COMPUTER SIMULATION OF SURFACE WATER HYDROLOGY AND SALINITY WITH AN APPLICATION TO STUDIES OF COLORADO RIVER MANAGEMENT

by

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PREFACE

A thesis of the same title was submitted by Arthur R. Jensen in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Environmental Engineering Science at the California Institute of Technology; this report is essentially identical except for a few minor revisions. The research described was performed under the supervision of Dr. E. J. List, Associate Professor of Environmental Engineering Science, and a member of the Environmental Quality Laboratory staff.

Dr. Jensen obtained his Bachelor of Science degree in Engineering Science at the University of California at Berkeley in June of 1970. He entered the California Institute of Technology in the fall of 1970, receiving his Masters degree in June 1971 and his Ph.D. in February of 1976 with specialization in water resources management. At the present time the author is employed by TRW, Inc., Washington Operations, in McLean, Virginia.

This EQL report describes one of a series of policy studies on environmental management problems. In particular, this study examines certain aspects of the management of the water resources in the Colorado River Basin, where water and energy resources are closely coupled. The generation of hydropower induces extra evaporation losses as does the use of water for makeup for cooling towers for thermal power plants. Rehabilitation of strip mined land, coal conversion plants, and oil shale processing will all increase consumptive use and produce additional residuals in the river. This report presents a computer model for water quantity and quality which may be used as a tool for policy studies for relating various energy activities to the Colorado River system. The work in this area is continuing at EQL with increased emphasis on economics.

Norman H. Brooks, Director
Environmental Quality Laboratory

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EXECUTIVE SUMMARY

The streamflow of the Colorado River is low and highly variable relative to the flows in other rivers of comparable drainage area. Rights to the consumptive use of the water have been legally allocated; however, the total allocated rights exceed the current long-term average flow of the river. The Colorado River Compact of 1922 defines the original division of water rights between the states within which the basin lies.

Present agricultural, municipal, and industrial uses of Colorado River water, and planned or authorized future projects will consume almost all of the available water supply. Potential future uses of water must compete for the remainder of the water resource. In particular, projects to develop the coal and shale oil resources in the basin could be constrained by the necessity to share the remaining supply with future municipal and agricultural users.

An examination has been made of alternative ways to manage the operation of the major storage reservoirs in the basin (Lake Mead and Lake Powell). Certain of these alternatives are shown to increase the supply of water relative to the supply attainable under the management constraints imposed by the Colorado River Compact.

The water supply can be increased by operating the reservoirs at lower levels, thereby decreasing the total amount of evaporation from the reservoir system. Under the alternative management scheme, the reservoirs are operated with sufficient storage capacities to provide a reliable supply of water to downstream users. Some loss in hydroelectric generating capacity is experienced as a result of decreasing reservoir

storage capacity. However, the losses in hydroelectric power are found to be small in comparison to the fossil fuel or nuclear power capacity that could use the conserved water as makeup water for cooling towers.

The concentration of dissolved solids, a major concern in the Colorado River basin, is also examined in the study. Results indicate that water quality may be improved under the alternative reservoir management scheme.

The results of the study, as well as indicating how more water might be made available for development of the energy resources in the basin, suggest that potential exists for improving the management of the water resources in the Colorado River basin.

In addition, the computer analyses performed during the course of the study demonstrate the limitations of computer models of the Colorado River and how their output must be interpreted given the constraints of uncertainty and limited calibration data.

ABSTRACT

Management of a large river basin requires information regarding the interactions of variables describing the system. A method has been developed to determine these interactions so that the resources management within a given river basin can proceed in an optimal way. The method can be used as a planning tool to display how different management alternatives affect the behavior of the river system. Direct application is made to the Colorado River Basin.

The Colorado River has a relatively low and highly variable streamflow. Allocated rights to the consumptive use of the river water exceed the present long-term average flow. The naturally high total dissolved solids concentration of the river water continues to increase due to the activities of man. Current management policies in the basin have been the products of compromises between the seven states and two countries which are traversed by the river or its tributaries. The anticipated use of the scarce supply of water in the extraction and processing of energy resources in the basin underwrites the need for planning tools which can illuminate many possible management alternatives and their effects upon water supply, water quality, power production, and the other concerns of the Colorado River water users.

A computer simulation model has been developed and used to simulate the effects of various management alternatives upon water conservation, water quality, and power production. The model generates synthetic sequences of streamflows and total dissolved solids (TDS) concentrations. The flows of water and TDS are then routed through the major reservoirs of the system, Lakes Powell and Mead.

Characteristics of system behavior are examined from simulations using different streamflow sequences, upstream depletion levels, and reservoir operating policies. Reservoir evaporation, discharge, discharge salinity, and power generating capacity are examined.

Simulation outputs show that the probability with which Lake Powell fails to supply a specified target discharge is highly variable. Simulations employing different streamflow sequences result in probabilities of reservoir failure which differ by as much as 0.1.

Three levels of Upper Colorado River Basin demands are imposed on the model: 3.8 MAF/yr (4.7 km^3/yr), 4.6 MAF/yr (5.7 km^3/yr), and 5.5 MAF/yr (6.8 km^3/yr). Two levels of water demand are imposed below Lake Mead: 8.25 MAF/yr (10.2 km^3/yr) and 7.0 MAF/yr (6.8 km^3/yr).

Although the effects of reservoir operations upon water quality are made uncertain by a lack of knowledge regarding the chemical limnology of Lake Powell, two possible lake chemistry models have been developed, and the predicted impacts of changes in reservoir operation upon water quality are presented.

The current criteria for the operations of Lakes Powell and Mead are based upon 75 years of compromises and agreements between the various water interests in the Colorado River Basin. Simulations show that Lake Powell will be unable to conform to these operating constraints at the higher levels of water demand.

An alternative form of reservoir operation is defined and compared to the existing policy on the basis of reliability of water supply, conservation of water, impact upon water quality, and the effect upon power generation.

Ignoring the current institutional operating constraints, and attempting only to provide a reliable supply of water at the locations of water demand, is shown to be a superior management policy. This alternate policy results in the conservation of as much as 0.25 MAF/yr (0.3 km^3/yr) of water. The impact of the alternate operating policy upon hydroelectric power generation and the potential use of the conserved water for development of energy resources is discussed.

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LIST OF SYMBOLS

Symbol	Unless redefined within the text for a particular purpose, the symbols on the left denote the following:
${}_t a_m$	serial correlation regression coefficient;
A	reservoir surface area;
AGI	net agricultural depletion, DIV-RET;
b_{ts}	cross-correlation regression coefficient;
BS	reservoir bank storage;
C	total dissolved solids (TDS) concentration;
C_g	TDS concentration of the ground water component of total streamflow;
C_s	TDS concentration of the surface runoff component of total streamflow;
${}_t C_m^y$	average TDS concentration during month m, of year y, in tributary t streamflow;
CH	historical or recorded TDS concentration;
CN	TDS concentration under natural conditions (no streamflow depletions by man);
D	reservoir discharge;
D_t	target reservoir discharge;
DIV	irrigation diversion;
DMI	diversion for municipal and industrial use;
DPL	total depletions;

LIST OF SYMBOLS (Continued)

Symbol	
DTAGI	net effect of agricultural diversions upon total dissolved solids mass flow;
DTDPL	net effect of municipal and industrial diversions upon TDS mass flow;
DTEXP	effect of exportation of water upon TDS mass flow;
E	reservoir evaporation;
EXP	water exported to other river basins;
${}_tH_m^y$	historical, recorded, or gauged streamflow;
I	reservoir inflow;
K	constant;
m	month of the year;
M	transient time;
n	sample size;
N	Sample size, number of years simulated;
${}_tN_m^y$	natural, undepleted streamflow;
p_m	fraction of total depletion occurring in each month;
P_c	power capacity in MW;
P_o	power output in GWH;
Q	discharge, streamflow;
Q_g	ground water component of total streamflow;
Q_o	streamflow for which $Q_T = Q_g$;
Q_s	surface runoff component of total streamflow;
Q_T	total streamflow;

LIST OF SYMBOLS (Continued)

Symbol	
r	Q_g/Q_T;
R	random component of flow;
RET	irrigation return flow;
s	denotes tributary;
s_t	fraction of total depletion occurring in each tributary;
S	reservoir storage;
SP_M	maximum storage allowed in Lake Powell;
t	denotes tributary;
T	total dissolved solids mass flow;
TD	municipal and industrial diversion of TDS flow;
TDIV	irrigation diversion of TDS flow;
TDR	municipal and industrial return flow of TDS;
TEX	export of TDS flow to other water basins;
TH	historical or recorded TDS flow;
TN	natural TDS flow;
TP	mass of TDS precipitated in Lake Powell;
TRET	irrigation return flow of TDS;
TS	mass of TDS stored in a reservoir;
y	year;
β	streamflow exponent in stream salinity model;
ε	residual streamflow;
γ	constant;
ρ	correlation coefficient

CHAPTER 1

INTRODUCTION

1.1 Project Objectives

The purpose of this research is to develop a systematic method of examining the effect of management operations and resource development on the water supply and water quality within a given river basin. The work is applied to the Colorado River Basin and possible management strategies which provide efficient use of the water resource while reducing the magnitude of water quality problems are examined.

