)+DASS1(N,I)-DPPT1(N,I)
      DASS1(N,I)=DPPT1(N,I)
  105 IF(DASS2(N,I).LE.DPPT2(N,I)) GO TO 103
      DASS3(N,I)=DASS3(N,I)+DASS2(N,I)-DPPT2(N,I)
      DASS2(N,I)=DPPT2(N,I)
      GO TO 103
  104 IF(DASS1(N,I).LE.DPPT1(N,I)) GO TO 103
      DASS1(N,I)=DPPT1(N,I)
      DASS3(N,I)=DASS3(N,I)+DASS1(N,I)-DPPT1(N,I)
  103 CONTINUE
      RETURN
      END
      SUBROUTINE BODDO(N,IT)
C *** SUBROUTINE TO CALCULATE SOURCES AND SINKS OF BOD AND DO
      COMMON AHEAD(5),ASURF(380),BHEAD(5),C1(4,380),C2(4,380),C3(4,380),
     2CHEAD(5),CIN1(4,380),CIN2(4,380),CPPT(4),DC1(750),DC2(750),
     3DIFUC1(750),DIFUC2(750),DN1(380),DN2(380),              E1(750),
     4E2(750),EV(380),ICALL(4),IENDL(750),IENDH(750),IINF1(30),IINF2(30)
     5,IOTF1(30),           IOTF2(30),L2CA(750),L2NA(380),DASS1(4,380),
     6DASS2(4,380),DASS3(4,380),DPPT1(4,380),DPPT2(4,380),NAMEC(4),
     7Q1(750),Q2(750),QCOEF1(750),QCOEF2(750),QIN1(380),QIN2(380),
     8QOUT1(380),QOUT2(380),V1(750),V2(750),VDIFUC(380),VOL1(380),
     9VOL2(380),VOLF1(750),VOLF2(750),
     1AD,ADB,AM,AMB,AR,BUR,    CFM,DELT,E1C,E2C,EVC,FRAC,IBUR,IE1,IE2,
     2ISKIP,NC1,NCONST,NIF1,NIF2,NLN,NN1,NOF1,         NOF2,NP,NPOUT,NTDS,
     3NTS,P1,P2,RDIS,TEMP,THETA,TTIME,VS,IBB
      DIMENSION AIR(380),ITV1(380),TV1(380)
C
      IF(IT.GT.1) GO TO 100
C *** CONVERT K'S FROM DAY-1 TO SECONDS-1 AND ADJUST FOR TEMPERATURE
      TAT=THETA**(TEMP-20.)
      AD=(AD/86400.)*TAT
      AM=(AM/86400.)*TAT
      ADB=(ADB/86400.)*TAT
      AMB=(AMB/86400.)*TAT
C *** CONVERT BUR FROM GRAMS/METER**2/DAY TO GRAMS/FT**2/SEC
      BUR=BUR/930001.824
C *** CALCULATE AVG. VELOCITY FOR NODE
      DO 202 I=1,NC1
  202 ITV1(I)=0
      DO 203 I=1,NC1
      IL=IENDL(I)
      IH=IENDH(I)
      TV1(IL)=TV1(IL)+ABS(V1(I))
      ITV1(IL)=ITV1(IL)+1
      TV1(IH)=TV1(IH)+ABS(V1(I))
  203 ITV1(IH)=ITV1(IH)+1
C *** CALCULATE REAERATION COEFFICIENT FOR EACH NODE
      DO 201 I=1,NN1
      AIR(I)=AR*((TV1(I)/FLOAT(ITV1(I)))**P1)*DN1(I)**P2
      IF(AIR(I).GT.1.0) AIR(I)=1.0
      IF(AIR(I).LT..05) AIR(I)=.05
C *** ADJUST FOR TEMPERATURE AND CONVERT FROM DAY-1 TO SEC-1
  201 AIR(I)=(AIR(I)*1.02**(TEMP-20.))/86400.
      L=N+1
      Y=VS*DELT
```

```
C
C *** DECAY BOD AND DO
C
  100 DO 101 I=1,NN1
C *** CALCULATE MASS OF DO REQUIRED FOR AEROBIC CONDITIONS
C *** LAYER 1
      SA=C1(N,I)*VOL1(I)*DELT
      DASSA1=AD*SA
      DASSB1=C1(L,I)*VOL1(I)
C *** TEST IF BOD DEMAND IS GREATER THAN DO AVAILABLE
      IF(DASSA1.GT.DASSB1) GO TO 102
      DASS1(N,I)=DASS1(N,I)-DASSA1
      DASS1(L,I)=DASS1(L,I)-DASSA1
      GO TO 103
  102 DASS1(L,I)=DASS1(L,I)-DASSB1
C *** REDUCE K DUE TO LACK OF DO
      A=AM+((AD-AM)/(DASSA1/VOL1(I)))*C1(L,I)
      IF(A.LT.AM) A=AM
      DASS1(N,I)=DASS1(N,I)-A*SA
C *** LAYER 2
  103 IF(L2NA(I).EQ.0) GO TO 104
      SA=C2(N,I)*VOL2(I)*DELT
      DASSA2=AD*SA
      DASSB2=C2(L,I)*VOL2(I)
      IF(DASSA2.GT.DASSB2) GO TO 105
      DASS2(N,I)=DASS2(N,I)-DASSA2
      DASS2(L,I)=DASS2(L,I)-DASSA2
      GO TO 104
  105 DASS2(L,I)=DASS2(L,I)-DASSB2
      A=AM+((AD-AM)/(DASSA2/VOL2(I)))*C2(L,I)
      IF(A.LT.AM) A=AM
      DASS2(N,I)=DASS2(N,I)-A*SA
C *** LAYER 3
  104 SA=C3(N,I)*ASURF(I)*DELT
      DASSA3=ADB*SA
      DASSB3=C3(L,I)*ASURF(I)
      IF(DASSA3.GT.DASSB3) GO TO 205
      DASS3(N,I)=DASS3(N,I)-DASSA3
      DASS3(L,I)=DASS3(L,I)-DASSA3
      GO TO 106
  205 DASS3(L,I)=DASS3(L,I)-DASSB3
      A=AMB+((ADB-AMB)/(DASSA3/ASURF(I)))*C3(L,I)
      IF(A.LT.AMB) A=AMB
      DASS3(N,I)=DASS3(N,I)-A*SA
C
C *** SETTLE BOD
C
C *** LAYER 1
  106 YDN1=Y/DN1(I)
      IF(YDN1.GT.1.) YDN1=1.
      BODS1=YDN1*C1(N,I)*VOL1(I)
      DASS1(N,I)=DASS1(N,I)-BODS1
      IF(L2NA(I).EQ.0) GO TO 107
C *** LAYER 2
      YDN2=Y/DN2(I)
      IF(YDN2.GT.1.) YDN2=1.
      BODS2=YDN2*C2(N,I)*VOL2(I)
      DASS2(N,I)=DASS2(N,I)-BODS2+BODS1
      DASS3(N,I)=DASS3(N,I)+BODS2
      GO TO 108
  107 DASS3(N,I)=DASS3(N,I)+BODS1
C
C *** DO UPTAKE BY BENTHIC DEPOSITS
C
  108 IF(C3(N,I).LE.0.) GO TO 110
      UPTAKE=BUR*ASURF(I)*DELT
      IF(L2NA(I).EQ.0) GO TO 109
C *** FROM LAYER 2
      IF(UPTAKE.GT.DASSB2) UPTAKE=DASSB2
      DASS2(L,I)=DASS2(L,I)-UPTAKE
      DASS3(L,I)=DASS3(L,I)+UPTAKE
      GO TO 110
C *** FROM LAYER 1
  109 IF(UPTAKE.GT.DASSB1) UPTAKE=DASSB1
      DASS1(L,I)=DASS1(L,I)-UPTAKE
      DASS3(L,I)=DASS3(L,I)+UPTAKE
C
C *** REAERATION AT SURFACE
C
C *** CALCULATE DO SATURATION FOR THE NODE IN GRAMS/LITER
  110 CS=(7.726317-.01552*TEMP-.031077*C1(NTDS,I)+.00003534*C1(NTDS,I)
     $*C1(NTDS,I))/1000.
      DASS1(L,I)=DASS1(L,I)+ATR(I)*(CS-C1(L,I))*VOL1(I)*DELT
C
C *** AVOID NEGATIVE DO OR SUPERSATURATION OF DO
      CSD1=CS*VOL1(I)
      IF(DASS1(L,I).LT.0.) DASS1(L,I)=0.0
      IF(DASS1(L,I).GT.CSD1) DASS1(L,I)=CSD1
      IF(L2NA(I).EQ.0) GO TO 101
      CS2=(7.726317-.01552*TEMP-.031077*C2(NTDS,I)+.00003534*C2(NTDS,I)
     $*C2(NTDS,I))/1000.
      CSD2=CS2*VOL2(I)
      IF(DASS2(L,I).LT.0.) DASS2(L,I)=0.0
      IF(DASS2(L,I).GT.CSD2) DASS2(L,I)=CSD2
  101 CONTINUE
      RETURN
      END
      SUBROUTINE OUTPUT(IP)
C *** SUBROUTINE FOR OUTPUT
      COMMON AHEAD(5),ASURF(380),BHEAD(5),C1(4,380),C2(4,380),C3(4,380),
     2CHEAD(5),CIN1(4,380),CIN2(4,380),CRPT(4),DC1(750),DC2(750),
     3DIFUC1(750),DIFUC2(750),DN1(380),DN2(380),               E1(750),
     4E2(750),EV(380),ICALL(4),IENDL(750),IENDH(750),IINF1(30),IINF2(30)
     5,IOTF1(30),               IOTF2(30),L2CA(750),L2NA(380),DASS1(4,380),
     6DASS2(4,380),DASS3(4,380),DPPT1(4,380),DPPT2(4,380),NAMEC(4),
     7Q1(750),Q2(750),QCOEF1(750),QCOEF2(750),QIN1(380),QIN2(380),
     8QOUT1(380),QOUT2(380),V1(750),V2(750),VDIFUC(380),VOL1(380),
     9VOL2(380),VOLF1(750),VOLF2(750),
     1AD,ADB,AM,AMB,AP,BUR,     CFM,DELT,E1C,E2C,EVC,FRAC,IBUR,IE1,IE2,
     2ISKIP,NC1,NCONST,NIF1,NIF2,NLN,NN1,NOF1,        NOF2,NP,NPOUT,NTDS,
     3NTS,P1,P2,RDIS,TEMP,THETA,TTIME,VS,IBB
C
      IF(IP.GT.0) GO TO 100
      IF(ISKIP.EQ.0) GO TO 300
```

```
C
C *** OUTPUT INITIAL CONDITIONS
C
C *** CHANNEL DATA OUTPUT
      WRITE(NP,50)
   50 FORMAT(1H1,51X,'CHANNEL DATA',//,22X,'************ LAYER 1 ********
     $***',3X,'*********** LAYER 2 ************')
      WRITE(NP,51)
   51 FORMAT(1X,'CHANNEL  LOW   HIGH  VELOCITY      FLOW      DIFF COEF
     $VELOCITY      FLOW       DIFF COEF',/,1X,' NUMBER  NODE  NODE  FEET/
     $SEC   FT**3/SEC  FT**2/SEC    FEET/SEC    FT**3/SEC    FT**2/SEC' )
      DO 516 I=1,NC1
      IF(L2CA(I).EQ.0) GO TO 517
      WRITE(NP,52) I,IENDL(I),IENDH(I),V1(I),Q1(I),E1(I),V2(I),Q2(I),
     $E2(I)
      GO TO 516
  517 WRITE(NP,53) I,IENDL(I),IENDH(I),V1(I),Q1(I),E1(I)
  516 CONTINUE
   52 FORMAT(3X,I3,4X,I3,3X,I3,3X,F8.5,E12.4,1X,F10.4,3X,F8.5,E12.4,
     $1X,F10.4)
   53 FORMAT(3X,I3,4X,I3,3X,I3,3X,F8.5,E12.4,1X,F10.4,8X,'NC',8X,'NC'
     $,10X,'NC')
C *** NODE DATA OUTPUT
      WRITE(NP,54)
      WRITE(NP,55) (NAMEC(N),N=1,NCONST)
      WRITE(NP,56) ((AHEAD(M),M=1,5),N=1,NCONST)
      WRITE(NP,57) ((BHEAD(M),M=1,5),N=1,NCONST)
   54 FORMAT(1H1,46X,'INITIAL NODE CONCENTRATIONS',/)
   55 FORMAT(24X,5(2X,'******',A4,' ******'))
   56 FORMAT(2X,'NODE    VERT DIFF COEF',5(5A4))
   57 FORMAT(1X,'NUMBER     FT**2/SEC',3X,5(5A4))
      DO 518 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 519
      WRITE(NP,58) I,EV(I),((C1(N,I),C2(N,I)),N=1,NCONST)
      GO TO 518
  519 WRITE(NP,59) I,(C1(N,I),N=1,NCONST)
  518 CONTINUE
   58 FORMAT(2X,I3,3X,F10.10,3X,5(2(2X,F8.4)))
   59 FORMAT(2X,I3,8X,'NO COEF',3X,5(2X,F8.4,3X,'NO NODE'))
      IF(IBB.EQ.0) GO TO 300
      WRITE(NP,68)
   68 FORMAT(//,1X,'LAKE BOTTOM DATA'/)
      WRITE(NP,69) (NAMEC(N),N=1,NCONST)
   69 FORMAT(2X,'NODE',1X,5(2X,A4,1X,'CONC'))
      WRITE(NP,70) ((CHEAD(M),M=1,2),N=1,NCONST)
   70 FORMAT(1X,'NUMBER',5(3X,2A4)/)
      DO 529 I=1,NN1
  529 WRITE(NP,71) I,(C3(N,I),N=1,NCONST)
   71 FORMAT(2X,I3,1X,5(7X,F8.3))
C *** OUTPUT INFLOW AND OUTFLOW DATA
  300 WRITE(NP,60)
   60 FORMAT(1H1,20X,'INFLOW AND OUTFLOW DATA',//)
      WRITE(NP,61) (NAMEC(N),N=1,NCONST)
   61 FORMAT(1X,' NODE    LAYER    INFLOW',4X,5(A4,7X))
      WRITE(NP,62) (BHEAD(2),N=1,NCONST)
   62 FORMAT(1X,'NUMBER',11X,'CFS',6X,5(A4,7X))
      IF(NIF1.EQ.0) GO TO 520
      DO 521 I=1,NIF1
      J=IINF1(I)
  521 WRITE(NP,63) IINF1(I),QIN1(J),(CIN1(N,J),N=1,NCONST)
   63 FORMAT(2X,I3,6X,'1',4X,F7.2,5(3X,F8.4))
  520 IF(NIF2.EQ.0) GO TO 522
      DO 523 I=1,NIF2
      J=IINF2(I)