Existing and anticipated future patterns of water use are incorporated in the study. However, some legal or institutional constraints on the operation of the river system are relaxed in the formation of certain management alternatives. The comparison between these alternate management policies and those defined by current institutional constraints is an objective of this study.

To accomplish these objectives, a computer simulation model of a large portion of the basin was developed. The model simulates the flows of water and total dissolved solids through the river system, including the major regulatory reservoirs. Reservoir modeling includes evaporation, mixing, and hydropower generation.

The model is used to study the relationships between the hydrologic, water quality, and institutional variables of the river system. In particular, the maximum storage required to meet basin water demands is examined, both within the context of existing institutional operating constraints and without. A comparison of management strategies is made, indicating the costs, in terms of water supply, water quality, and hydropower capacity, of adopting one strategy over another. These comparisons are made for various levels of water demands.

1.2 Project Relevancy

The need for better planning tools and methods has become well recognized as water management systems have become increasingly complex (N.A.S., 1968, p. 97; O'Brien, 1975). The planning process serves to display a range of alternatives from which the most desirable, on the basis of some set of criteria, may be selected. The information obtained during the development and use of planning tools serves as data for the decision process. In that context, the National Academy of Sciences has stressed the need for planning studies to consider alternatives

> ...both within the existing laws and policy structure and on the basis of the assumption that existing laws and policies might be changed to permit a wider choice of alternatives, so that government representatives and the courts will have a better understanding of the consequences of existing arrangements and of the opportunities afforded by new ones. (N.A.S.; 1968, p. 85)

Management studies contracted or funded by the regulatory agencies involved often fail to include examination of policy alternatives that represent a radical departure from established procedures. This study hopes, by example, to inspire new interest in this activity.

The following sections discuss the applicability of the study to the Colorado River Basin and sketch the history of development and legal institutions in the basin.

1.2.1 Relevancy of Application to the Colorado River Basin

Few river basins exemplify the need for development of a systematic method of rational management of water resources better than the Colorado River. The relatively low natural run-off, the high degree of resource development, and the fact that the river traverses two countries and seven states combine to generate a complex problem in water management. Water rights to the river have been contested for over 75 years. The net result has been the aggregation of a massive and, in some areas inconclusive, body of legislation and court rulings adjudicating a deteriorating and diminishing river flow.

Over the years many millions of dollars have been spent developing the water resources of the basin. The high salinity of river water at the Mexican border and the necessity of meeting federal water quality standards have resulted in large expenditures for salinity control (U.S.C.; 1974). Unless a method of analysis is developed which enables a clear choice to be made between alternative operating policies for the river, there is some doubt that further monies will be spent in the way most likely to produce a long lasting solution.

1.2.2 Early Development of the Colorado River Basin

The Colorado River Basin, technically divided into an Upper and Lower Basin (see Figure 1.1), has a total area of approximately 244,000 square miles (635,000 km^2) and carries an average annual natural flow of between 13 and 15 million acre-feet (15.6 to 18 km^3/yr). Of this amount, over 5 MAF/yr is exported from the basin to the Arkansas, Missouri and Great Basins, and to the Southern California area.

By way of comparison, the flow per unit of basin area for four U.S. rivers is shown below.

River Basin	Drainage Area (in millions)		Runoff		Runoff per unit area	
	(acres)	(km^2)	(MAF/yr)	(km^3/yr)	(in/yr)	(cm/yr)
Colorado	156.0	0.63	15.0	18.5	1.15	2.92
Mississippi	790.0	3.2	440.0	543.0	6.7	17.0
Columbia	165.0	0.67	180.0	222.0	13.1	33.3
Delaware	7.9	0.03	14.0	17.0	20.9	53.1

It is interesting to note that the Columbia Basin, while of approximately the same size as the Colorado, carries an order of magnitude larger flow. Because of the geographic and geologic conditions in the basin, silting and salting problems in the Colorado Basin are more pronounced than elsewhere. The same factors contribute to the irregularities in flow. These qualities characterize the Colorado River as an arid or semi-arid river basin.

Settlement of the Upper Basin by outsiders began in about 1860 and resulted in the irrigation of 800,000 acres (3200 km^2) by 1905.

FIGURE 1.1

The Colorado River Basin and Major Storage Reservoirs

Key:
1. Fountenelle Reservoir
2. Flaming Gorge Reservoir
3. Blue Mesa Reservoir
4. Morrow Point Reservoir
5. Navajo Reservoir
6. Lake Powell, Glen Canyon Dam
7. Lake Mead, Hoover Dam
8. Lake Mohave, Davis Dam
9. Lake Havasu, Parker Dam

Sources: U. S. Bureau of Reclamation, Quality of Water: Colorado River Basin, Progress Report No. 5 (Jan., 1971); frontispiece.
Reader's Digest Assoc., Reader's Digest Great World Atlas (1963); p. 46.

Due largely to land reclamation projects the acreage of irrigated land nearly doubled by 1920, at which time growth began to level off, acreage increasing by only 1500 acres (6 km^2) between 1920 and 1965 (U.S. Bureau of Reclamation, 1971; p. 12).

Although irrigation had begun in both the Upper and Lower Basins at about the same time, development of the southern region was initially slower largely because of the difficulties of diverting a river with such large fluctuations in flow. However, beginning with the first large scale diversions through the Imperial Valley Canal in 1901, development of the Lower Basin proceeded rapidly.

1.2.3 Development of the Institutional Setting

The basin states were active in determining surface water rights in the form of the doctrine of prior appropriation. In 1902, the Federal Reclamation Act paved the way for developing a general body of rights on the federal level, and authorized the Secretary of the Interior to develop water resources (U.S.C., 1902; see also U.S.C., 1968).

In 1922, Lower Basin water interests proposed before Congress an enormous storage reservoir and hydroelectric power project, later to become Hoover Dam. This same year the Upper Basin, fearing that the Lower Basin would accumulate rights to a majority of the river flow, desired the formulation of some agreement concerning the right to use Colorado River water.

The water rights dispute that developed between the Upper and Lower Basins, and which strains negotiations even today, has resulted in a body of legislation controlling the use of water and the operation of related facilities throughout the basin. A brief summary of the legislation and court rulings relevant to this study follows. [For a more complete discussion of the legal and political history of the Colorado River see N.A.S. (1968); and Mann *et al.* (1974)].

The Colorado River Compact of 1922

The agreement eventually reached between the Upper and Lower Basins, referred to as the Compact of 1922, legally defines the Upper and Lower Basins and assigns rights to Colorado River water to each basin (N.A.S., 1968). On the basis of hydrologic records available at the time, the mean flow of the river as measured at the boundary of the two basins, Lee Ferry, Arizona, was taken to be 15 MAF/yr (18 km^3/yr).* The Compact divides this quantity equally between the Upper and Lower Basins, providing rights for the use of 7.5 MAF/yr (9.2 km^3/yr) to each basin. Three additional articles state that (1) the Upper Basin shall not allow the flow into the Lower Basin to fall below an aggregate of 75 MAF for any period of ten consecutive years; (2) that the Lower Basin might increase its beneficial consumptive use by 1 MAF/yr; and (3) that any quantity of water subsequently promised to Mexico must be contributed by both the Upper and Lower Basins equally.

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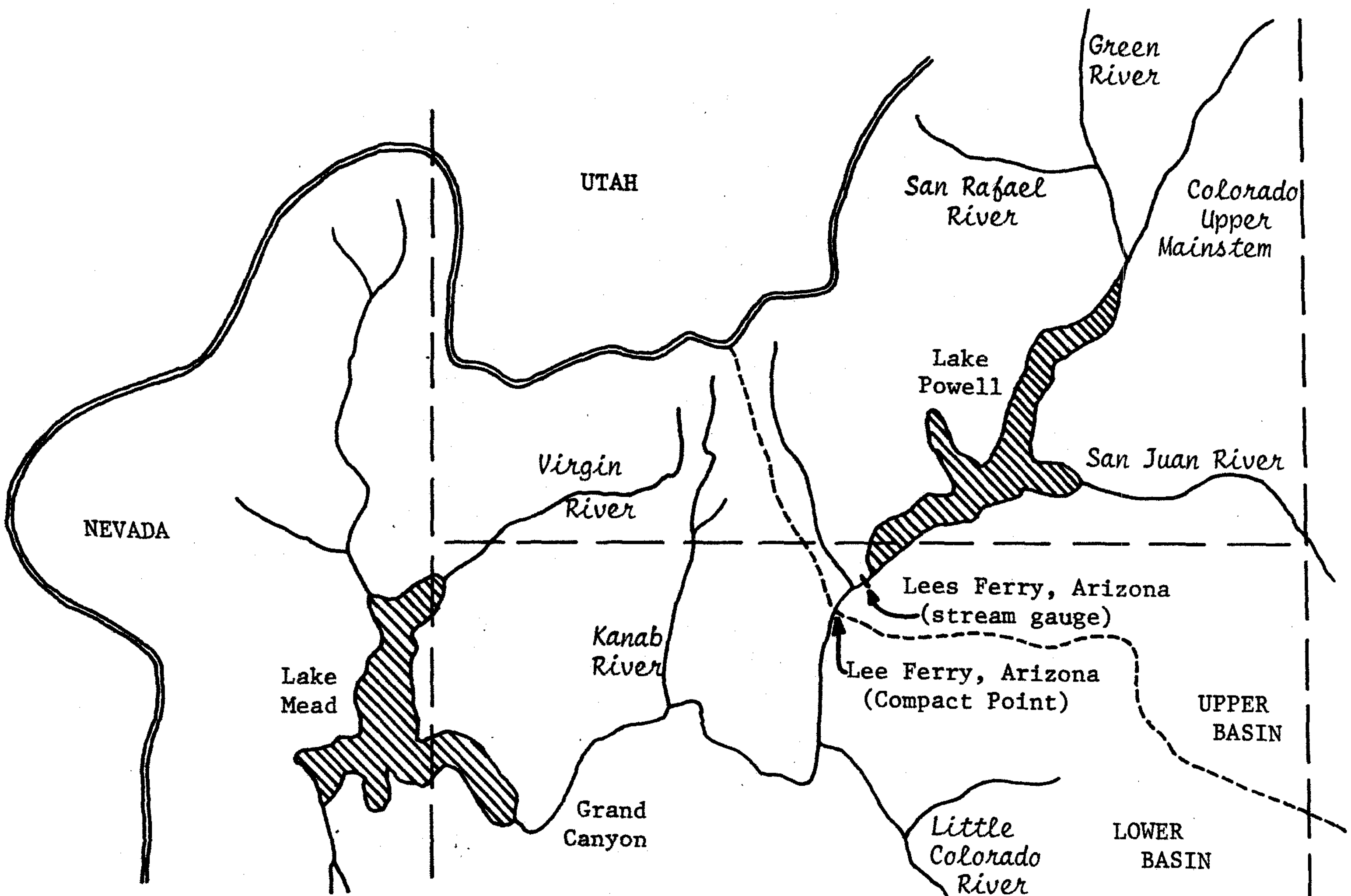
*The Upper and Lower Basins are divided at *Lee Ferry*, Arizona, one mile below the junction of the Paria and Colorado Rivers. The flow of the Colorado River is gauged at *Lees Ferry*, Arizona, 0.8 miles above the Paria River and 16 miles below Glen Canyon Dam, as shown in Figure 1.2.

FIGURE 1.2

Detailed Map of the Lake Powell-Mead Area
(not to scale)



Source: Colorado River Board of California, Annual Report, 1972, p. 2.

Although several articles of the Compact are still under dispute it forms the basis for what is known as the "Law of the River".

The Boulder Canyon Project Act of 1928

The Boulder Canyon Project Act (BCPA), among other provisions, authorized the construction of Hoover Dam and recommended an apportionment of the Lower Basin's 7.5 MAF/yr between Arizona, California, and Nevada. The proposed division may be summarized as follows: Arizona is to receive 2.8 MAF/yr (3.4 km^3/yr), California 4.4 MAF/yr (5.4 km^3/yr), and Nevada 0.3 MAF/yr (0.4 km^3/yr); any surplus of water may be shared equally by Arizona and California; and should any deficit exist with regard to our obligation to Mexico, Arizona and California would each contribute one-half the Lower Basin's share of the deficiency (U.S.C., 1928).

The 1944 Treaty with Mexico

This treaty insures an annual delivery of 1.5 MAF (1.8 km^3) to Mexico, and 1.7 MAF (2.0 km^3) in years of surplus. The quality of Colorado River water entering Mexico is not mentioned in the 1944 treaty.

The Upper Colorado River Basin Compact of 1949

For the Upper Basin states to receive federal support for water storage projects it was necessary for them to divide their 1922 Compact apportioned water. The agreement reached, embodied in the Upper Colorado River Basin Compact, provided the following:

(1) To Arizona, the consumptive use of 50,000 AF/yr (0.062 km^3/yr);

(2) To the remaining Upper Basin states, the following percentages of flow remaining after depletions by Arizona:

Colorado	51.75%	
New Mexico	11.25%	
Utah	23.00%	
Wyoming	14.00%	(U.S.C., 1949)

The Colorado River Storage Project Act of 1956

This act authorized the Secretary of the Interior to construct, operate, and maintain the Colorado River storage project and participating projects, consisting essentially of four Upper Basin reservoirs, including Glen Canyon Dam. Glen Canyon Dam, which forms Lake Powell, was completed in 1963 and has a total active capacity of 25 MAF (30.8 km^3) (U.S.C., 1956).

Arizona vs. California, 1963

A conflict remained between the State of Arizona and the other Basin states with regard to precisely which Basin waters were being apportioned by the 1922 Compact and the Boulder Canyon Project Act of 1928. Arizona contended that the river water being divided was the average annual flow measured at Lees Ferry, Arizona.

On this basis Arizona demanded that the flows of tributaries in Arizona, notably the Gila River, not be counted in making up the Lower Basin and Arizona allotments.

The conflict remained unresolved, and in 1952 the State of Arizona brought suit against the State of California and seven public agencies (U.S. Supreme Court Reporter, 1963). The public agencies involved were the Palo Verde Irrigation District, Imperial Valley Irrigation District, Coachella Valley County Water District, M.W.D. of Southern Calif., City of L.A., City of San Diego, and County of San Diego. At issue were the clarification of the role of tributary flows and the limitation of consumptive use by the State of California so as not to restrict Arizona's use of 2.8 MAF/yr of the flow passing Lees Ferry.

In 1963 the Supreme Court ruled in favor of Arizona. Significant elements of the decision were (1) that the division of the Lower Basin allotment recommended by the BCPA was in fact a legally binding apportionment scheme; and (2) that Arizona tributaries were exempt from the allotments specified by the 1922 Compact and the BCPA.

Thus, the total demand on the river, as measured at the division between the Upper and Lower Basins at Lees Ferry, Arizona, would be 17.5 MAF/yr (21 km^3/yr): 7.5 MAF for each basin, 1.5 MAF for Mexico, plus 1.0 MAF for losses enroute to the Mexican border (U.S. Supreme Court Reporter, 1963).

A summary of current state water rights appears in Table 1.1.

TABLE 1.1

Summary of Current Colorado River Basin Water Rights

Upper Basin States*	(MAF/yr)	(km^3/yr)
Arizona	0.05	0.06
Colorado	3.86	4.76
New Mexico	0.84	1.04
Utah	1.71	2.11
Wyoming	1.04	1.28
Subtotal	7.50	9.25
Lower Basin States		
Arizona	2.80	3.45
California	4.40	5.43
Nevada	0.30	0.37
Subtotal	7.50	9.25
Additional to the Lower Basin	1.00	1.23
U. S. TOTAL	16.00	19.73
Mexico	1.50	1.85
GRAND TOTAL	17.50	21.58

*Based on the percentages established by the Upper Colorado River Basin Compact when applied to the full 1922 Compact allotment of 7.5 MAF/yr.

The Colorado River Basin Project Act of 1968 and the Colorado River Reservoir Operating Criteria of 1970

The CRBPA, besides authorizing the Central Arizona Project and several other water projects in the basin, initiated investigations leading to a comprehensive management plan and reservoir operating criteria for the Colorado River Basin. In addition, the act directed that for a period of ten years following the passage of the act (until 1978), no studies for augmenting the flow of the river by importing waters from other drainage basins may be undertaken (U.S.C., 1968).

The Operating Criteria appeared in the Federal Register in 1970 (U.S. Department of the Interior, 1970). Two significant provisions of these criteria are the following: (1) the Upper Basin must attempt to deliver 8.25 MAF (10.1 km^3) annually to the Lower Basin, 7.5 MAF by the 1922 Compact, and one-half the Mexican allotment of 1.5 MAF; and (2) the levels of Lake Mead and Lake Powell should be equalized at the end of each water year, except in violation of the Compact, for the purpose of making the two basins share the losses or excesses from years of high or low runoff.