  523 WRITE(NP,64) IINF2(I),QIN2(J),(CIN2(N,J),N=1,NCONST)
   64 FORMAT(2X,I3,6X,'2',4X,F7.2,5(3X,F8.4))
      WRITE(NP,65)
      IF(NOF1.EQ.0) GO TO 525
      DO 526 I=1,NOF1
      J=IOTF1(I)
  526 WRITE(NP,66) IOTF1(I),QOUT1(J)
   65 FORMAT(/2X,'NODE    LAYER    OUTFLOW',/,1X,'NUMBER',12X,'CFS')
   66 FORMAT(2X,I3,6X,'1',5X,F7.2)
   67 FORMAT(2X,I3,6X,'2',5X,F7.2)
  525 IF(NOF2.EQ.0) GO TO 301
      DO 528 I=1,NOF2
      J=IOTF2(I)
  528 WRITE(NP,67) IOTF2(I),QOUT2(J)
  301 GO TO 101
C
C *** OUTPUT AFTER TIME TTIME
C
  100 GO TO (201,202),IP
  201 WRITE(NP,72) TTIME
   72 FORMAT(1H1,21X,'NODE CONCENTRATIONS AFTER',F8.2,' HOURS'//)
      WRITE(NP,73) (NAMEC(N),N=1,NCONST)
   73 FORMAT(7X,5(3X,'******',A4,' ******'))
      WRITE(NP,74) ((AHEAD(M),M=1,5),N=1,NCONST)
   74 FORMAT(2X,'NODE',1X,5(5A4))
      WRITE(NP,75) ((BHEAD(M),M=1,5),N=1,NCONST)
   75 FORMAT(1X,'NUMBER',5(5A4))
      DO 530 I=1,NN1
      IF(L2NA(I).EQ.0) GO TO 531
      WRITE(NP,76) I,((C1(N,I),C2(N,I)),N=1,NCONST)
      GO TO 530
  531 WRITE(NP,77) I,(C1(N,I),N=1,NCONST)
  530 CONTINUE
   76 FORMAT(2X,I3,2X,5(2(2X,F8.4)))
   77 FORMAT(2X,I3,2X,5(2X,F8.4,3X,'NO NODE'))
      IF(IBB.EQ.0) GO TO 101
      WRITE(NP,68)
      WRITE(NP,69) (NAMEC(N),N=1,NCONST)
      WRITE(NP,70) ((CHEAD(M),M=1,2),N=1,NCONST)
      DO 532 I=1,NN1
  532 WRITE(NP,71) I,(C3(N,I),N=1,NCONST)
      GO TO 101
C
C *** OUTPUT CONSTANTS AND OPTIONS USED
C
  202 WRITE(NP,78)
      WRITE(NP,79) DELT,FRAC
      WRITE(NP,88) EVC
      WRITE(NP,80) E1C
      WRITE(NP,82) E2C
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      WRITE(NP,84) RDIS
      WRITE(NP,89) TEMP,THETA
      WRITE(NP,86) BUR
      WRITE(NP,85) AD,AM,ADB,AMB,AF,P1,P2,VS
   78 FORMAT(41X,'CONSTANTS AND OPTTONS USED'//)
   79 FORMAT(1X,'TIME STEP=',F4.1,1X,'HOURS',8X,'UPSTREAM CONCENTRATION
     $FACTOR=',F4.2,/)
   80 FORMAT(1X,'CONSTANT DIFFUSION COEFFICIENT USED IN LAYER 1. EC1=',
     $F12.10,1X,'FT**2/SEC'/)
   82 FORMAT(1X,'CONSTANT DIFFUSION COEFFICIENT USED IN LAYER 2. EC1=',
     $F12.10,1X,'FT**2/SEC'/)
   84 FORMAT(1X,'TDS REDISSOLVING COEFFICIENT(RDIS)=',E10.4,'  1/DAY'/)
   85 FORMAT(1X,'AEROBIC BOD DECAY RATE FOR BRINE=',F5.3,1X,'DAY-1',8X,
     $'ANAEROBIC BOD DECAY RATE FOR BRINE=',F5.3,1X,'DAY-1',//,1X,'AEROB
     $IC BOD DECAY RATE FOR THE BENTHIC DEPOSIT=',F5.3,1X,'DAY-1',8X,'AN
     $AEROBIC BOD DECAY RATE FOR THE BENTHIC DEPOSIT=',F5.3,1X,'DAY-1',/
     $/,1X,'DO AERATION COEFFICIENTS AR=',F6.3,2X,' P1=',F6.3,2X,' P2=',
     $F6.3,8X,'BOD SETTLING VELOCITY=',F5.3,' FT/SEC'/)
   86 FORMAT(1X,'CONSTANT BENTHIC UPTAKE OF DO IS ASSUMED. BUR=',F5.2,
     $' GRAMS/METER**2/DAY')
   88 FORMAT(1X,'THE VERTICAL DIFFUSION COEFFICIENT IS GIVEN A VALUE =',
     $F12.10,1X,'FT**2/SEC'/)
   89 FORMAT(1X,'TEMPERATURE =',F4.1,1X,'C',8X,'THE TEMPERATURE CORRECTI
     $ON FACTOR FOR BOD DECAY(THETA)=',F6.3,/)
  101 RETURN
      END
```

SAMPLE INPUT

```
CARD 1
   5     6     9
CARD 2
 373  745   144  254     3     7     9    12     0     1     1     1     1
CARD 3
   1     1     1     1
CARD 4
       3.         1.0    28.3 1605     0.0        0.5        3.8        7.8     .000015
     7.0          1.03
CARD 5
   6.E-3
CARD 6
 TDS BOD   DO  CON
CARD 7
  LAYER 1    LAYER 2
CARD 8
   G/L        G/L
CARD 3
 C/FT**2
CARD 10
        .1       .015          .1        .015        12.9          .5       -1.5
CARD 11
   0     2     0
CARD 12
-     692.6-    3192.6-    3231.2-    3269.8-    3258.4-    3494.1-    3332.7-    3371.3
-    3359.9-    3398.5-    3387.1-    3422.8-    3161.4-    4360.0-    4060.0-    3560.0
-    2560.0-    1360.0      692.6     2500.0-     200.0-     200.0-     250.0-     650.0
-     400.0-     200.0-     250.0-     200.0-     250.0-     850.0-     500.0-    1000.0
-    2400.0     4560.0-     200.0     1000.0      800.0-    1000.0-    1200.0-    1000.0
-     360.0-     400.0-     200.0-    2100.0-    2200.0-    2350.0-    2950.0-    3250.0
-    3400.0-    3550.0-    3650.0-    3800.0-    4200.0-    4200.0-    3200.0-    1000.0
-    1500.0-    7000.0-    9000.0-    3000.0-    4000.0-    5000.0-    4400.0-    4200.0
-    4700.0-    1400.0-     300.0     1092.6     2300.0     1700.0-     100.0-     100.0
-      50.0-     100.0-      50.0-     100.0-     100.0-     100.0-     450.0-     500.0
-    2000.0-    4600.0      500.0     5500.0     2000.0-    6000.0     6560.0-    1000.0
      800.0      400.0      600.0-     500.0-    4500.0-    2100.0      200.0-     600.0
-     350.0-     250.0-     350.0-    1450.0-    1950.0-    1950.0-    2450.0-    2450.0
-    1300.0-    2000.0-    1350.0-    1800.0-    1760.0-    3260.0-    7160.0-   12660.0
-   17160.0-   15160.0-   10160.0     4235.0-    4435.0-    4035.0-    2435.0-    2500.0
-    3000.0-    2200.0-     400.0     1442.6      500.0     1700.0      250.0     1550.0
     1260.0-     260.0     1060.0-     660.0      260.0-     310.0     1060.0-     660.0
      260.0-     310.0      560.0-    1210.0      260.0-     260.0      560.0-    1310.0
      260.0-     260.0      260.0-     300.0      500.0-    1000.0     3300.0-    4000.0
     8000.0-    2000.0    17000.0-    7000.0     5000.0-    5000.0     5000.0-   16000.0
    11000.0-   10365.0-    1000.0-     435.0-    4000.0-    2900.0-    1600.0-    1000.0
-     250.0-     850.0-     300.0-    1800.0-    1800.0-    2350.0-    2350.0-    2400.0
-    1900.0-    1900.0-    1500.0-    1800.0-    1000.0-   13000.0-    8000.0-    8000.0
-    5000.0-   13000.0-    3000.0-     220.0-    2020.0-    1420.0-     320.0     2192.6
     2550.0     2860.0     1700.0-     400.0     1300.0-     400.0      300.0-    1450.0
      300.0-    1450.0      300.0-    1100.0     4300.0-    1000.0    15000.0-    5000.0
     3000.0-   10000.0     7000.0-   20365.0-    1215.0-    2020.0-    3500.0-    2700.0
-    1120.0-     200.0-    1300.0-    1200.0-    4200.0-    5300.0-    4450.0-    1600.0
-   20500.0-   23500.0-   27000.0-   25000.0-    1000.0-    1700.0-    2000.0-     720.0
-    2415.0-    2800.0-    7400.0-    2400.0      300.0-     700.0-     465.0-    1315.0
-    1600.0-    2200.0-     700.0     6040.0     4460.0     3900.0     1000.0-    2000.0
-    4000.0    32100.0    17000.0     6500.0-   10000.0-   25365.0-   20000.0-    1000.0
-     950.0-     950.0-    1000.0-    1000.0-    1115.0-    1000.0-     800.0-     800.0
-     800.0-     200.0-     400.0-     400.0-    1000.0-    4200.0-    3600.0-    3600.0
-    2600.0-     600.0-    3000.0-   13000.0-   14000.0-   27000.0-   14000.0-    8200.0
-    3200.0     1000.0      200.0-     115.0-     600.0-     200.0-     200.0     7040.0
     7660.0     3300.0     1000.0-    3000.0-    6000.0    33500.0    28000.0     7500.0
     3000.0-   38365.0-    2500.0-    6000.0-    6100.0-    1800.0-    1200.0-    1115.0
-    1400.0-     400.0-     400.0-     200.0-     460.0-    5000.0-    3000.0     4000.0
     6500.0     5500.0-     700.0-   10500.0-   15000.0-   15000.0-   21000.0      700.0
-    1300.0     2200.0     7300.0     2115.0     2000.0     1000.0      600.0      200.0
-    4000.0-    9600.0-    1900.0-    1015.0-    1000.0-     400.0-    6500.0     2000.0
-     500.0-     400.0-     815.0      400.0     7500.0    12200.0     1300.0-    6000.0
-    5500.0-    5000.0    39700.0    37800.0    17000.0     3000.0-   32365.0-   41000.0
-   12500.0-    7100.0-    2000.0-     600.0-    2215.0-     200.0     1000.0     3700.0
     8700.0     7000.0     3900.0     3500.0-    2000.0-    3000.0-    2000.0-   10000.0
     1000.0     2000.0     2900.0     2400.0     1800.0-    1000.0-   13500.0-    8000.0
-    1500.0     1000.0-     100.0     7700.0    11000.0-    1400.0-   11000.0-    3800.0
-    1800.0    40000.0     4300.0    13000.0     2000.0-   24365.0-   51000.0-   15500.0
-    8400.0-     100.0     1700.0     6400.0     7500.0     6300.0     2500.0      700.0
     2700.0-    2000.0     1000.0-    1000.0-   10000.0     1000.0      500.0-   15000.0
-    8000.0-    2000.0-    2000.0     6000.0     6300.0-    2500.0-    9800.0    78000.0
    48000.0    10000.0     4000.0-   15365.0-   60000.0-   15000.0-   10000.0     9500.0
    15000.0     2000.0     2000.0     2000.0-   10395.0     1000.0-   11000.0-    3000.0
-    3000.0-   18000.0-    3000.0-    4650.0-    8000.0-    3000.0     2800.0-    2800.0
    23000.0    61000.0    10000.0     4000.0-    2990.0-   24955.0-   41500.0-   23000.0