The Federal Water Pollution Control Act Amendments of 1972 and the Colorado River Salinity Control Act of 1974

The FWPCA Amendments require each state to propose numerical standards of water quality (U.S.C., 1972). A conflict arose as to the applicability of numerical salinity standards in the Colorado River Basin, where salinity levels are the result of many highly variable natural and man-made processes. An agreement between the Environmental

Protection Agency (EPA) and the basin states calls for the maintenance of salinity at or below 1972 levels, until such time as numerical standards are adopted (U. S. EPA, 1974). The Colorado River Salinity Act prescribes salinity control measures for limiting salinity to levels acceptable to users in both the U.S. and Mexico, and for complying with the adopted salinity standards (U.S.C., 1974). The Colorado River Basin Salinity Control Forum was subsequently formed with representatives from each state to work with the EPA in seeking solutions to the salinity problem and to develop the required numerical standards.

The Salinity Control Act authorizes the construction of a large desalting plant near the U.S.-Mexico border and investigation of sixteen other projects for the control of specific point and diffuse salinity sources throughout the river basin.

The following points summarize the legislation and court decisions described above:

(1) Rights to the consumptive use of Colorado River water totaling 17.5 MAF/yr (20.3 km^3/yr) have been established, 7.5 MAF/yr to each basin, 1.5 MAF/yr to Mexico. The inherent variability of Colorado River runoff has been recognized by the condition that the Upper Basin allow 7.5 MAF to pass the Compact point, Lee Ferry, Arizona, each year, or not less than 75 MAF in each ten-year period. The Operating Criteria of 1970 provide for a delivery of 8.25 MAF/yr to the Lower Basin whenever reservoir and runoff conditions permit.

(2) The Compact of 1922 and the pieces of legislation which followed were derived from compromise and agreement between interests competing for the resources of the basin.

(3) Recent attention has been focused on the salinity problems of the basin, and solutions are being sought which will satisfy agreements made with Mexico and conform to the conditions of the Federal Water Pollution Control Act Amendments, while allowing development in the Upper Basin to continue.

1.2.4 Recent Developments in the Colorado River Basin

Establishment of states rights to the consumptive use of Colorado River water spurred agricultural, municipal, and industrial development and increased exportation from both the Upper and Lower Basins.

The various projects undertaken at a multitude of locations along the Colorado River have each had some set of direct benefits, i.e., flood control, increased irrigation, development of municipal and industrial water supplies, hydroelectric power, and so forth.

Besides providing or controlling quantities of water, several of these projects have been designed with features intended to control water quality in the form of total dissolved solids (TDS) and suspended sediment.

The regulation of river flow fluctuations performed by the numerous storage dams has resulted in less erosion and a corresponding lower silt load. At Lee Ferry downstream from Glen Canyon Dam, and the point of separation between the Upper and Lower Basins, the suspended sediment load had varied with river flow from between 20 and 143 million tons/year before the filling of Lake Powell behind the dam, and has since dropped to less than 6 million tons/year (the dam was constructed to accept the sediment and maintain operation of most of its design features for over 200 years).

The major storage projects presently in operation are shown in Figure 1.1. They are the Fountenelle and Flaming Gorge Reservoirs on the Green River, Blue Mesa and Morrow Point Reservoir on the Colorado Upper Main stem, Navajo Reservoir on the San Juan River, and Lakes Powell, Mead, Mohave, and Havasu on the Colorado River.

The Colorado River Aqueduct in California, the large irrigation developments in California and Arizona, the Central Arizona Project now under construction, and other Lower Basin water projects, will utilize the entire annual allotment of water to the Lower Basin within the next ten to twenty years (Weber et al., 1975). Table 1.2 summarizes the projected water depletions of the Upper and Lower Basins.

The Upper Basin is developing at a slower rate, and it is expected that full use of allotted water will not be possible in light of required deliveries of water to the Lower Basin. Future development will likely involve the use of water in extracting and utilizing the vast energy resources in the Upper Basin. The extent of

TABLE 1.2

Present and Future Consumptive Use of Colorado River Water by State

	1968 (1)		1980 (2)		1990 (2)		2000 (2)	
	MAF/yr	(km^3/yr)	MAF/yr	(km^3/yr)	MAF/yr	(km^3/yr)	MAF/yr	(km^3/yr)
Upper Basin								
Arizona	0.02	(0.02)	0.05	(0.06)	0.05	(0.06)	0.05	(0.06)
Colorado	1.91	(2.36)	2.09	(2.58)	2.47	(3.05)	2.79	(3.44)
New Mexico	0.17	(0.21)	0.48	(0.59)	0.63	(0.78)	0.79	(0.97)
Utah	0.65	(0.80)	0.75	(0.92)	0.84	(1.04)	1.39	(1.71)
Wyoming	0.34	(0.42)	0.41	(0.51)	0.53	(0.65)	0.53	(0.65)
Subtotal	3.09	(3.81)	3.78	(4.06)	4.52	(5.58)	5.55	(6.83)
Lower Basin								
Arizona	0.97	(1.20)	2.80	(3.45)	2.80	(3.45)	2.80	(3.45)
California	4.76	(5.87)	4.40	(5.43)	4.40	(5.43)	4.40	(5.43)
Nevada	0.03	(0.37)	0.15	(0.18)	0.23	(0.28)	0.30	(0.37)
Subtotal	5.76	(7.10)	7.35	(9.06)	7.43	(7.16)	7.50	(9.25)
Losses Hoover Dam to Mexico (3)	0.55	(0.68)	0.55	(0.68)	0.55	(0.68)	0.55	(0.68)
Mexico	1.56	(1.92)	1.59	(1.96)	1.59	(1.96)	1.59	(1.96)
TOTAL	10.96	(13.51)	13.27	(16.36)	14.09	(17.38)	15.19	(18.72)

(1) 1968 Upper Basin data taken from "Upper Colorado River Water Uses with Projected Depletions at Lee Ferry," USBR (undated, received 1971), [reservoir evaporation included]; Lower Basin data from the Metropolitan Water District of Southern California, Report for the Fiscal Year July 1, 1967 to June 30, 1968, L. E. Monroe, ed., 1968; page 136.

(2) Estimates compiled on the basis of type of use for future water projects from USBR, 1971 (above); "Upper Colorado Region Comprehensive Framework Study-Main Report," by the Upper Colorado Region State-Federal Inter-Agency Group, June 1971, Table 5; and Ribbens, Richard W. and Robert F. Wilson, "Applications of a River Network Model to Water Quality Investigations for the Colorado River," (Denver, Colorado: USBR, 1973), Tables IX and X.

(3) Losses of water enroute to Mexico are usually listed separately, since neither basin desires to have this quantity charged against its allotment.

such development and its impact on water quality is difficult to judge at the present time (Weber, 1975). It is anticipated that future municipal and industrial uses will conform to a policy of no effluent return, minimizing man-made salt loading and other pollution.

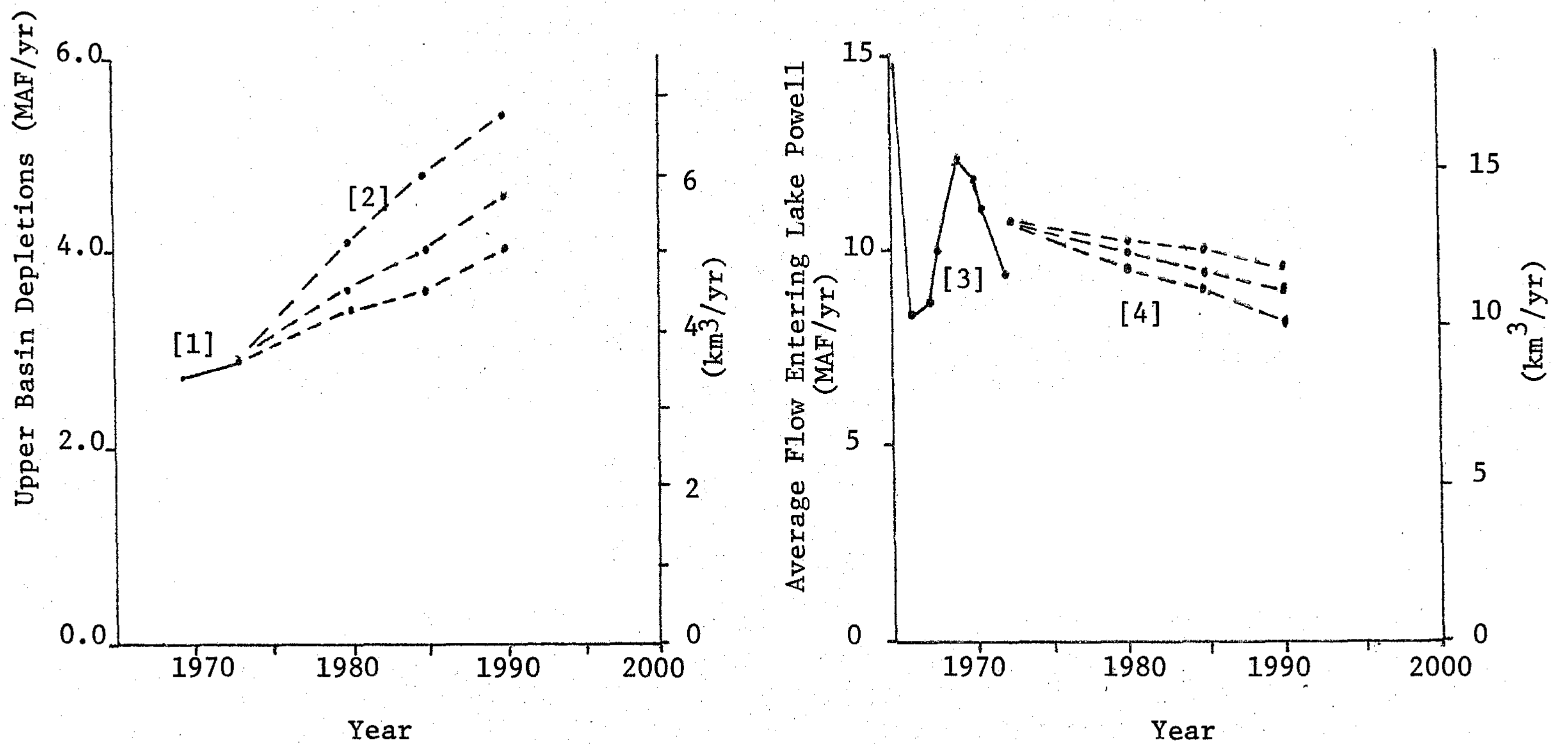
The most recent estimates of future depletions are taken from Weber's study, and are shown in Figure 1.3. A range of projected depletions was used in their study of proposed salinity control projects. U.S. Bureau of Reclamation water use projections are given in Table 1.2 by state. The total use by sub-basin corresponds with the mid-range estimates given by Weber.

The present strategy for salinity control involves a basin wide effort by the U.S. Bureau of Reclamation in cooperation with the seven Basin states and the Environmental Protection Agency (Colorado River Board of California, 1974). The factors responsible for the increase in salinity and the possible areas for control measures are recognized to be the following: natural point and diffuse dissolved solids sources, concentration through evapotranspiration, irrigation return flows, and loss of dilution water through irrigation canal seepage. Control measures proposed include diversion or plugging of natural point sources; desalination, diversion, or special use of diffuse sources; suppression of evapotranspiration; improvement of irrigation efficiency and structures; massive desalination; and streamflow augmentation (Maletic, 1974).

The basin wide approach to salinity control is the most rational given the spatial distribution of sources and the cooperative effort

FIGURE 1.3

Projected Future Depletions in the Upper Colorado River Basin



(1) Source: "Upper Colorado River Water Uses with Projected Depletions at Lee Ferry," USBR (undated), pp. 1-4. Received upon request from L. M. Butterfield, Active, Regional Supervisor of Water and Land Operations, USBR Regional Office-Region 4, Salt Lake City, Utah (August 19, 1971).

(2) Source: Weber, Ernest M., Christopher S. Donabedian, and Merlin B. Tostrud, "Models Applied to Salinity Projections," paper presented at the Seminar on Colorado River Basin Modeling Studies," Utah State University, Logan, Utah, July 17, 1975; Table 1.

(3) Source: Estimated from United States Geological Survey (USGS) streamflow records for the period 1965 to 1973. USGS Water Supply Papers. (See reference following Chapter 2 for a listing of Water Supply Papers used.)

(4) Source: Calculated assuming an average inflow of 13.6 MAF/yr (16.8 km^3/yr) and applying data from Weber et al., Table 1.

required to meet proposed salinity standards. Many of the control measures, such as increased irrigation efficiency and streamflow augmentation, raise water rights questions which must eventually be answered.

1.2.5 Project Applications

The continued development of the Upper Basin water allotment and the water quality problems the basin will continue to face will demand an assessment of water management and allocation throughout the Colorado River Basin. This study is both to serve as an example of the types of management alternatives which could be considered, and to provide a method for evaluating their worth.

In particular this study examines the operation of Lakes Powell and Mead. Both reservoirs presently regulate the flow of water into the Lower Basin and generate hydroelectric power. Little use of the water is made in the rugged canyon land between the two reservoirs, and little future use is anticipated. Their combined active storage capacity is slightly over 52 MAF (64 km^3). The combined evaporation with both reservoirs full is calculated to be 1.7 MAF/yr (2.1 km^3/yr). At a typical operating storage of 80% maximum, the combined evaporation is 1.4 MAF/yr (1.7 km^3/yr).

One objective of this study is to determine the storage required to maintain Lower Basin deliveries below both Lakes Powell and Mead for various levels of Upper Basin depletions. For cases where downstream demands can be met below Lake Mead without utilizing the full capacity of Lake Powell, savings in evaporation, subsequent reductions in total dissolved solids concentrations, and losses of hydropower generating capacity are assessed. Implied in these cases is a rejection of the institutional constraints governing releases from Lake Powell. Comparisons of operation with and without Lake Powell discharge constraints are made and alternative uses of the conserved evaporation, in particular for non-hydroelectric power generation, are examined.

1.3 The Approach Used in This Study and Its Relation to Previous Work

1.3.1 The Simulation Process

A primary study objective is to develop a method for assessing the water supply, water quality, and hydroelectric power generation which may be expected upon implementation of a given management scheme. Alternative management strategies will then be compared on the basis of these expected outputs. The stochastic, or randomly varying, nature of streamflow inputs to the system requires that many observations of system operation need to be made to estimate the expected system output.

To accomplish this task, a model of the river system has been constructed using sub-models describing relevant hydrologic, water quality (in this case salinity), and power production processes in the basin. The hydrologic sub-model generates long sequences of synthetic streamflows which statistically resemble the recorded flow sequence. The water quality sub-model produces sequences of synthetic total dissolved solids concentrations. A third sub-model determines reservoir storage, reservoir losses, and outflow salinity. Additional sub-models model reservoir discharge and power production.

Model parameters such as correlation coefficients and reservoir evaporation rates are used in these sub-models. The model variables describing the hydrology, salinity, and power production of the system for a given time period are called system variables. Variables defining the operational constraints which in turn define a given management configuration, such as water demand and maximum reservoir storage, are called system control variables. System response, or performance, is defined to be the mean, or in some cases even the entire probability distribution, of some or all of the system variables.

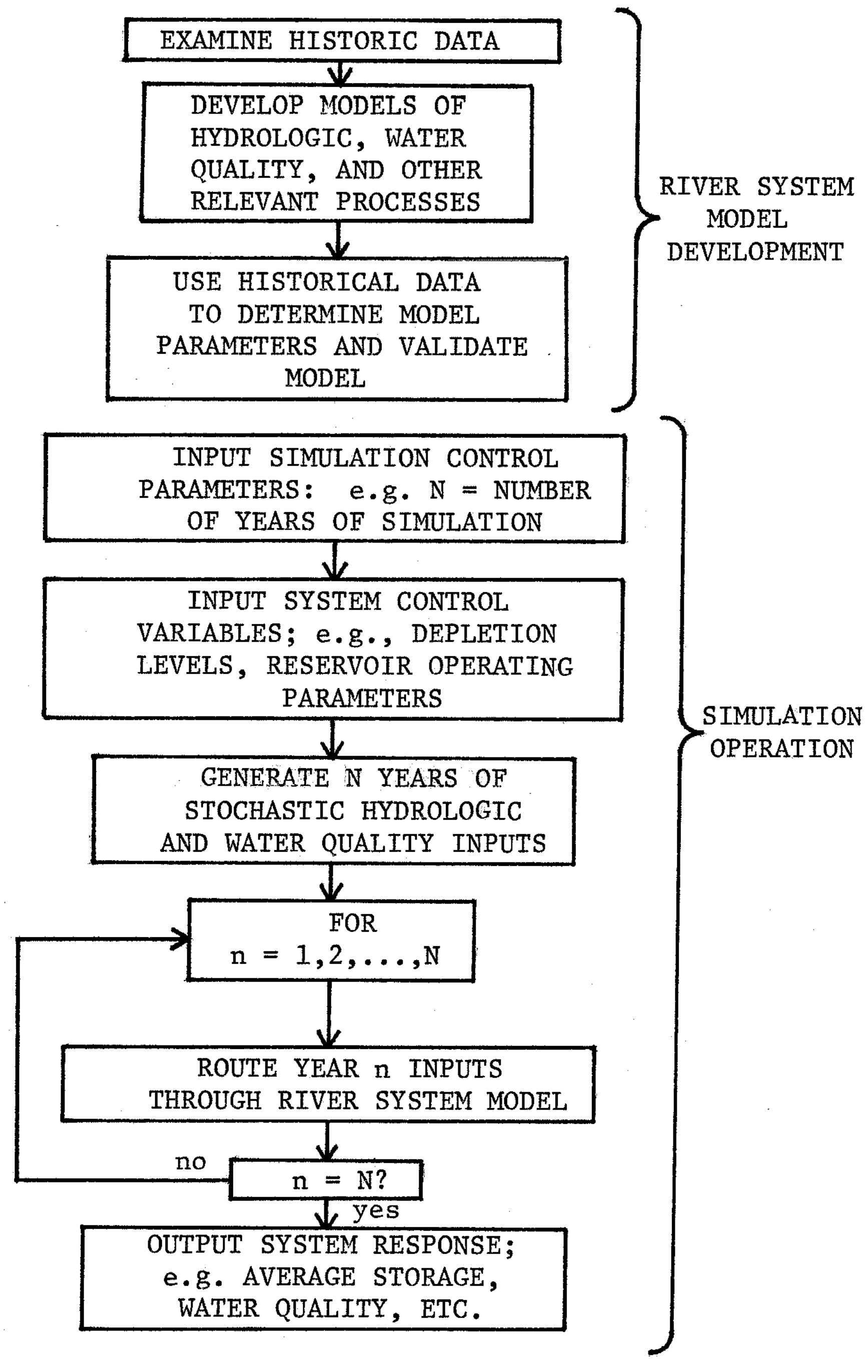
Finally, simulation is the process of observing the operation of the system for a long sequence of stochastic streamflow inputs and recording the system response. Figure 1.4 displays the modeling and simulation process.