-    6000.0     3000.0    24000.0     3990.0      990.0-    3000.0      500.0-   12000.0
-   14000.0-   29000.0-   21000.0-   20000.0-   19455.0-   19000.0-    3000.0    21000.0
    40000.0    30000.0     7000.0     1000.0-    9000.0-   29455.0-   37000.0-   23000.0
    20000.0    19000.0     9000.0     6000.0     3000.0     1000.0     1000.0      500.0
-   29455.0-   30500.0-   23500.0-    4000.0     1000.0      500.0    41000.0    40000.0
    10000.0     4000.0-    3000.0-   74455.0-   36000.0-   18000.0-    4000.0    41000.0
    48000.0    15000.0     3000.0     3000.0     1000.0-    1000.0-    3000.0-   72455.0
-   34000.0-   16000.0-    7000.0      500.0-    5705.0-   10000.0-    2000.0    73000.0
    43000.0    16000.0-    7500.0-   26250.0-   29705.0-   24000.0-    5000.0-    4000.0
    10000.0    17000.0    30000.0    28000.0    10000.0-   11455.0-    1932.0-    1444.0
-    8250.0-    8250.0-   33523.0-    5488.0-    5444.0-    1000.0-    3000.0-    5000.0
-    5000.0-    1000.0    23000.0    36000.0     3000.0-     500.0-    6250.0-    6250.0
-   33523.0-    9488.0-    6444.0     3000.0     9000.0     3000.0     3000.0-    1000.0
-    5000.0-   26000.0-   21000.0-    2250.0-    2250.0-   12523.0-   14488.0-    7444.0
-   20000.0-    2000.0-     500.0-    1000.0-    5000.0-    9200.0-    1200.0    20000.0
    31000.0     8000.0     1500.0-    3750.0-    1750.0-    8523.0-   10288.0-   15444.0
-   20000.0-    1200.0     1000.0     2000.0-    1500.0-     250.0-    1000.0-    1000.0
-    1000.0-    1300.0-     156.0-    2000.0-    1000.0-    8523.0-   10288.0-   15144.0
-   21144.0-    2144.0      788.0     1000.0     1000.0     3000.0     1000.0     2000.0
     1000.0     1000.0      694.0      788.0    50000.0     7000.0     1000.0-    2000.0
-    3000.0-    6523.0-   11288.0-   14144.0-   21144.0-    1838.0      694.0-     335.0
      788.0    10000.0     2000.0     4000.0     7000.0    11000.0    11000.0    20000.0
     1694.0     3318.0      300.0-    4000.0-    6000.0-   10523.0-   11788.0-   23144.0
-    2838.0-    3462.0     4047.0     8000.0    10684.0    12523.0    12000.0    12000.0
     2694.0    13462.0-     400.0     1088.0    12000.0     1000.0-    6684.0-    7839.0
-   10000.0-   11288.0-   13938.0-   13606.0    10400.0     4735.0    23000.0     6000.0
     7000.0    10000.0    21144.0    13694.0    23806.0-     400.0-    2000.0-    7684.0
-   10839.0-   21144.0-    3838.0-   23950.0    10600.0    12000.0     2735.0    16000.0
    22000.0    24000.0     3694.0    23950.0-   10000.0-    1000.0    24000.0     2000.0
-   13684.0-   12839.0-     838.0-   24094.0    10000.0     1600.0    13855.0    25844.0
    12998.0    12159.0    24094.0-   10000.0-    5000.0-    7855.0-     838.0-   12000.0
-   12773.0    10000.0     5000.0     4455.0     6000.0      994.0    22773.0    11773.0
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-  14000.0-   5000.0-  10455.0-    838.0-  15617.0-   7000.0-   1000.0  13000.0
   1000.0  10455.0   3855.0-   9000.0-   3600.0-   9000.0-  13000.0-   4000.0
-  2000.0-   1855.0   2000.0   3600.0   3000.0   4000.0   7455.0    500.0
-  5355.0-   3000.0-   9000.0-  11455.0-   2000.0-    500.0   2000.0    400.0
   5455.0    500.0-   755.0-   3000.0-   2500.0   2855.0-  15000.0-  35000.0
CARD 13
     50.0-    200.0-    300.0-    400.0-    500.0-    944.5-   1200.0-   1338.1
    194.5    494.5    438.1    344.5    344.5    689.0    500.0    382.6
-  1000.0    184.5    479.0-    260.6-    316.1-   1471.6-   2282.6-   1582.6
-  1000.0    200.0   1177.7    400.0   1500.0   1500.0-    200.0-    200.0
-  2000.0    190.0    567.7-    200.0-    400.0-    400.0-    600.0-    800.0
-   500.0    800.0-    100.0   1267.7-    200.0   1900.0-    200.0   1700.0
-   200.0    200.0-    200.0    200.0-    300.0-   2000.0    100.0-    617.0
    700.0    300.0   2100.0   2000.0   2300.0    200.0-   1400.0-    217.0
   1467.7-    100.0   1800.0-    300.0   2000.0-    300.0-   1800.0-   231.
    367.7   2519.7   4219.7   1438.7-    500.0   1000.0-    852.0    750.0
   1938.7-    555.0    926.0    675.0    750.0-   1255.0-   3255.0     74.0
   1863.7   1430.0   2000.0-   3315.0-    430.0-   3000.0-   4000.0   2293.0
   4000.0   3000.0-   7315.0   2218.0-    200.0-    220.0-   2035.0   6412.0
   3000.0-   5500.0-   2110.0    500.0-    420.0-    340.0   5892.0   3900.0
-  5600.0-   2470.0-   2775.0   1700.0    400.0-    220.0    200.0   3897.0
   5180.0-   5000.0-   2710.0    125.0   4002.0   3500.0-   5200.0-    530.0
-   554.0-   3000.0   5662.0   3680.0-   4400.0-   3554.0   4442.0    200.0
    380.0-   3174.0-   700.0-    784.0   1200.0   7902.0-   3900.0-   3091.0
-   800.0   1125.0   2100.0   1680.0-    200.0-   1231.0-   1000.0-   3000.0
-  1443.0-    763.0   6907.0-    500.0-   2788.0-   1680.0-    780.0   6737.0
    308.0-   1500.0-   700.0-   1000.0-   3000.0-   1000.0-    808.0-   1182.0
-  2322.0-    792.0    150.0   6717.0-    646.0-   1880.0-   2560.0-    800.0
     75.0-    200.0-    200.0-    600.0-    180.0-    666.0-   1500.0-   3000.0
-  1000.0   1972.0-    466.0-   1086.0-   1480.0   5000.0   1752.0-    900.0
-  2626.0-   2500.0   2200.0    332.0    212.0-    434.0-    309.0   1200.0
-   800.0-   2000.0-   2645.0-    327.0   2180.0   1760.0   1595.0    375.0
-   400.0-    182.0   3000.0   1600.0-    655.0-    800.0-   1890.0-    565.0
-   200.0    925.0   1505.0   1000.0    280.0-    200.0-    305.0   1000.0
-   170.0-    100.0-   1430.0-    480.0-    525.0   2000.0   1880.0   1490.0
   1050.0-    200.0    100.0   1100.0    200.0    320.0-    200.0-    800.0
-   445.0   1075.0    455.0    555.0    535.0    463.0    800.0    200.0
-   200.0-    748.0    766.0    966.0    766.0     18.0
CARD 14
  1    0    0    0
CARD 15
  1    0    0    0
CARD 16
  0    0    0    0
CARD 17
      0.        0.        .004
CARD 18
      0.        0.        .002
CARD 19
     100.     10000.      0.
CARD 20
133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0132.5132.0
133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0133.0
133.0133.0133.0133.0133.0132.5132.5132.5132.5132.0131.5130.5130.0130.0130.0132.5
132.0131.5130.5130.0130.0130.0130.0133.0133.0132.5132.5132.5132.5132.5132.5132.5
132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5
132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5132.5
132.5132.5132.5132.0130.0130.0130.0130.0130.0132.5132.5132.5132.5132.5132.5132.5
132.5132.0132.0131.5130.0130.0130.0130.0130.0130.0132.5132.5132.5132.5132.5132.0
132.0132.0131.5131.5131.0130.5130.5130.5130.5130.5130.5130.5130.5130.5132.0132.0
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131.0131.0131.0130.5130.5130.5130.5130.5130.5130.5130.5130.5130.5131.0131.0130.0
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135.0135.0135.0135.0134.5135.0135.0135.0135.0135.0135.0135.0135.0135.0135.0135.0
135.0135.0133.0130.5130.5
CARD 21
260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0
260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0260.0
260.0260.0260.0258.5260.0260.0260.0259.5254.5250.0260.0260.0257.0253.5250.5253.0
257.0260.0253.5250.5253.0257.0252.5250.0253.0257.0259.0250.0253.0250.5259.5252.5
250.0253.0256.5259.5252.0250.0253.0256.0259.0260.0260.0253.0255.5258.0260.0259.5
260.0253.0255.0257.0259.0260.0258.5259.5260.0254.5256.0258.0259.0260.0257.5259.0
259.5260.0253.5255.5256.5257.5259.0259.5256.5257.0258.5259.0254.5256.0256.5257.5
258.5259.5255.5256.0256.5257.5258.0258.5253.5255.0255.5256.0256.5257.5257.5254.5
255.5255.5256.0256.5257.0254.5255.0255.5256.0256.0257.0254.5255.0255.0256.0254.0
CARD 23
   161300.    2.  .020    0.    0.
   171300.    2.  .020    0.    0.
    47 260.   .5  .020    0.    0.
   105 520.   .5  .020    0.    0.
   186 415.   1.  .020    0.    0.
   315 335.   2.  .020    0.   10.
   341 120.   2.  .020    0.    0.
CARD 24
    4244.5 312.    0.    0.    0.
    5244.5 312.    0.    0.    0.
    6338.1 312.    0.    0.    0.
    7244.5 312.    0.    0.    0.
    8244.5 312.    0.    0.    0.
    9244.5 312.    0.    0.    0.
   10244.5 312.    0.    0.    0.
   11244.5 312.    0.    0.    0.
   12338.1 312.    0.    0.    0.
CARD 25
    3238.6
    4238.6
    5238.6
    6885.7
    7238.6
    8238.6
    9238.6
   10238.6
   11238.6
   12885.7
   13238.6
   14238.6
CARD 27
 340.    0.    0.    0.