Management comparisons are made on the basis of changes in system response. Given a set of response criteria, the response of a simulation model may be optimized by a search procedure (Emshoff and Sisson, 1970). An alternative approach, useful when optimization criteria are difficult to establish, or when the possible combinations of control variables are too numerous, is to perform selective simulations (Buras, 1972; Linsley and Franzini, 1972). The second approach, selective simulation, is used in this study to examine a few management alternatives of interest.

If the state of the system at any given time is defined to be the amount of water and total dissolved salts stored in each reservoir, obtaining stationary distributions of system variables requires

FIGURE 1.4

The Modeling and Simulation Processes



observing the system during many transitions between probable states. Operations in successive time periods are not independent, and the serial correlation structure of inputs must be modeled. In this type of simulation, static simulation, the control variables are held constant throughout the simulation. Static simulation is commonly used to answer design questions pertaining to required reservoir storage capacity or in searching for optimal reservoir release rules (Fiering, 1961; Loucks, 1968; Moran, 1970).

In dynamic simulation, control variables are made to change from time period to time period in accord with projections of future water demand or other management constraints. Simulation using stochastic inputs is used to provide insight to the future outputs of the system. In order to obtain the distribution of output at some future time, many simulation runs are required. Dynamic simulation is typically used in studying optimal operation of reservoirs or systems of reservoirs (Askew, 1974; Hall et al., 1968; McBean and Schaake, 1973).

1.3.2 River Basin Modeling and Management Studies

Analysis of river basin management schemes using simulation with stochastic inputs has developed largely over the past fifteen to twenty years. Much of the work has been in the area of optimization of reservoir operation. Well established optimization procedures have been presented in books by Maas et al. (1962), Kindswater (1964), Buras (1972), and Linsley and Franzini (1972).

In contrast to studies of reservoir systems, simulation studies of hydrologic and water quality aspects of river management schemes have been performed. The state of the art of water quality simulation has been presented by Orlob (1973). Recent applications to problems with stochastic inputs include the work of Grantham et al. (1971), Sigualdason et al. (1972), and the ongoing study of the Colorado River Basin by the Bureau of Reclamation.

The USBR is currently engaged in developing a dynamic simulation model of hydrology and salinity in the Colorado River Basin for use in studying projections of future operation and in assessing future stream salinities (Ribbens and Wilson, 1973; Hendrick and Gibbs, 1974; and Flucher et al., 1975). At the present time an interim salinity routing model is used in conjunction with a stochastic hydrologic model. The entire simulation model is expected to be completed within the year. The dynamic character of the USBR model makes it well suited to short term (five to ten year) operational studies. In contrast, the approach in this study is a static simulation model which examines the steady state response of the river system. It is valuable in examining questions of a long term planning or design nature.

Other studies of portions of the Colorado Basin include simulation modeling performed at the Utah Water Resources Laboratory of the University of Utah (Hyatt et al., 1970; Dixon et al., 1970; Dixon and Hendricks, 1970). In these studies of streamflows and stream salinities within the Upper Colorado Basin, a hybrid-computer model was constructed and used to examine the short term effects of irrigation practice on salinity over a detailed spatial grid of the area. Howe and Orr (1974) at the University of Colorado, have used a simulation model of the Upper Basin to examine economic incentives for salinity reduction.

Previous and current work related to the development of the hydrologic, water quality, and reservoir sub-models is presented in the discussions of their development in Chapters 2 through 4.

1.4 Organization of the Report

Chapter 2 contains a detailed development of the hydrologic model used in this study and the application of the model to the Colorado River Basin. The stream salinity model is formulated and its application discussed in Chapter 3. Reservoir models of Lakes Powell and Mead are presented in Chapter 4.

The aggregation of the above sub-models to form the river system model is described in Chapter 5, together with model validation. Also included in Chapter 5 is a description of the steps required to perform a simulation and an accounting of system variables and system control variables used in subsequent studies. Chapter 6 is a discussion of tests of the modeled system performed for the purpose of identifying characteristics of system response and providing information useful in interpreting simulation outputs.

Finally, Chapter 7 presents the results and interpretations of the management studies described briefly in Sections 1.1 and 1.2.4.

A summary section is included at the end of each chapter. Chapter 8 summarizes the entire report and indicates areas of possible future research.

CHAPTER 2

THE HYDROLOGIC MODEL

2.1 Introduction

The purpose of the hydrologic model is to supply synthetic sequences of streamflows and to model the passage of flows through the two major reservoirs of the Colorado River system.

The central element of hydrologic models used in simulation studies is a synthetic streamflow generator. Fiering (1961, 1964, 1967), Jackson (1975a,b,c), Matalas (1967a,b), and others have developed methods of generating synthetic flow sequences. Matalas (1967a), Pegram and James (1972), and Young and Pisano (1968) have developed computational features of multilag-multivariate streamflow models. This chapter includes an examination of hydrologic data analysis and existing techniques of streamflow synthesis. A method for generating serially and cross-correlated monthly flows is presented in Section 2.2.

Numerous studies have been made of various portions of the Colorado River system by the United States Bureau of Reclamation and various university researchers. The Upper Colorado River Commission sponsored research by the University of Colorado, Colorado State University, and the University of Denver to provide information about annual run-off flowing into Lake Powell (Brittan, 1961; Garnsey _et al._, 1961; Julian, 1960, 1961; Yevdjevich, 1961). Hyatt _et al._ (1970), have authored a number of publications of the Utah Water Resources Laboratory in which an analogue computer model of flow and salinity was constructed to study the Upper Colorado River Basin. The UWRL model was a composite of detailed sub-basin models. The Bureau of Reclamation (USBR) has constructed its own digital computer model of the Colorado River reservoir system for the purpose of scheduling releases (Clinton, 1972). The USBR model has also been used to study the effects of periods of high and low flow on the system, but uses only historical flow sequences and does not model water quality. A new model of the basin is presently being developed by the USBR which will simulate hydrologic and salinity flows, and is scheduled for completion in 1976.

Section 2.3 defines the elements of the Colorado River Basin model used in the author's study. Preliminary analysis of historical flow records is performed, followed by application of the streamflow generating scheme introduced in Section 2.2. The remainder of the chapter is devoted to an evaluation of the synthetic flow generator.

2.2 Hydrologic Simulation

Synthetic hydrology, also called operational hydrology, has been developed over the last twenty years as a tool for planning and studying the operation of systems of water projects (Jackson, 1975a). The usefulness of simulation studies using synthetic streamflow sequences was recognized when standard optimization techniques became impractical in the face of the many constraints and variables necessary to describe the operation of multiple reservoir systems (Linsley and Franzini, 1972). Systematic use of operational hydrology provided a method for examining a variety of alternative configurations and policies. A myriad of models for streamflow generation have been developed, each having advantages or disadvantages depending upon the intended use of the simulation model, the data available for model calibration, and the degree of detail required.

2.2.1 Preliminary Data Analysis

Prior to adopting a specific synthetic streamflow generation procedure it is necessary to determine the requirements of the study at hand. The temporal and spatial resolution required by the study must be established. Next, since synthetic streamflow generation proceeds from a stationary probability distribution of streamflow (on which trends or cycles may be superposed), it is usually necessary to examine the historical data for trends and cycles (Matalas, 1967a; Yevjevich, 1972).

The first step in trend analysis, when sufficient data are available, is to restore the measured streamflows to a natural state by adding to the record of a given river gauge all measured diversions and other man-made flow alterations which are known to have occurred upstream of the gauge over the period of measurement.

A non-parametric run test may be performed on the natural flow sequence to identify any non-stationarity in the mean square of the data (Bendat and Piersol, 1971). Any non-stationarity, or trend, observed may be removed from the data by either the least squares fit procedure for trends of polynomial form, or the average slope method, for simple linear trends. Implicit in the application of these techniques are the assumptions that the available data properly reflect any non-stationarity that exists, and that the trend is defined to be any frequency component whose period is longer than the length of the streamflow record.

The elimination of trends and cycles from the measured streamflow data results in a time sequence having a stationary probability distribution. Distribution parameters may then be estimated for use in calibrating a synthetic flow generation model.

2.2.2 Synthetic Streamflow Models

Jackson (1975a), in a discussion of the state-of-the-art of operational hydrology, categorized existing streamflow simulation models into descriptive and prescriptive models, depending upon their intended use. Descriptive models are those which attempt to describe the underlying physical processes of a watershed system, so as to provide insights into the nature of these processes and the operation of the watershed system. Prescriptive models are those which provide synthetic watershed outputs which are statistically indistinguishable from the historical outputs. The prescriptive models are intended to supply inputs to simulation models for planning and management studies.

Of the existing prescriptive models, three basic forms may be identified: (1) fractional noise models, (2) broken-line models, and (3) autoregressive Markovian models. The fractional noise models, introduced by Mandlebrot and Wallis (1968, 1969), and the broken-line models, developed by Rodriguez-Iturbe et al. (1972a,b), have been criticized as imposing stringent conditions upon sample size, or in being too awkward for hydrologic applications (Jackson, 1975a). The Markovian models of the form suggested by Thomas and Fiering (1963), and Fiering and Jackson (1971), are well suited for utilizing the commonly short records of hydrologic data. These models have the added advantage of being structurally simple and easy to modify. The basic Thomas-Fiering model for producing annual streamflows at a single location, has been modified to provide monthly or seasonal flows at any number of locations (Fiering, 1961, 1964, 1967; Fiering and Jackson, 1971; and Pegram and James, 1972). Other formulations of the autoregressive Markovian streamflow model have been presented by Young and Pisano (1968), and Matalas (1967a).

An example of a Thomas-Fiering model for producing monthly streamflows for several tributaries, exhibiting both lag-one autocorrelation and cross-correlation, is developed in Section 2.2.3 and applied to the Colorado River Basin in Section 2.3.

2.2.3 Development of a Lag-one, Multisite Streamflow Model

As mentioned previously, synthetic streamflow generation requires the determination of the probability distributions for the natural flows of each tributary. When modeling monthly flows, the task becomes one of determining the distribution of flows for each month and each tributary. These distributions may be made functions of previous flows and streamflows in other tributaries. In general, the flow of a given tributary for a given month and year is assumed to consist of a deterministic component and a random component, as shown in Equation (2.1):

$$ {}_tQ_m^y = {}_tD_m^y + {}_tR_m^y \ , \tag{2.1} $$

where, ${}_tQ_m^y$ = the synthesized tributary flow,

$_{t}D_{m}^{y}$ = the deterministic component of the flow, and

$_{t}R_{m}^{y}$ = the random component of flow.

The deterministic component defines the relationship of the flow in tributary t, year y, and month m to the flows in the previous months and in other tributaries. In general, the distribution of natural flows is not well approximated by any theoretical distribution, such as the standard or log-normal distributions. Ideally, the deterministic component of flow can be defined so that the distribution of the remaining portion of natural flow (i.e., the distribution of the random component) can be approximated by one of several theoretical distributions. In practice, the portion of the natural flow which remains after removing the deterministic component represents the portions of the flow corresponding to physical processes not modeled by the deterministic component. In this treatment the various elements in the deterministic component are removed from the historical natural flow data in a stepwise progression. This development follows the work of Fiering (1961, 1967) and Fiering and Jackson (1971).

At each step, averages, variances, and correlation coefficients are approximated by their maximum likelihood estimates. The notation introduced in this section is representative of that used throughout this chapter. As before, t signifies the tributary for which flows are to be synthesized for year y and month m. A bar identifies a time average over all years y, y = 1, 2, ... n, where n is the total number of years of historical data used in the study. An epsilon represents the residual flow after each step of analysis has been performed and is labeled by the number of the step in parentheses.

2.2.3.1 Removal of the Monthly Mean

Equation (2.2) shows the removal of the monthly mean from the historical natural flow data and the production of the first residual.

(2.2) $${}_tN_m^y = {}_t\overline{N}_m + {}_t\varepsilon_m^y\,(1) \text{ or,}$$

(2.3) $${}_t\varepsilon_m^y(1) = {}_tN_m^y - {}_t\overline{N}_m$$

where,

${}_tN_m^y$ = natural, undepleted flow in tributary t, for year y, and month m, as measured at a specified gauging station in (MAF/yr); and,

${}_t\varepsilon_m^y(1)$ = the step one residual.

The residual has zero mean, and variance equal to that of the original natural flow, ${}_tN_m^y$.

2.2.3.2 Removal of Lag-one Autocorrelation

When it is desired to model flow distributions for each month, as in this formulation, it is often necessary to model any persistency or correlation between one month and the preceding months. Inclusion of persistence in the model insures that, as in nature, high or low runoff periods are grouped together. Further, when the distribution of annual flows generated by the model is compared to those of nature, the autocorrelative structure of the model produces the extreme wet or dry years observed in nature, a property not preserved if the monthly flows are generated independent of one another.

Correlograms of the residuals defined by Equation (2.3) indicate for what time lags significant autocorrelation exists. The typical situation encountered when treating monthly hydrologic data is for the lag-one correlation to be the only correlation of significance. In this case the lag-one autocorrelation is removed from the data as shown by Equation (2.4) in terms of the original data.

$$(2.4) \qquad {}_tN_m^y = {}_t\overline{N}_m + ({}_ta_m) \cdot ({}_tN_{m-1}^y - {}_t\overline{N}_{m-1}) + {}_t\varepsilon_m^y(2),$$

where ${}_ta_m$ is the regression coefficient between flows in months m and m-1.

In terms of the residuals Equation (2.4) becomes:

$$(2.5) \qquad {}_t\varepsilon_m^y(1) = ({}_ta_m) \cdot {}_t\varepsilon_{m-1}^y(1) + {}_t\varepsilon_m^y(2), \text{ or}$$

$$(2.6) \qquad {}_t\varepsilon_m^y(2) = {}_t\varepsilon_m^y(1) - ({}_ta_m) \cdot {}_t\varepsilon_{m-1}^y(1).$$

The regression coefficient, ${}_ta_m$, is determined by minimizing the variance of ${}_t\varepsilon_m^y(2)$. (See Appendix A for details of the computation.)

2.2.3.3 Removal of Cross Correlation Between Tributaries

Visual or statistical examination of the residuals from step two above may indicate that significant cross correlation is present between the tributary flows. This conclusion would be expected if it is known that the tributary basins are subject to common weather patterns.

When generating synthetic tributary flows in which the deterministic component of flow may contain cross-correlation terms, it is necessary to begin synthesis for one tributary whose flows are relatively independent of the flows of other tributaries. Calculation and examination of the cross-correlation coefficients of the step-two residuals should indicate appropriate dependency relationships between the tributary flows. In ambiguous cases, where correlation coefficients do not serve to define a hierarchy of tributary flow dependencies, observed climatological patterns may reveal which tributary flows are representative of conditions over the entire river basin.

The correlative relationships established are summarized in Equation (2.7) in terms of the step two residuals.

$$(2.7) \qquad {}_t\varepsilon_m^y(2) = \sum_{s \in S} [(b_{ts}) \cdot {}_s\varepsilon_m^y(2)] + {}_t\varepsilon_m^y(3),$$

where b_{ts} is the regression coefficient between tributaries t and s, and S is the set of tributary flows with which the flows of tributary t are cross-correlated. Solving for the step three residuals yields Equation (2.8).

$$(2.8) \qquad {}_t\varepsilon_m^y(3) = {}_t\varepsilon_m^y(2) - \sum_{s \in S} [(b_{ts}) \cdot {}_s\varepsilon_m^y(2)].$$

The regression coefficients, b_{ts} are estimated by minimizing the variance of the residual, ${}_t\varepsilon_m^y(3)$ (see Appendix A for details of the computation). In some cases the cross-correlation between tributaries exhibits seasonal dependency. In this case the parameter estimates, denoted by ${}_m b_{ts}$, must be determined using the flow data of the appropriate month, m, rather than the entire flow sequence.

2.2.3.4 Treatment of Random Component

It was stated at the beginning of section 2.2.3 that one goal in the construction of the deterministic component of the streamflow model is to isolate the randomness of natural processes. If the deterministic component is defined in accordance with the analysis of this section then the remaining residuals are assumed to contain only information pertaining to the randomness of the natural streamflow.