```

SAMPLE OUTPUT

CONSTANTS AND OPTIONS USED

TIME STEP= 3.0 HOURS   UPSTREAM CONCENTRATION FACTOR=1.00

THE VERTICAL DIFFUSION COEFFICIENT IS GIVEN A VALUE = .0000150000 FT**2/SEC

CONSTANT DIFFUSION COEFFICIENT USED IN LAYER 1. EC1=3.8000000119 FT**2/SEC

CONSTANT DIFFUSION COEFFICIENT USED IN LAYER 2. EC1=3.8000000119 FT**2/SEC

THE REDISSOLVING COEFFICIENT(RDIS)= .5001-02 1/(DAY)

TEMPERATURE = 7.0 C   THE TEMPERATURE CORRECTION FACTOR FOR BOD DECAY(THETA) 1.030

CONSTANT BENTHIC UPTAKE OF DO IS ASSUMED. RURT= .50 GRAMS/METER**2/DAY
AEROBIC BOD DECAY RATE FOR BRINE= .100 DAY-1   ANAEROBIC BOD DECAY RATE FOR BRINE= .015 DAY-1

AEROBIC BOD DECAY RATE FOR THE BENTHIC DEPOSIT= .000 DAY-1   ANAEROBIC BOD DECAY RATE FOR THE BENTHIC DEPOSIT= .000 DAY-1

DO AERATION COEFFICIENTS AR=12.900 P1= .500 P2=-1.500   BOD SETTLING VELOCITY= .000 FT/SEC

OUTPUT IF ISKIP=1

CHANNEL DATA

CHANNEL NUM	LOW NODE	HIGH NO.	LAYER 1 VELOCITY FEET/SEC	LAYER 1 FLOW FT**3/SEC	LAYER 1 DIFF COEF FT**2/SEC	LAYER 2 VELOCITY FEET/SEC	LAYER 2 FLOW FT**3/SEC	LAYER 2 DIFF COEF FT**2/SEC
1	1	2	-.01128	-.5926+03	.3800+01	NC	NC	NC
2	2	3	-.02923	-.3193+04	.3800+01	NC	NC	NC
3	3	4	-.02430	-.3231+04	.3800+01	NC	NC	NC
4	4	5	-.02477	-.3270+04	.3800+01	.00364	.5000+02	.3800+01
5	5	6	-.02463	-.3250+04	.3800+01	-.00981	-.2000+03	.3800+01
6	6	7	-.02547	-.3434+04	.3800+01	-.01098	-.3000+03	.3800+01
7	7	8	-.02525	-.3337+04	.3800+01	-.01366	-.4000+03	.3800+01
8	8	9	-.02554	-.3371+04	.3800+01	-.01666	-.5000+03	.3800+01
9	9	10	-.02545	-.3360+04	.3800+01	-.03206	-.9445+03	.3800+01
10	10	11	-.02575	-.3398+04	.3800+01	-.04321	-.1200+04	.3800+01
11	11	12	-.02566	-.3387+04	.3800+01	-.06704	-.1338+04	.3800+01
12	12	13	-.02712	-.3427+04	.3800+01	NC	NC	NC
13	13	14	-.03071	-.3161+04	.3800+01	NC	NC	NC
14	15	16	-.03774	-.4360+04	.3800+01	NC	NC	NC
15	16	17	-.07744	-.4060+04	.3900+01	NC	NC	NC
16	17	18	-.08201	-.2560+04	.3800+01	NC	NC	NC
17	18	19	-.07674	-.2560+04	.3800+01	NC	NC	NC
18	19	20	-.05466	-.1360+04	.3800+01	NC	NC	NC
19	1	21	.00357	.5926+03	.3800+01	NC	NC	NC
20	2	22	.01511	.2500+04	.3300+01			

:

REPEATS FOR 746(NC1) CHANNELS

INITIAL NODE CONCENTRATIONS

NODE NUMBER	VERT DIFF COFF FT**2/SEC	****** TDS ****** LAYER 1 G/L	LAYER 2 G/L
1	NO COEF	133.0000	NO NODE
2	NO COEF	133.0000	NO NODE
3	NO COEF	133.0000	NO NODE
4	.0000150000	133.0000	260.0000
5	.0000150000	133.0000	260.0000
6	.0000150000	133.0000	260.0000
7	.0000150000	133.0000	260.0000
8	.0000150000	133.0000	260.0000
9	.0000150000	133.0000	260.0000
10	.0000150000	133.0000	260.0000
11	.0000150000	133.0000	260.0000
12	.0000150000	133.0000	260.0000
13	NO COEF	133.0000	NO NODE
14	NO COEF	133.0000	NO NODE
15	NO COEF	133.5000	NO NODE
16	NO COEF	133.0000	NO NODE
17	NO COEF	133.0000	NO NODE
18	NO COEF	133.0000	NO NODE
19	NO COEF	133.0000	NO NODE
20	NO COEF	133.0000	NO NODE

:

REPEATS FOR 373(NN1) NODES

INFLOW AND OUTFLOW DATA

NODE NUMBER	LAYER	INFLOW CFS	TDS G/L
16	1	1300.00	2.0000
17	1	1300.00	2.0000
47	1	260.00	.5000
105	1	520.00	.5000
186	1	415.00	1.0000
315	1	375.00	2.0000
341	1	120.00	2.0000
4	2	244.50	312.0000
5	2	244.50	312.0000
6	2	338.10	312.0000
7	2	244.50	312.0000
8	2	244.50	312.0000
9	2	244.50	312.0000
10	2	244.50	312.0000
11	2	244.50	312.0000
12	2	338.10	312.0000

NODE NUMBER	LAYER	OUTFLOW CFS
3	1	238.60
4	1	238.60
5	1	238.60
6	1	885.70
7	1	238.60
8	1	238.60
9	1	238.60
10	1	238.60
11	1	238.60
12	1	885.70
13	1	238.60
14	1	238.60

OUTPUT IF IBB=1

LAKE BOTTOM DATA

NODE NUMBER	TDS CONC G/FT**2
1	100.000
2	100.000
3	100.000
4	100.000
5	100.000
6	100.000
7	100.000
8	100.000
9	100.000
10	100.000
11	100.000
12	100.000
13	100.000
14	100.000
15	100.000

:

REPEATS FOR 373(NN1) NODES

NODE CONCENTRATIONS AFTER 3.00 HOURS

NODE NUMBER	****** TDS ****** LAYER 1 G/L	LAYER 2 G/L	******
1	133.0000	NO NODE	
2	133.0000	NO NODE	
3	133.0000	NO NODE	
4	133.0620	262.1778	
5	133.0574	260.9559	
6	133.0550	261.0984	
7	133.0541	260.6592	
8	133.0537	260.6320	
9	133.0536	260.6290	
10	133.0540	260.6547	
11	133.0547	260.7029	
12	133.0598	262.1258	
13	133.0000	NO NODE	
14	133.0000	NO NODE	
15	132.4438	NO NODE	
16	125.7259	NO NODE	
17	126.0412	NO NODE	
18	132.8724	NO NODE	
19	132.7437	NO NODE	
20	132.5575	NO NODE	

⋮

REPEATS FOR 373(NN1) NODES

OUTPUT IF IBB=1

LAKE BOTTOM DATA

NODE NUMBER	TDS CONC G/FT**2
1	100.000
2	100.000
3	100.000
4	100.000
5	100.000
6	100.000
7	100.000
8	100.000
9	100.000
10	100.000
11	100.000
12	100.000
13	100.000
14	100.000

⋮

REPEATS FOR 373(NN1) NODES

APPENDIX B

WATER AND SALINITY BALANCE MODEL

The water and salinity balance model was formulated to simulate the water and salinity balance for Great Salt Lake on a monthly basis. However, the stability criteria dictated by the vertical mass transport between layers of the south arm restricted the time step used in the simulation to less than a monthly period. A 12 hour time step was used in simulating the water and salinity balance during this study.

Data input to the model consist of initial lake conditions and information related to the monthly water balance. The initial conditions input to the model include the initial volume and surface area of both arms, the initial total dissolved solids concentration associated with the north arm and each layer of the south arm, and the initial mass of salt on the bottom of each arm. The monthly water balance data include the surface and groundwater inflows, the rate of precipitation, the potential rate of evaporation, and the evapotranspiration. In the model this information is converted to units compatible with the calculation of the water balance on a time period of less than one month. The method which is used in the model to reduce the monthly data to compatible units restricts the model to a water year simulation and a maximum time step of 24 hours.

The program outputs the initial lake conditions and the simulated lake conditions at the end of each month. The output includes the inflow and outflow from each arm of the lake in acre-feet during the month and the elevation in feet, volume in acre-feet, and concentration of total dissolved solids in grams per liter for each arm at the end of each month of the water year. The model requires approximately 6.5 seconds of computer use time on a UNIVAC 1108 to simulate a complete water year.

INPUT DATA LAYOUT

Card	Col.	Identifier	
Card 1	1-5	NP	Card input devise code
	6-10	NP	Output devise code for print
		FORMAT (16I5)	
Card 2	1-5	NEDZ	Number of south arm brine layer
	6-10	IF	First south arm brine layer which contributed to flow north through the causeway fill
	11-15	IFCE	First south arm brine layer which contributed to flow north through the causeway's east culvert
	16-20	IFCW	First south arm brine layer which contributes to flow north through the causeway's west culvert
	21-25	NTS	Number of time steps during simulation period
	26-30	DELT	Length of time step (Hours)
	31-35	NYR	Number of years to be simulated
	36-40	NITE	Maximum number of iterations in calculating causeway flows
		FORMAT (16I5)	
Card 3	1-10	ELEVS	Initial surface elevation of south arm (feet above mean sea level)
	11-20	ELEVN	Initial surface elevation of north arm (feet above mean sea level)
	21-30	CPPT	Concentration at which the precipitation of TDS begins (g/l)
	31-40	RDIS	Redissolving coefficient (Day^{-1})
	41-50	VOLS	Initial volume of south arm (acre feet)
	51-60	VOLN	Initial volume of north arm (acre feet)
	61-70	CF	Conversion factor (Liters/acre feet)
	71-80	CFM	Conversion factor (Liter/cubic feet)
	1-10	EEC	Elevation of bottom of causeway's east culvert (feet above mean sea level)
	11-20	EWC	Elevation of bottom of causeway's west culvert (feet above mean sea level)
	21-30	QSEO	Initial estimate of north to south flow through the east culvert (cfs)
	31-40	QNEO	Initial estimate of south to north flow through the west culvert (cfs)
	41-50	QSWO	Initial estimate of north to south flow through the west culvert (cfs)
	51-60	QNWO	Initial estimate of south to north flow through the west culvert (cfs)
	61-70	EPP	Accuracy desired in calculating culvert flows (cfs)
	71-80	W	Culvert width (feet)
		FORMAT (8F10.0)	
Card 4	1-10	CKQ	Coefficient for adjusting ΔH
		FORMAT (8F10.0)	
Card 5	1-5	DELZ(1)	Thickness of layer 1 (feet)
	.	.	
	.	.	
		DELZ(NEDZ)	Initial thickness of layer NEDZ
		FORMAT (16F5.0)	
Card 6	1-10	E(1)	Vertical diffusion coefficient between layer 1 and layer 2 (Ft^2/sec)
		.	
		.	
		E(NEDZ-1)	Vertical diffusion coefficient between layer NEDZ-1 and layer NEDZ
		FORMAT (8F10.0)	
Card 7	1-10	AREAB	Area of lake bottom underlying layer 1 of the south arm (acres)
	21-30	AREA(1)	Surface area of layer 1 (acres)
	.	.	
	.	.	
		AREA(NEDZ-1)	Surface area of layer NEDZ-1
		FORMAT (8F10.0)	
Card 8	1-10	VOL(1)	Volume of layer 1 (acre feet)
	.	.	
	.	.	
		VOL(NEDZ-1)	Volume of layer NEDZ-1
		FORMAT (8F10.0)	
Card 9	1-5	CN	Initial concentration of north arm brine (g/l)
	6-10	C(1)	Initial concentration of layer 1 (g/l)
	.	.	
	.	.	
		C(NEDZ)	Initial concentration of layer (NEDZ)
		FORMAT (16F5.0)	
Card 10	1-10	DASSBS	Initial mass of salt on the bottom of the south arm (million metric tons)
	11-20	DASSBN	Initial mass of salt on the bottom of the north arm (million metric tons)
		FORMAT (8F10.0)	
Card 11	1-5	FLW(1,1)	Surface inflow to lake for month 1 year 1 (thousands of acre feet per month)
	.	.	
	.	.	
	56-60	FLW(12,1)	Surface inflow to lake month 12 year 1
		Repeat 1 card for each NYR years	
		FORMAT (12F5.0, 20X)	
Card 12	1-5	PPT(1,1)	Precipitation for month 1 year 1 (inches per month)
	.	.	
	.	.	
	56-60	PPT(12,1)	Precipitation for month 12 year 1 (inches per month)
		Repeat 1 card for each NYR years	
		FORMAT (12F5.0, 12X)	
Card 13	1-5	PEVAP(1,1)	Potential evaporation for month 1 year 1 (inches per month)
	.	.	
	.	.	
	56-60	PEVAP(1,12)	Potential evaporation for month 12 year 1
		Repeat 1 card for each NYR years	
		FORMAT (12F5.0, 12X)	
Card 14	1-5	ELC(1)	Pan evaporation coefficient for month 1
	.	.	
	.	.	
	56-60	ELC(12)	Pan evaporation coefficient for month 12
		FORMAT (12F5.0, 12X)	

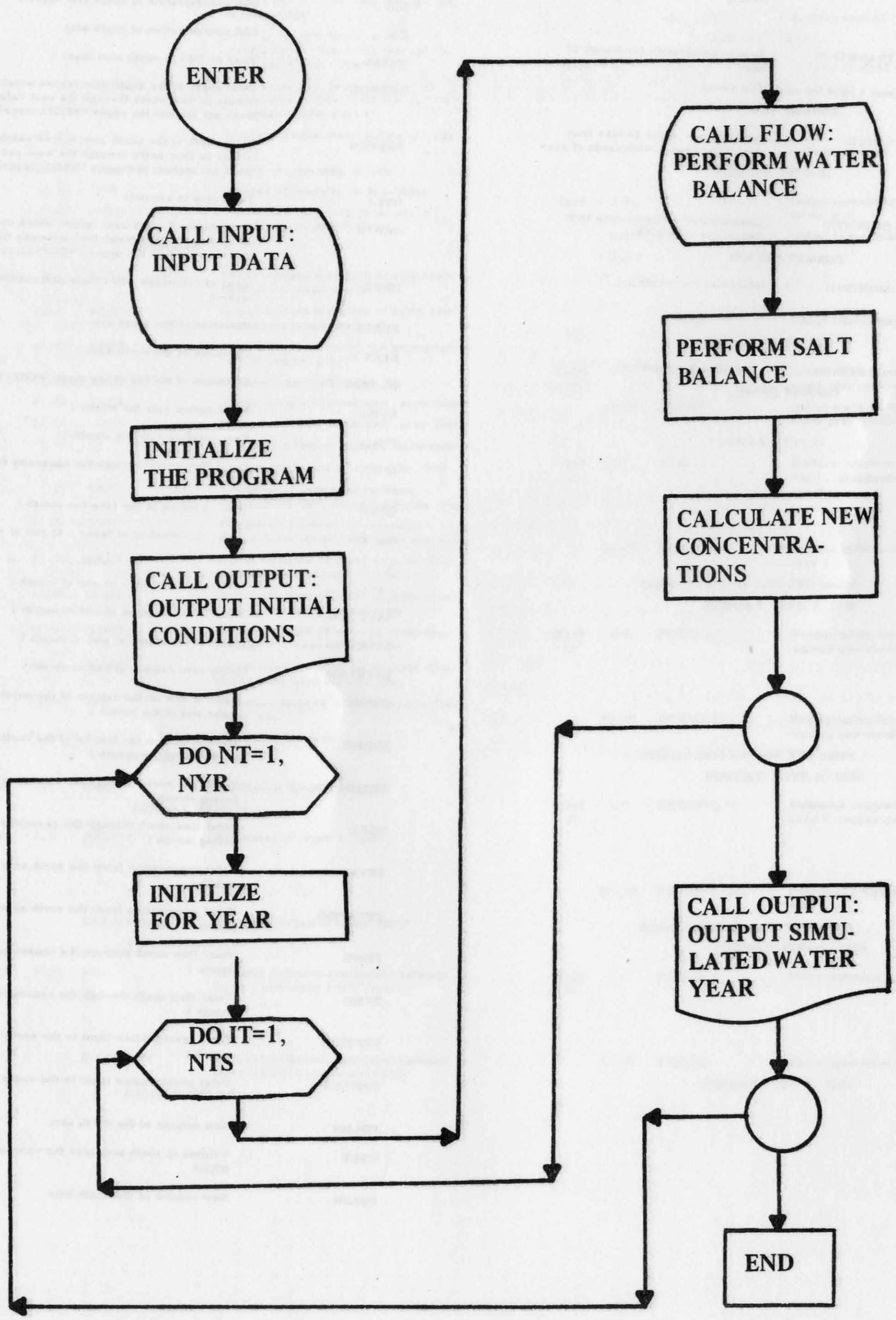
	Col.	Identifier	
Card 15	1-5	TRANS(1, 1)	Evapotranspiration for month 1 year 1 (thousands of acre feet per month)
	.	.	
	.	.	
	.	.	
	56-60	TRANS(12, 1)	Evapotranspiration for month 12 year 1
	Repeat 1 card for each NYR years		
	FORMAT (12F5.0, 12X)		
Card 16	1-5	GWD(1)	Groundwater inflow to lake from desert for year 1 (thousands of acre feet per month)
	.	.	
	.	.	
	.	.	
		GWD(NYR)	Groundwater inflow to lake from desert for year NYR
	FORMAT (16F5.0)		
Card 17	1-4	MONTH(1)	Identifier for month 1
	.	.	
	.	.	
	45-48	MONTH(12)	Identifier for month 12
	FORMAT (20A4)		

Table B-1. Principal variables in the water and salinity balance model.

Table B1. Principal Variables in the Water and Salinity Balance Model

Variable	Description
C(I)	TDS concentration of south arm layer I
CN	TDS concentration of north arm
DASS(I)	Mass of TDS in south arm layer I
DEEPCE	Total depth of the south arm layers which contribute to flow north through the east culvert [does not include the upper (NEDZ) layer]
DEEPCW	Total depth of the south arm layers which contribute to flow north through the west curvert [does not include the upper (NEDZ) layer]
DELT	Time step in seconds
DEPTH	Total depth of south arm layers which contribute to flow north through the causeway fill [does not include the upper (NEDZ) layer]
DPPT(I)	Mass of TDSwhich will create saturation in layer I
ELEVS	Elevation of the south arm
ELEVN	Elevation of the north arm
ELNDZN	Elevation of the top of the layer NEDZ-1
EVP(I)	Evaporation rate for month I
P(I)	Precipitation rate for month I
Q(I)	Total flow north through the causeway for layer I
QIN(I)	Rate of inflow to the lake for month I
SAVEC(I, I)	TDS concentration of layer I at end of month I
SAVECN	[illegible] north [illegible]
SAVELN(I)	North arm elevation at end of month I
SAVELS(I)	South arm elevation at end of month I
SAVEVN(I)	North arm volume at end of month I
SAVEVS(I)	South arm volume at end of month I
SDBN(I)	Mass of salt on the bottom of the north arm at the end of the month I
SDBS(I)	Mass of salt on the bottom of the south arm at the end of the month I
TCN(I)	Total flow north through the causeway's culverts during month I
TCS(I)	Total flow south through the causeway's culverts during month I
TEVAPN(I)	Total evaporation from the north arm during month I
TEVAPS(I)	Total evaporation from the south arm during month I
TFN(I)	Total flow north through the causeway during month I
TFS(I)	Total flow south through the causeway during month I
TPPTN(I)	Total precipitation input to the north arm during month I
TPPTS(I)	Total precipitation input to the south arm during month I
VOLNN	New volume of the north arm
VOLT	Volume of south arm less the volume of layer NEDZ
VOLSN	New volume of the south arm

WATER AND SALINITY BALANCE MODEL



WATER AND SALINITY BALANCE MODEL LISTING

```
      COMMON AREA(50),C(50),DASS(50),DELZ(50),DPPT(50),E(50),ELC(12),
     1EVP(12),FLW(12,40),GWI(12,40),PEVAP(12,40),PPT(12,40),P(12),
     2Q(50),QIN(12),SAVEVS(12),SAVEVN(12),SAVEC(50,12),SAVECN(12),
     3SAVELS(12),SAVELN(12),SDBN(12),SDBS(12),TEVAPN(12),TEVAPS(12),
     4TFN(12),TFS(12),TPPTN(12),TPPTS(12),VOL(50),MONTH(12),
     5TCN(12),TCS(12),
     4IDELT,JF,JFCE,JFCW,JFM,NEDZ,NEDZM,NITE,NP,NTS,NYR,
     5AREAB,CKQ,          CF,CFM,CN,CPPT,DASSBN,DASSBS,DEEPCE,DEEPCW,
     6DELT,DEPTH,EEC,EWC,ELEVS,ELEVN,ELNDZM,EPP,QNEO,QNWO,QSEO,QSWO,
     7RDIS,VOLN,VOLS,VOLT,W,VOLSN,VOLNN,DELTZN,QST
      CALL INPUT
C *** SUM THE CONSTANT VOLUMES
      VOLT=0.
      DO 103 I=1,NEDZM
  103 VOLT=VOLT+VOL(I)
      VOL(NEDZ)=VOLS-VOLT
      DEPTH=0.
      DO 202 IJ=JF,NEDZM
  202 DEPTH=DEPTH+DELZ(IJ)
      DEEPCE=0.
      DO 203 IJ=JFCE,NEDZM
  203 DEEPCE=DEEPCE+DELZ(IJ)
      DEEPCW=0.
      DO 204 IJ=JFCW,NEDZM
  204 DEEPCW=DEEPCW+DELZ(IJ)
C *** ESTABLISH MASS IN EACH LAYER AND MASS AT WHICH PPT BEGINS
      DO 104 I=1,NEDZ
      DASS(I)=VOL(I)*C(I)*CF
  104 DPPT(I)=VOL(I)*CPPT*CF
      DASSN=VOLN*CN*CF
      DPPTN=VOLN*CPPT*CF
C *** CHANGE AREA TO FEET**2
      DO 301 I=1,NEDZM
  301 AREA(I)=AREA(I)*43560.
      AREAB=AREAB*43560.
      IP=0
      NT=0
      CALL OUTPUT(IP,NT)
      AKCP=1./(12.*24.*3600.)
C *** ENTER MAIN LOOPS
      DO 200 NT=1,NYR
      DO 208 I=1,12
      TPPTS(I)=0.
      TPPTN(I)=0.
      TEVAPS(I)=0.
      TEVAPN(I)=0.
      TCN(I)=0.
      TCS(I)=0.
      TFN(I)=0.
  208 TFS(I)=0.
      DO 207 I=1,12
      GO TO(206,205,206,206,105,206,205,206,205,206,206,205),I
  105 QIN(I)=(FLW(I,NT)/28.)*.50417
C *** P AND EVP AS FT/SEC
      P(I)=(PPT(I,NT)/28.)*AKCP
      EVP(I)=(PEVAP(I,NT)/28.)*AKCP
      GO TO 207
  205 QIN(I)=(FLW(I,NT)/30.)*.50417
      P(I)=(PPT(I,NT)/30.)*AKCP
      EVP(I)=(PEVAP(I,NT)/30.)*AKCP
      GO TO 207
  206 QIN(I)=(FLW(I,NT)/31.)*.50417
      P(I)=(PPT(I,NT)/31.)*AKCP
      EVP(I)=(PEVAP(I,NT)/31.)*AKCP
  207 CONTINUE
      I=1
      ICT=0
      DO 199 IT=1,NTS
C *** ESTABLISH FLOWS BETWEEN THE NORTH AND SOUTH ARMS
      CALL FLOW(I,ICT)
C *** MOVEMENT OF TDS
C *** SOUTH ARM
      DIFF1=AREA(1)*E(1)*CFM*((C(2)-C(1))/(.5*(DELZ(2)+DELZ(1))))
C *** BOTTOM LAYER
      DASS(1)=DASS(1)+(QST*CN*CFM+DIFF1)*DELT
      DO 106 IM=2,NEDZM
      DIFF2=AREA(IM)*E(IM)*CFM*((C(IM+1)-C(IM))/(.5*(DELZ(IM+1)+DELZ(IM)
     $)))
      DASS(IM)=DASS(IM)+(DIFF2-DIFF1-Q(IM)*C(IM)*CFM)*DELT
  106 DIFF1=DIFF2
C *** TOP LAYER
      DASS(NEDZ)=DASS(NEDZ)+(-Q(NEDZ)*C(NEDZ)*CFM-DIFF1)*DELT
      IF(DASS(1).GE.DPPT(1)) GO TO 107
      IF(DASSBS.LE.0.) GO TO 107
      DIS=RDIS*(CPPT-C(1))*DELT*VOL(1)*CF
      IF(DIS.GT.DASSBS) DIS=DASSBS
      DASS(1)=DASS(1)+DIS
      DASSBS=DASSBS-DIS
C *** CALCULATE PRECIPITATION OF SALT
  107 L=NEDZ
  109 IF(DASS(L).LE.DPPT(L)) GO TO 108
      SPPT=DASS(L)-DPPT(L)
      DASS(L)=DPPT(L)
      DASS(L-1)=DASS(L-1)+SPPT
  108 L=L-1
      IF(L.GT.1) GO TO 109
      IF(DASS(1).LE.DPPT(1)) GO TO 110
      SPPT=DASS(1)-DPPT(1)
      DASS(1)=DPPT(1)
      DASSBS=DASSBS+SPPT
C *** NORTH ARM
  110 DO 111 IJF=1,NEDZ
  111 DASSN=DASSN+Q(IJF)*C(IJF)*CFM*DELT
      DASSN=DASSN-QST*CN*CFM*DELT
C *** TEST TO DISSOLVE OR PRECIPITATE SALT
      SUBN=DASSN-DPPTN
      IF(SUBN) 112,114,113
C *** DISSLOVE SALT
  112 IF(DASSBN.LE.0.) GO TO 114
      DIS=RDIS*(CPPT-CN)*DELT*VOLN*CF
      IF(DIS.GT.DASSBN) DIS=DASSBN
      DASSN=DASSN+DIS
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      IF(DASSN.GT.DPPTN) GO TO 214
      DASSBN=DASSBN-DIS
      GO TO 114
  214 DASSN=DPPTN
      DASSBN=DASSBN-DIS+DASSN-DPPTN
      GO TO 114
C *** CALCULATE PRECIPITATION OF SALT
  113 DASSN=DASSN-SUBN
      DASSBN=DASSBN+SUBN
C *** CONVERT TO NEW CONCENTRATIONS
  114 VOLN=VOLNN
      VOLS=VOLSN
      VOL(NEDZ)=VOLSN-VOLT
      DELZ(NEDZ)=DELTZN
      DPPT(NEDZ)=VOL(NEDZ)*CPPT*CF
      DPPTN=VOLN*CPPT*CF
      DO 115 IK=1,NEDZ
  115 C(IK)=DASS(IK)/(VOL(IK)*CF)
      CN=DASSN/(VOLN*CF)
  199 CONTINUE
      IP=1
      CALL OUTPUT(IP,NT)
  200 CONTINUE
      STOP
      END
      SUBROUTINE INPUT
      COMMON AREA(50),C(50),DASS(50),DELZ(50),DPPT(50),E(50),ELC(12),
     1EVP(12),FLW(12,40),GWI(12,40),PEVAP(12,40),PPT(12,40),P(12),
     2Q(50),QIN(12),SAVEVS(12),SAVEVN(12),SAVEC(50,12),SAVECN(12),
     3SAVELS(12),SAVELN(12),SDBN(12),SDBS(12),TEVAPN(12),TEVAPS(12),
     4TFN(12),TFS(12),TPPTN(12),TPPTS(12),VOL(50),MONTH(12),
     5TCN(12),TCS(12),
     4IDELT,JF,JFCE,JFCW,JFM,NEDZ,NEDZM,NITE,NP,NTS,NYR,
     5AREAB,CKQ,           CF,CFM,CN,CPPT,DASSBN,DASSBS,DEEPCE,DEEPCW,
     6DELT,DEPTH,EEC,EWC,ELEVS,ELEVN,ELNDZM,EPP,QNEO,QNWO,QSEO,QSWO,
     7RDIS,VOLN,VOLS,VOLT,W,VOLSN,VOLNN,DELTZN,QST
      DIMENSIONGWD(40),TRANS(12,40)
      READ(5,1) NR,NP
    1 FORMAT(16I5)
      READ(NR,1) NEDZ,JF,JFCE,JFCW,NTS,IDELT,NYR,NITE
      NEDZM=NEDZ-1
      JFM=JF-1
      READ(NR,2)       ELEVS,ELEVN,CPPT,RDIS,VOLS,VOLN,CF,CFM,EEC,EWC,
     $QSEO,QNEO,QSWO,QNWO,EPP,W
      READ(NR,2) CKQ
    2 FORMAT(8F10.0)
C
C *** INPUT THICKNESS OF EACH LAYER(FEET)
C
      READ(NR,3) (DELZ(J),J=1,NEDZ)
    3 FORMAT(16F5.0)
C *** INPUT DIFFUSION COEFFCIIENTS (FT**2/SEC.)
      READ(NR,2)(E(J),J=1,NEDZM)
C *** INPUT SURFACE AREA FOR EACH LAYER IN SOUTH ARM(ACRES)
      READ(NR,2) AREAB,(AREA(J),J=1,NEDZM)
C *** INPUT VOLUMES (ACRE-FEET)
      READ(NR,2) (VOL(J),J=1,NEDZM)
C *** INPUT INITIAL CONCENTRATIONS IN EACH LAYER (G/L)
      READ(NR,3) CN,(C(J),J=1,NEDZ)
C *** INPUT INITIAL MASS ON BOTTOM OF BOTH ARMS (MILLION METRIC TONS)
      READ(NR,2) DASSBS,DASSBN
C *** INPUT DATA FOR WATER BALANCE
C *** MONTHLY INFLOW IN THOUSANS OF ACRE FEET
      READ(NR,4) ((FLW(I,N),I=1,12),N=1,NYR)
    4 FORMAT(12F5.0,20X)
C *** MONTHLY PRECIP IN INCHES
      READ(NR,4) ((PPT(I,N),I=1,12),N=1,NYR)
C *** MONTHLY POTENTIAL EVAPORATION IN INCHES
      READ(NR,4) ((PEVAP(I,N),I=1,12),N=1,NYR)
      READ(NR,4) (ELC(I),I=1,12)
C *** MONTHLY EVAPOTRANSPIRATION IN THOUSANDS OF ACRE FEET
      READ(NR,4) ((TRANS(I,N),I=1,12),N=1,NYR)
C *** MONTHLY GROUNDWATER INFLOW FROM DESERT IN THOUSANDS OF ACRE FEET
      READ(NR,3) (GWD(N),N=1,NYR)
      READ(NR,5) (MONTH(I),I=1,12)
    5 FORMAT(20A4)
C *** DATA REDUCTION
C *** CONVERT FROM METRIC TONS TO GRAMS
      DASSBS=DASSBS*10.**12
      DASSBN=DASSBN*10.**12
C *** TOTAL INFLOW TO THE LAKE
      DO 106 N=1,NYR
      DO 105 I=1,12
      GWI(I,N)=(.06*FLW(I,N)+GWD(N))*1000.
  105 FLW(I,N)=(FLW(I,N)-TRANS(I,N))*1000.+GWI(I,N)
  106 CONTINUE
      DELT=FLOAT(IDELT)*3600.
      ELNDZM=ELEVS-DELZ(NEDZ)
      RDIS=RDIS/86400.
      RETURN
      END
      SUBROUTINE FLOW(I,ICT)
      COMMON AREA(50),C(50),DASS(50),DELZ(50),DPPT(50),E(50),ELC(12),
     1EVP(12),FLW(12,40),GWI(12,40),PEVAP(12,40),PPT(12,40),P(12),
     2Q(50),QIN(12),SAVEVS(12),SAVEVN(12),SAVEC(50,12),SAVECN(12),
     3SAVELS(12),SAVELN(12),SDBN(12),SDBS(12),TEVAPN(12),TEVAPS(12),
     4TFN(12),TFS(12),TPPTN(12),TPPTS(12),VOL(50),MONTH(12),
     5TCN(12),TCS(12),
     4IDELT,JF,JFCE,JFCW,JFM,NEDZ,NEDZM,NITE,NP,NTS,NYR,
     5AREAB,CKQ,           CF,CFM,CN,CPPT,DASSBN,DASSBS,DEEPCE,DEEPCW,
     6DELT,DEPTH,EEC,EWC,ELEVS,ELEVN,ELNDZM,EPP,QNEO,QNWO,QSEO,QSWO,
     7RDIS,VOLN,VOLS,VOLT,W,VOLSN,VOLNN,DELTZN,QST
C *** INCREMENT I (COUNTER ON MONTH) IF APPROPRIATE
      ICT=ICT+IDELT
      GO TO(116,115,116,116,114,116,115,116,115,116,116,115),I
  114 IF(ICT.GT.672) GO TO 215
      GO TO 117
  115 IF(ICT.GT.720) GO TO 215
      GO TO 117
  116 IF(ICT.GT.744) GO TO 215
      GO TO 117
  215 SAVEVS(I)=VOLS
      SAVEVN(I)=VOLN
      SAVECN(I)=CN
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      SAVELS(I)=ELEVS
      SAVELN(I)=ELEVN
      SDBS(I)=DASSBS
      SDBN(I)=DASSBN
      DO 214 IL=1,NEDZ
  214 SAVEC(IL,I)=C(IL)
      I=I+1
      ICT=IDELT
  117 CONTINUE
C *** ESTABLISH AVERAGE CONCENTRATION
      CS=0.
      DO 118 II=1,NEDZ
  118 CS=CS+C(II)*(VOL(II)/VOLS)
      GO TO (121,120,121,121,119,121,120,121,120,121,121,120),I
  119 IF(ICT.GT.336) GO TO 122
      ITEMP=2*I-1
      GO TO 125
  122 ITEMP=2*I
      GO TO 125
  120 IF(ICT.GT.360) GO TO 123
      ITEMP=2*I-1
      GO TO 125
  123 ITEMP=2*I
      GO TO 125
  121 IF(ICT.GT.372) GO TO 124
      ITEMP=2*I-1
      GO TO 125
  124 ITEMP=2*I
C *** BRINE TEMPERATURE
  125 TEMPB=12.5+12.*SIN(.262*FLOAT(ITEMP)-3.53)
C *** SPECIFIC GRAVITY
      F=((8.*TEMPB-TEMPB**2+132416.)/132432.)/.99823
      S1=(1.+.63*CS/1000.)*F
      S2=(1.+.63*CN/1000.)*F
      A=S2-S1
      B=ELEVS-ELEVN
      B=B-CKQ*B**.6
C *** SURFACE AREAS OF EACH ARM IN FEET**2
      ELS4=ELEVS-4000.
      ASURFS=(509380.-7262.5*ELS4+34.1625*ELS4**2-.052836*ELS4**3)*1000.
     $*43560.
      ELN4=ELEVN-4000.
      ASURFN=(960910.-14644.8*ELN4+74.3108*ELN4**2-.1255*ELN4**3)*1000.
     $*43560.
C *** CALCULATE PRECIPITATION INPUT(CFS)
      APS=P(I)*ASURFS
      APN=P(I)*ASURFN
      TPPTS(I)=TPPTS(I)+APS*DELT
      TPPTN(I)=TPPTN(I)+APN*DELT
C *** CALCULATE EVAPORATION RATE(CFS)
      EVAPS=EVP(I)*ASURFS*ELC(I)*(1.-.778*C(NEDZ)/(1000.*S1))
      EVAPN=EVP(I)*ASURFN*ELC(I)*(1.-.778*CN/(1000.*S2))
      EVAPN=EVAPN*1.2
      TEVAPS(I)=TEVAPS(I)+EVAPS*DELT
      TEVAPN(I)=TEVAPN(I)+EVAPN*DELT
C *** FLOW THROUGH CAUSEWAY
C
C *** EAST CULVERT FLOWS BY ITERATION
      Y1=ELEVS-EEC
      Y2=Y1-B
      YL1=-6.3*Y2-5.84*A*Y1+7.09*Y1
      YL2=6.39*Y2+5.94*A*Y1-6.23*Y1
      IF(YL1.LT..1) YL1=.1
      IF(YL2.LT..1) YL2=.1
      CFS=(3.55*(Y1-(YL1+YL2))/(Y1-Y2))-1.02
      CFSP=(3.83*(Y1-(YL1+YL2))/(Y1-Y2))-1.19
      IF(CFS.LT..01) CFS=.01
      IF(CFS.GT.3.0) CFS=3.0
      IF(CFSP.LT..01) CFSP=.01
      IF(CFSP.GT.3.0) CFSP=3.0
      CFSP1=CFSP+1.
      CFS1=CFS+1
      DO 126 ITI=1,NITE
      VSE=QSEO/(W*YL2)
      CFSD=CFS*VSE/CFS1
      QNE=         (Y1-YL1-YL2-CFS*VSE**2/64.4)*64.4/CFS1+CFSD**2
      IF(QNE.GT.0.) GO TO 325
      QNE=0.
      VNE=0.
      GO TO 228
  325 QNE=W*YL1*(QNE**.5-CFSD)
      IF(QNE.LT.0.) QNE=0.
      VNE=QNE/(W*YL1)
  228 CFSPD=CFSP*VNE/CFSP1
      QSE=         ( Y2-YL2-YL1*S1/S2-CFSP*VNE**2/64.4)*64.4/CFSP1+CFSPD**2
      IF(QSE.GT.0.) GO TO 327
      QSE=0.
      GO TO 328
  327 QSE=W*YL2*(QSE**.5-CFSPD)
      IF(QSE.LT.0.) QSE=0.
  328 TOT=ABS(QNEO-QNE)+ABS(QSEO-QSE)
      IF(TOT.LE.EPP) GO TO 127
      QSEO=QSE
  126 QNEO=QNE
  127 IF(QSE.LT.1.) QSE=1.
      IF(QNE.LT.1.) QNE=1.
      Y1=ELEVS-EWC
      Y2=Y1-B
      YL1=-6.3*Y2-5.94*A*Y1+7.09*Y1
      YL2=6.39*Y2+5.94*A*Y1-6.23*Y1
      IF(YL1.LT..1) YL1=.1
      IF(YL2.LT..1) YL2=.1
      CFS=(3.55*(Y1-(YL1+YL2))/(Y1-Y2))-1.02
      CFSP=(3.83*(Y1-(YL1+YL2))/(Y1-Y2))-1.19
      IF(CFS.LT..01) CFS=.01
      IF(CFS.GT.3.0) CFS=3.0
      IF(CFSP.LT..01) CFSP=.01
      IF(CFSP.GT.3.0) CFSP=3.0
      CFS1=CFS+1
      CFSP1=CFSP+1.
      DO 128 ITI=1,NITE
      VSW=QSWO/(W*YL2)
      CFSD=CFS*VSW/CFS1
      QNW=         (Y1-YL1-YL2-CFS*VSW**2/64.4)*64.4/CFS1+CFSD**2
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      IF(QNW.GT.0.) GO TO 329
      QNW=0.
      VNW=0.
      GO TO 232
  329 QNW=W*YL1*(QNW**.5-CFSD)
      IF(QNW.LT.0.) QNW=0.
      VNW=QNW/(W*YL1)
  232 CFSPD=CFSP*VNW/CFSP1
      QSW=      ( Y2-YL2-YL1*S1/S2-CFSP*VNW**2/64.4)*64.4/CFSP1+CFSPD**2
      IF(QSW.GT.0.) CO TO 331
      QSW=0.
      GO TO 332
  331 QSW=W*YL2*(QSW**.5-CFSPD)
      IF(QSW.LT.0.) QSW=0.
  332 TOT=ABS(QNWO-QNW)+ABS(QSWO-QSW)
      IF(TOT.LE.ESP) GO TO 129
      QSWO=QSW
  128 QNWO=QNW
  129 IF(QSW.LT.1.) QSW=1.
      IF(QNW.LT.1.) QNW=1.
      Q1F=6.9835-1675.*A+158.97*B+45535.*A**2-3773.3*A*B+14.01*B**2
     $-429070.*A**3.+34904.*A**2.*B-631.2*A*B**2.+48.556*B**3.
     $+1302000.*A**4.-105270.*A**3.*B-176.07*A*B**3.-5.4593*B**4.+3352.1
     $*A**2.*B**2.
      Q1F=Q1F*69.3936
      IF(Q1F.LT.0.0) Q1F=0.
      Y2F    =19.307+242.23*A-35.429*B-4339.9*A**2.+407.5*A*B
     $+14.332*B**2.+19021.*A**3.-1466.8*A**2.*B-45.647*A*B**2.
     $-3.8069*B**3.
      Q2F    =(2.1629+1290.3*A-113.24*B-19649.*A**2.-912.81*A*B
     $+196.17*B**2.+195100.*A**3.+20974.*A**2.*B-1861.6*A*B**2.
     $-18.802*B**3.-629690.*A**4.-66502.*A**3.*B+308.06*A*B**3.
     $-15.187*B**4.+2965.3*A**2.*B**2.)*(1.-((4139.5-ELEVS)/Y2F)*1.312)
      Q2F=Q2F*69.3936
      IF(Q2F.LT.0.) Q2F=0.
C *** TOTAL MONTHLY FLOWS THROUGH CAUSEWAY
      TFN(I)=TFN(I)+(QNE+QNW+Q1F)*DELT
      TFS(I)=TFS(I)+(QSE+QSW+Q2F)*DELT
      TCN(I)=TCN(I)+(QNE+QNW)*DELT
      TCS(I)=TCS(I)+(QSE+QSW)*DELT
C *** NEW VOLUMES
      QST=QSE+QSW+Q2F
      AQF=QNE+QNW+Q1F-QSE-QSW-Q2F
      VOLNN=VOLN+(AQF+APN-EVAPN)*DELT/43560.
      ELEVN=4182.592+(VOLNN/10983.23-224.32)**.5
      VOLSN=VOLS+(QIN(I)+APS-AQF-EVAPS)*DELT/43560.
      ELEVS=4186.393+(VOLSN/25079.62-201.277)**.5
      DELTZN=ELEVS-ELNDZM
C *** CALCULATE SOUTH TO NORTH FLOW OF THE VARIOUS LAYERS
      DO 130 IJ=1,NEDZ
  130 Q(IJ)=0.
C *** FILL FLOW
      TDEPTH=DEPTH+DELZ(NEDZ)
      DO 131 IJ=JF,NEDZ
  131 Q(IJ)=Q1F*(DELZ(IJ)/TDEPTH)
C *** CULVERT FLOWS
      TDE=DEEPCE+DELZ(NEDZ)
      DO 132 IJ=JFCE,NEDZ
  132 Q(IJ)=Q(IJ)+QNE*(DELZ(IJ)/TDE)
      TDW=DEEPCW+DELZ(NEDZ)
      DO 133 IJ=JFCW,NEDZ
  133 Q(IJ)=Q(IJ)+QNW*(DELZ(IJ)/TDW)
      RETURN
      END
        SUBROUTINE OUTPUT(IP,NT)
      COMMON AREA(50),C(50),DASS(50),DELZ(50),DPPT(50),E(50),ELC(12),
     1EVP(12),FLW(12,40),GWI(12,40),PEVAP(12,40),PPT(12,40),P(12),
     2Q(50),QIN(12),SAVEVS(12),SAVEVN(12),SAVEC(50,12),SAVECN(12),
     3SAVELS(12),SAVELN(12),SDBN(12),SDBS(12),TEVAPN(12),TEVAPS(12),
     4TFN(12),TFS(12),TPPTN(12),TPPTS(12),VOL(50),MONTH(12),
     5TCN(12),TCS(12),
     4IDELT,JF,JFCE,JFCW,JFM,NEDZ,NEDZM,NITE,NP,NTS,NYR,
     5AREAB,CKQ,          CF,CFM,CN,CPPT,DASSBN,DASSBS,DEEPCE,DEEPCW,
     6DELT,DEPTH,EEC,EWC,ELEVS,ELEVN,ELNDZM,EPP,QNEO,QNWO,QSEO,QSWO,
     7RDIS,VOLN,VOLS,VOLT,W,VOLSN,VOLNN,DELTZN,QST
      IF(IP.GT.0) GO TO 200
      WRITE(NP,1)
    1 FORMAT(1H1,25X,'INITIAL CONDITIONS'//)
      WRITE(NP,2)
    2 FORMAT(1X,'SOUTH ARM',30X,'NORTH ARM'/)
      WRITE(NP,3) ELEVS,ELEVN,VOLS,VOLN,CN
    3 FORMAT(1X,'ELEVATION',F9.2,21X,'ELEVATION',F9.2,/,1X,'VOLUME',
     $F9.0,1X,'ACRE-FEET',14X,'VOLUME',F9.0,1X,'ACRE-FEET',/,40X,'C',
     $13X,F6.2)
      DO 101 I=1,NEDZ
      IPT=NEDZ-I+1
      IF(IPT.EQ.NEDZ) GO TO 102
      WRITE(NP,4) IPT,C(IPT),E(IPT),DELZ(IPT),VOL(IPT)
      GO TO 101
  102 WRITE(NP,5) IPT,C(IPT),DELZ(IPT),VOL(IPT)
  101 CONTINUE
    4 FORMAT(/1X,'LAYER ',I2,/,1X,'C ',11X,F6.2,' GRAMS/LITER',/,1X,'E',8
     $X,F9.7,' FT**2/SEC',/,1X,'DELZ ',8X,F6.1,' FEET'/,1X,'VOLUME',3X,F9
     $.0,'ACRE-FEET')
    5 FORMAT(/1X,'LAYER 'I2,/,1X,'C',11X,F6.2,' GRAMS/LITER',/,1X,
     $'DELZ',8X,F6.1,' FEET',/,1X,'VOLUME',3X,F9.0,' ACRE-FEET')
      GO TO 201
  200 DO 107 I=1,12
      TPPTS(I)=TPPTS(I)/43560.
      TFS(I)=TFS(I)/43560.
      TCS(I)=TCS(I)/43560.
      TEVAPS(I)=TEVAPS(I)/43560.
      TPPTN(I)=TPPTN(I)/43560.
      TFN(I)=TFN(I)/43560.
      TCN(I)=TCN(I)/43560.
      TEVAPN(I)=TEVAPN(I)/43560.
      SDBS(I)=SDBS(I)/10.**12
  107 SDBN(I)=SDBN(I)/10.**12
      DBS=DASSBS/10.**12
      DBN=DASSBN/10.**12
      WRITE(NP,10) NT
   10 FORMAT(1H1,1X,'YEAR',I3)
      WRITE(NP,11) (MONTH(I),I=1,6)
   11 FORMAT(/,1X,'MONTH',4X,6(10X,A4))
```

```
      WRITE(NP,12) (SAVELS(I),I=1,6)
   12 FORMAT(1X,'SOUTH ARM',/,1X,'ELEVATION',3X,6(4X,F10.2))
      WRITE(NP,13) (SAVEVS(I),I=1,6)
   13 FORMAT(1X,'VOLUME',6X,6(4X,F10.0))
      WRITE(NP,22) (FLW(I,NT),I=1,6)
   22 FORMAT(1X,'TOTAL INFLOW',6(4X,F10.1))
      WRITE(NP,23) (GWI(I,NT),I=1,6)
   23 FORMAT(1X,'GW INFLOW',3X,6(4X,F10.1))
      WRITE(NP,18) (TPPTS(I),I=1,6)
   18 FORMAT(1X,'PPT',9X,6(4X,F10.0))
      WRITE(NP,21) (TEVAPS(I),I=1,6)
   21 FORMAT(1X,'EVAPORATION',1X,6(4X,F10.0))
      WRITE(NP,19) (TFN(I),I=1,6)
   19 FORMAT(1X,'FLOW NORTH',2X,6(4X,F10.0))
      WRITE(NP,25) (TCN(I),I=1,6)
   25 FORMAT(1X,'FLOW NORTH C',6(4X,F10.0))
      WRITE(NP,20) (TFS(I),I=1,6)
   20 FORMAT(1X,'FLOW SOUTH',2X,6(4X,F10.0))
      WRITE(NP,26) (TCS(I),I=1,6)
   26 FORMAT(1X,'FLOW SOUTH C',6(4X,F10.0))
      WRITE(NP,14)
   14 FORMAT(1X,'CONCENTRATIONS')
      DO 105 IL=1,NEDZ
      IPT=NEDZ-IL+1
  105 WRITE(NP,15) IPT,(SAVEC(IPT,I),I=1,6)
   15 FORMAT(1X,'LAYER ',I2,4X,6(4X,F10.2))
      WRITE(NP,24) (SDBS(I),I=1,6)
   24 FORMAT(1X,'BOTTOM MASS',1X,6(4X,F10.1))
      WRITE(NP,16) (SAVELN(I),I=1,6)
   16 FORMAT(/,1X,'NORTH ARM',/,1X,'ELEVATION',3X,6(4X,F10.2))
      WRITE(NP,13) (SAVEVN(I),I=1,6)
      WRITE(NP,18) (TPPTN(I),I=1,6)
      WRITE(NP,21) (TEVAPN(I),I=1,6)
      WRITE(NP,17) (SAVECN(I),I=1,6)
   17 FORMAT(1X,'CONCENTRATION',3X,F10.2,5(4X,F10.2))
      WRITE(NP,24) (SDBN(I),I=1,6)
      WRITE(NP,11) (MONTH(I),I=7,12)
      WRITE(NP,12) (SAVELS(I),I=7,11),ELEVS
      WRITE(NP,13) (SAVEVS(I),I=7,11),VOLS
      WRITE(NP,22) (FLW(I,NT),I=7,12)
      WRITE(NP,23) (GWI(I,NT),I=7,12)
      WRITE(NP,18) (TPPTS(I),I=7,12)
      WRITE(NP,21) (TEVAPS(I),I=7,12)
      WRITE(NP,19) (TFN(I),I=7,12)
      WRITE(NP,25) (TCN(I),I=7,12)
      WRITE(NP,20) (TFS(I),I=7,12)
      WRITE(NP,26) (TCS(I),I=7,12)
      WRITE(NP,14)
      DO 106 IL=1,NEDZ
      IPT=NEDZ-IL+1
  106 WRITE(NP,15) IPT,(SAVEC(IPT,I),I=7,11),C(IPT)
      WRITE(NP,24) (SDBS(I),I=7,11),DBS
      WRITE(NP,16) (SAVELN(I),I=7,11),ELEVN
      WRITE(NP,13) (SAVEVN(I),I=7,11),VOLN
      WRITE(NP,18) (TPPTN(I),I=7,12)
      WRITE(NP,21) (TEVAPN(I),I=7,12)
      WRITE(NP,17) (SAVECN(I),I=7,11),CN
      WRITE(NP,24) (SDBN(I),I=7,11),DBN
  201 RETURN
      END
```

SAMPLE INPUT

```
CARD 1
   5    6
CARD 2
   5    2     3     4   731     12     20     15
CARD 3
  4199.2     4197.65        340.          .006   9161724.   4954008.   1237447.   78.31605
     4180.      4183.        600.            5.       600.         5.         2.        15.
CARD 4
 .35
CARD 5
  6.    5.    5.    5. 9.20
CARD 6 .
  .000006      .00025      .00025      .00025      .00025
CARD 7
   35643.     157685.    248243.    303654.    351646.
CARD 8
  708498.   1019538.   1329256.   1629620.
CARD 9
 340. 255. 138. 138. 138. 138. 139
CARD 10
        0.        750.
CARD 11
 95.4109.8117.1124.3145.2162.0163.4 66.6 58.6 38.9 36.2 52.6
 77.7 91.0 90.1 95.1 88.7145.2181.0160.1103.3 37.1 41.7 50.0
 82.0107.6166.4186.9173.3213.2234.1268.9100.8 38.8 43.3 48.4
 88.9106.4115.8109.3135.9179.1206.5375.1250.9 47.0 62.2 79.4
129.5131.2135.7132.6170.1192.2318.6284.5 71.5 42.4 65.5 81.5
 84.4110.7119.2114.0116.0119.0151.7 72.9 51.4 40.7 42.0 67.0
 92.3 83.6 85.4 90.1 93.0178.4194.497.0  41.9 34.5 36.1 39.7
 63.0 91.9 84.4 75.2 93.9109.5 91.0 29.7 26.6 26.0 25.8 36.8
 61.2 73.0 80.4 77.5219.9158.6292.7241.4102.1 42.1 34.4 38.6
 66.0 88.6 84.2 82.4135.7 96.1149.2162.2113.6 31.7 33.6 58.3
 69.9105.2 90.8 92.6 95.9113.0245.1325.0327.5 44.1 34.3 38.9
 66.3 89.6154.5139.7160.9139.0245.8300.9247.8 91.6114.7165.2
178.5186.5185.0187.2172.4135.9189.7130.4 39.8 36.7 36.7 45.8
 69.8 79.8 90.9 95.4 91.9130.3167.0258.6350.1 92.2 87.2107.5
156.4163.0162.2157.3124.7191.7176.9135.4219.6 46.9 95.2 64.5
124.1170.2182.9243.0210.0255.8406.0259.1122.0 71.8 49.0 56.8
 10.3162.8127.4221.3196.5148.9 84.8297.4270.3106.7 91.2 20.0
 46.8197.3169.9306.4271.9220.5510.2494.3448.3238.3103.2279.0
241.9236.0247.5282.2255.0281.2432.1382.7264.3136.6 95.8165.8
188.4203.6198.5222.7219.5311.2308.9366.8146.8 90.4 52.3150.9
CARD 12
 0.33 0.39 0.52 0.64 0.34 1.10 0.45 0.97 1.15 0.26 0.51 0.73
 0.44 1.19 0.57 1.31 0.39 0.25 1.28 0.91 1.34 0.34 0.65 0.79
 0.45 1.08 1.11 1.57 0.44 0.08 1.13 2.00 0.33 0.42 0.04 0.08
 1.05 0.32 0.76 0.70 0.59 1.50 2.39 3.38 1.62 0.23 0.66 0.29
 0.71 0.73 1.00 0.55 1.20 1.65 1.21 0.48 0.09 0.08 0.32 0.28
 0.00 0.86 0.34 0.82 1.00 0.79 1.02 1.58 1.14 0.07 1.06 1.31
  .24  .02  .71  .77  .19 1.20  .92  .58  .15  .06  .42  .39
  .75 1.12  .32  .00  .94 1.03  .56  .50  .05  .58  .76 1.29
 1.12  .84  .82  .79 1.21 1.33 1.83 2.09  .51  .64  .21  .22
  .41  .22  .05  .45  .37  .89 2.37 1.15 2.50  .02  .22 1.14
  .86 1.09  .45  .61  .28 1.23 2.08 2.40 2.31  .03  .04  .20
  .53 1.08 1.59  .82  .58  .04 1.35 1.58 1.40  .40 1.10 1.70
```

```
  .30 1.10  .80  .10  .70  .50 1.10 1.20  .10  .20  .10  .80
  .50  .70  .70 1.00  .30  .90 1.70 1.50 3.10  .38  .06  .45
  .78  .33 1.17  .38 1.25 1.72 1.82 1.58 1.58  .12 2.68  .22
 1.12  .60  .87 1.52 1.81  .19 1.07  .16 2.62  .45  .11  .46
 1.15  .34  .86 1.25  .44  .49 1.59 1.03 1.43  .54  .27 1.94
 1.34 1.58 1.43  .83 1.29  .56 1.99 1.18 1.19  .06 1.10  .73
 1.91 1.16 1.52  .60  .16  .74 2.48  .03  .40  .05  .18 1.07
 1.83  .97 1.05 1.20  .82 2.03 1.32 1.09  .53 1.77  .26 2.51
CARD 13
  5.0  3.3  0.5  0.6  1.0  3.3  7.7 11.1 11.1 14.0 13.1  9.1
  4.6  3.0  0.4  0.0  0.0  0.9  5.5 10.0 11.0 13.8 10.8  7.5
  4.5  0.8  0.8  0.9  0.0  3.9  6.6  7.8 12.2 13.5 12.4  8.7
  4.5  0.8  0.3  0.1  1.4  4.1  5.8  7.8 10.3 13.2 12.3  7.8
  4.4  0.9  0.7  0.2  2.4  3.3  5.7 10.5 13.1 14.5 12.5  8.9
  5.6  1.7  1.1  0.7  1.1  3.9  7.0  8.8 11.6 13.2 11.4  7.7
  4.7  2.2  0.4  .00  0.3  3.8  7.1 10.1 13.6 15.0 13.1  9.3
  4.9  2.5   .4   .2  1.2  3.8  7.6 11.2 14.2 14.4 12.0  8.0
  4.6  1.1   .1   .0   .4  2.9  7.2  8.6 11.5 13.1 13.0  9.2
  6.6  2.4   .4   .0  3.1  3.7  4.4  9.6  9.6 14.4 12.9  7.8
  5.3  2.2   .1   .0   .2   .5  5.6  8.8  8.6 14.6 12.6  9.0
  4.8  1.7   .8   .4   .8  3.1  6.2  8.6  9.9 12.8 10.3  6.6
  4.3  3.1   .4   .1   .4  3.7  7.0 10.5 13.9 15.5 12.7  8.5
  4.3  3.0   .4   .2   .9  4.1  5.8  8.2  8.2 12.2 12.1  7.7
  4.7  2.8   .0   .0   .9  4.8  5.7  8.8 10.8 14.4  9.8  7.9
  4.3  2.0   .2   .4   .2  3.3  6.8 11.0  9.8 13.1 13.2  8.9
  3.7  2.3   .7   .6  2.2  3.6  6.1  9.6 12.3 12.9 12.8  7.8
  4.2  2.5   .1   .1   .6  1.3  4.8  8.2 11.1 13.1 11.0  8.0
  3.4  1.2    .    .   .6  4.4  5.8 10.1 11.1 13.4 11.5  7.4
  4.1   .9    .    .   .1  2.0  5.9  9.8 11.7 12.6 12.6  6.9
CARD 14
  .60  .66  .65  .65  .65  .61  .61  .61  .65  .65  .65  .66
CARD 15
 12.0  6.1  2.1  2.4  3.7  7.4 13.5 19.4 21.4 26.9 22.7 17.0
 11.7  5.9  2.0  1.4  2.4  6.3 11.4 18.7 22.0 25.9 23.8 17.1
 12.1  4.7  2.2  2.7  2.8  7.8 12.9 19.7 23.3 27.0 22.8 17.7
 11.6  4.6  2.0  1.7  3.5  8.2 12.3 18.0 21.7 25.4 23.5 17.0
 11.7  7.4  2.1  2.0  4.5  7.7 12.1 21.0 23.5 26.0 24.2 17.2
 12.1  5.2  2.3  2.4  3.8  7.6 13.0 17.8 23.6 26.2 22.8 16.1
 11.9  5.4  2.0  1.8  3.1  7.8 12.8 18.8 23.1 27.3 21.9 17.5
 11.4  5.6  1.9  2.1  4.0  7.7 12.2 18.9 23.8 26.6 23.7 15.2
 11.1  4.8  1.8  1.3  3.5  6.8 13.5 18.7 22.4 25.9 22.7 17.1
 12.3  5.8  1.9  1.6  4.4  7.6 11.2 19.8 21.3 26.1 23.4 17.6
 12.0  5.4  1.8  1.9  2.0  5.1 11.5 18.2 21.0 27.1 22.3 16.4
 12.0  5.2  2.1  1.9  3.7  7.1 12.7 17.8 21.6 26.0 22.4 15.0
 12.0  6.1  1.9  1.9  3.5  7.7 10.2 20.2 22.7 27.5 23.2 17.4
 11.1  5.9  1.8  2.2  4.0  8.0 11.3 18.3 21.3 27.0 24.0 17.6
 11.7  6.0  1.6  1.5  3.6  8.4 11.8 18.5 22.5 26.8 21.7 16.3
 11.6  5.3  1.9  1.9  3.2  7.4 13.0 20.7 21.7 26.7 24.3 18.1
 10.7  5.4  2.2  2.3  4.4  7.5 11.3 18.9 22.8 26.4 24.1 15.8
 10.6  5.7  2.0  2.3  3.9  7.6 12.2 18.7 22.5 26.5 23.9 15.7
 10.7  5.1  1.5  2.1  3.7  8.7 12.3 19.3 23.0 25.8 23.3 16.2
 12.0  4.7  1.7  1.5  3.0  7.3 11.9 19.3 22.6 26.1 23.3 16.0
CARD 16
   8.   8.   8.   8.   8.   8.   7.   7.   7.   7.   8.   9.   9.   8.   8.  10.
  10.  10.   9.  10.
CARD 17
 OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP
```

SAMPLE OUTPUT

INITIAL CONDITIONS

SOUTH ARM

ELEVATION 4194.30
VOLUME [illegible] ACRE-FEET

NORTH ARM

ELEVATION 4193.60
VOLUME [illegible] ACRE-FEET
C 340.00

LAYER 5
C 240.00 GRAMS/LITER
DELZ 4.[illegible] FEET
VOLUME 1876188. ACRE-FEET

LAYER 4
C 240.00 GRAMS/LITER
E .0002500 FT**2/SEC
DELZ 5.0 FEET
VOLUME 1629620. ACRE-FEET

LAYER 3
C 240.00 GRAMS/LITER
E .0002500 FT**2/SEC
DELZ 5.0 FEET
VOLUME 1389256. ACRE-FEET

LAYER 2
C 240.00 GRAMS/LITER
E .0002500 FT**2/SEC
DELZ 5.0 FEET
VOLUME 1019538. ACRE-FEET

LAYER 1
C 278.00 GRAMS/LITER
E .0000060 FT**2/SEC
DELZ 6.0 FEET
VOLUME 708438. ACRE-FEET

YEAR 1

MONTH	OCT	NOV	DEC	JAN	FEB	MAR
SOUTH ARM						
ELEVATION	4194.31	4194.57	4194.94	4195.46	4195.91	4196.32
VOLUME	6621271.	6723714.	6880541.	7107811.	7321838.	7521118.
TOTAL INFLOW	129946.0	185112.0	201974.0	265680.0	229400.0	379748.0
GW INFLOW	17446.0	20212.0	20974.0	24580.0	22600.0	31348.0
PPT	39867.	21575.	31984.	57778.	71449.	7775.
EVAPORATION	84750.	39930.	4037.	8395.	4384.	70731.
FLOW NORTH	113390.	97038.	108256.	123736.	118777.	159924.
FLOW SOUTH	27497.	32725.	35162.	35944.	36339.	42412.
CONCENTRATIONS						
LAYER 5	238.02	232.99	226.29	217.40	209.89	202.93
LAYER 4	238.21	233.43	226.93	218.25	210.80	203.69
LAYER 3	238.56	233.98	227.61	219.08	211.66	204.46
LAYER 2	239.05	234.61	228.35	219.93	212.56	205.33
LAYER 1	278.35	278.69	276.82	272.79	269.12	264.63
BOTTOM MASS	989.3	980.2	970.1	959.5	949.4	937.5
NORTH ARM						
ELEVATION	4193.83	4194.03	4194.38	4194.82	4195.27	4195.54
VOLUME	3850446.	3901153.	3990449.	4106642.	4227905.	4304880.
PPT	23518.	12751.	18854.	33869.	41659.	4485.
EVAPORATION	55963.	26356.	2651.	5467.	2832.	45021.
CONCENTRATION	339.91	338.56	334.87	330.53	326.19	327.26
BOTTOM MASS	1000.4	999.8	996.8	990.0	979.9	967.0

MONTH	APR	MAY	JUN	JUL	AUG	SEP
SOUTH ARM						
ELEVATION	4196.68	4196.50	4196.35	4195.80	4195.17	4194.84
VOLUME	7702519.	7608898.	7535655.	7267884.	6986563.	6837062.
TOTAL INFLOW	427360.0	263946.0	117620.0	59408.0	37640.0	52108.0
GW INFLOW	34360.0	25546.0	17320.0	14308.0	12940.0	13408.0
PPT	45207.	6805.	109897.	18349.	4279.	17240.
EVAPORATION	151204.	246500.	230422.	298103.	284600.	186671.
FLOW NORTH	187266.	179693.	140755.	120553.	101808.	85957.
FLOW SOUTH	47303.	61314.	70416.	73125.	63166.	53778.
CONCENTRATIONS						
LAYER 5	196.20	198.56	200.80	210.43	220.95	226.87
LAYER 4	196.95	198.60	200.90	209.91	220.31	226.56
LAYER 3	197.71	198.93	201.28	209.89	220.15	226.60
LAYER 2	198.61	199.62	202.02	210.38	220.53	227.05
LAYER 1	261.89	263.98	269.35	274.14	277.18	279.73
BOTTOM MASS	925.4	912.8	901.3	890.2	879.7	870.1
NORTH ARM						
ELEVATION	4195.79	4195.83	4195.64	4195.13	4194.65	4194.34
VOLUME	4376120.	4344542.	4333739.	4202895.	4060409.	3990752.
PPT	25751.	3378.	63124.	10642.	2509.	10181.
EVAPORATION	94473.	133375.	144267.	198925.	183629.	122018.
CONCENTRATION	329.05	336.27	338.59	340.17	340.19	340.11
BOTTOM MASS	955.7	948.4	945.8	992.2	1052.3	1087.3