It was also noted that this randomness could be modeled by assuming it to have a form given by one of the several theoretical probability distributions. For instance, if the residuals for a given month and tributary could be shown to be normally distributed with zero mean and variance σ^2, then they may be generated by random selection from a normal population having the same mean and variance.

An alternative procedure for generating sequences of the random components for a given month and tributary is to sample randomly from the appropriate cumulative probability distribution function (C.D.F.). The C.D.F. is formed by ranking the n sample residuals in ascending order, and assigning to each the plotting number given by:

$$N = \frac{r}{n+1} \tag{2.9}$$

where, r = the rank of the sample.

Twelve such C.D.F.'s are required for each tributary, one for each month of the year. Their creation and use may be easily performed using digital computers, an advantage over the previous methods when several tributaries are to be treated.

2.2.3.5 Flow Generation Procedure

The generation of synthetic tributary streamflows proceeds as follows:

(1) For each month in succession a random flow component for each tributary is selected;

(2) Following the order prescribed by the cross correlation hierarchy, monthly natural flows, ${}_tQ_m^y$, are constructed using Equation (2.10).

$$(2.10) \qquad {}_tQ_m^y = {}_t\overline{N}_m + ({}_ta_m) \cdot [{}_tQ_{m-1}^y - {}_t\overline{N}_{m-1}] + \sum_{s \in S} (b_t) \cdot {}_sR_m^y + {}_tR_m^y$$

where ${}_tR_m^y$ denotes the random flow component for tributary t, month m, and year y. For the first month of generation, ${}_tQ_{12}^o$ is set to some arbitrary value, usually the average (Fiering and Jackson, 1971; p. 59).

It may be noticed from the structure of Equation (2.10) that negative flows could be generated if the correlated and random terms were negative and larger in magnitude than the average monthly flow. One of several methods may be used to deal with this situation: rejection of the flow followed by regeneration; truncation at some lower limit; or, taking absolute values. Each of these techniques necessarily distorts the low-flow tail of the distribution of generated flows. Distribution comparison tests can be used to determine whether the distributions of synthesized and historical streamflows lie within a specified confidence interval of one another.

2.3 Application of Streamflow Synthesis to the Colorado River Basin

2.3.1 Introduction

To reiterate, the purpose of synthesizing Colorado River Basin streamflows is to allow a variety of water resource management configurations to be studied by subjecting the system to a variety of streamflow sequences. A first step is to determine the spatial and temporal resolution of the model necessary to provide an adequate representation of system inputs. An examination of previous modeling work of the Colorado Basin was informative.

Several earlier studies of flows in the Colorado Basin were directed toward determining the reliable annual yield from the river system. This work was greatly inspired by the apparent overallocation of water rights by the Colorado River Compact of 1922. Some of these findings are discussed in Section 2.3.3 on trends and cycles. As the salinity of the river continued to increase it became apparent that relationships between flow and salinity could not be adequately understood on the basis of annual averages. As mentioned in Section 2.1, Hyatt et al. (1970) at the Utah Water Resources Laboratory in Logan, Utah, studied several sub-basins in the upper Colorado region. Their study examined the effects of irrigation and municipal water depletions on the salinity and hydrologic flows of the major Upper Colorado River Basin tributaries. This work resulted in an analog computer model of many portions of the Upper Basin, and incorporated several years of detailed climatological and agricultural data. Because of the short periods of record for the types of data that they used and the fine spatial and temporal grid size which their model embodied, their study was not deemed appropriate for the present project. Howe and Orr (1974 (a,b)) at the University of Colorado have created a similar model on a digital computer for studying economic trade-offs between various water uses in the Upper Colorado region. Again, the form of their model was not considered suitable for this study.

The Bureau of Reclamation has one existing Colorado River Basin computer model and another which is presently being constructed. The first model was primarily developed for scheduling releases of water from the various basin reservoirs. The USBR model includes all of the reservoirs shown in Figure 1.1 and extends as far south as the Imperial Dam near the Mexican border. The first model, however, does not include simulation of salinity flows in the river basin and is therefore not useful for studying the effects of water uses and reservoir regulation upon salinity. The model uses a basic time period of one month and produces a table of monthly reservoir releases. To the extent that this Bureau of Reclamation model was used for research purposes it was not run as a simulation model with stochastically generated inputs, but rather used historical sequences of flow to study periods of high and low water availability. A second Bureau of Reclamation model has been constructed for research purposes as well as reservoir regulation and includes salinity. It is not expected to be completed until late 1975 or early in 1976. The flow simulation portion of this model has recently been completed (Hendrick and Gibbs,1974). This USBR model generates synthetic stream flows corresponding to flows at a majority of the stream locations in the Upper Colorado River Basin presently being gauged by the U.S. Geological Survey. Although fewer gauging stations are incorporated in the model presented in this paper, the streamflow generators developed by the USBR and concurrently by the author have a similar correlative structure.

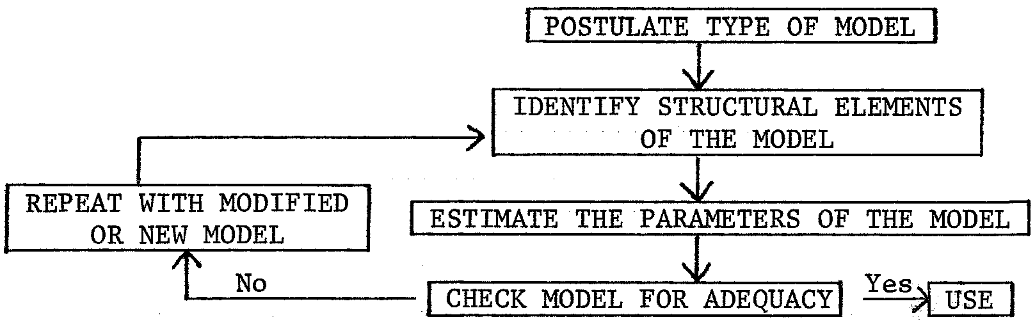
2.3.2 Choice of a Model

The study at hand requires a model unlike those mentioned above. To observe changes in the salinity, storage, and releases of Lakes Powell and Mead does not require the fine spatial detail present in the UWRL models. The existing Bureau of Reclamation model is not well suited to the task for three reasons: (1) it does not include salinity information; (2) it is concerned with details of reservoir release determination which would not greatly affect the type of information this study expects to produce; and (3) it is run using historical or short-term forecasted flows as opposed to synthetic flows.

In order to establish the form of the hydrologic model appropriate for this study it was necessary to determine the requirements of the study, examine the available data, and take into consideration the experience gained by previous researchers. The model was then formulated as a sequence of elements or submodels. The procedure for developing each submodel is shown diagramatically in Figure 2.1 (Raudkivi and Lawgun, 1974), below.

FIGURE 2.1

Submodel Selection Procedure



2.3.2.1 Hydrologic Model Requirements and Constraints

The spatial detail incorporated in the model is dictated by the requirement for an adequate stochastic description of the hydrologic and salinity inputs to Lake Powell. The basic time unit used in the model must be small enough to reflect any time variation in streamflow or salinity that would influence or be caused by the operation of the major reservoirs of the river system.

The form of the model is also constrained by the period of record of historical hydrologic and salinity data and by the temporal and spatial characteristics of the data. Figure 2.2 displays the hydrologic features of the Colorado River Basin and the locations of major gauging stations. Daily and monthly streamflow records at the lower gauges of the four largest Upper Basin tributaries exist back to and including 1931. (Some of the tributary flows have been recorded for a much longer period of time, but by themselves were inadequate for model calibration.) Salinity data at the major gauging stations extends back to and includes 1941.

FIGURE 2.2

Major Colorado River Basin Gauging Stations

Key:

1. Colorado River Gauge at Cisco, Utah
2. Green River Gauge near Green River, Utah
3. San Juan Gauge near Bluff, Utah
4. San Rafael River Gauge near Green River, Utah
5. Colorado River Gauge at Lees Ferry, Arizona
6. Colorado River Gauge below Hoover Dam

Sources: U. S. Bureau of Reclamation, Quality of Water: Colorado River Basin, Progress Report No. 5 (Jan., 1971); frontispiece.
Reader's Digest Assoc., Reader's Digest Great World Atlas (1963); p. 46.

The Colorado Upper Mainstem, the Green River, the San Juan River and the San Rafael River are used as the sources of stochastic inputs to the model. These tributaries contribute more than 96% of the flows of salt and water into Lake Powell as shown in the mass balance diagram in Figure 2.3. Synthetic streamflows for these rivers are generated for points corresponding to gauging stations just upstream of Lake Powell. This division of total inflow produces a statistically accurate description of total inflow to Lake Powell and allows for an accounting of the effects of Upper Basin development upon the flow and salinity of each tributary.

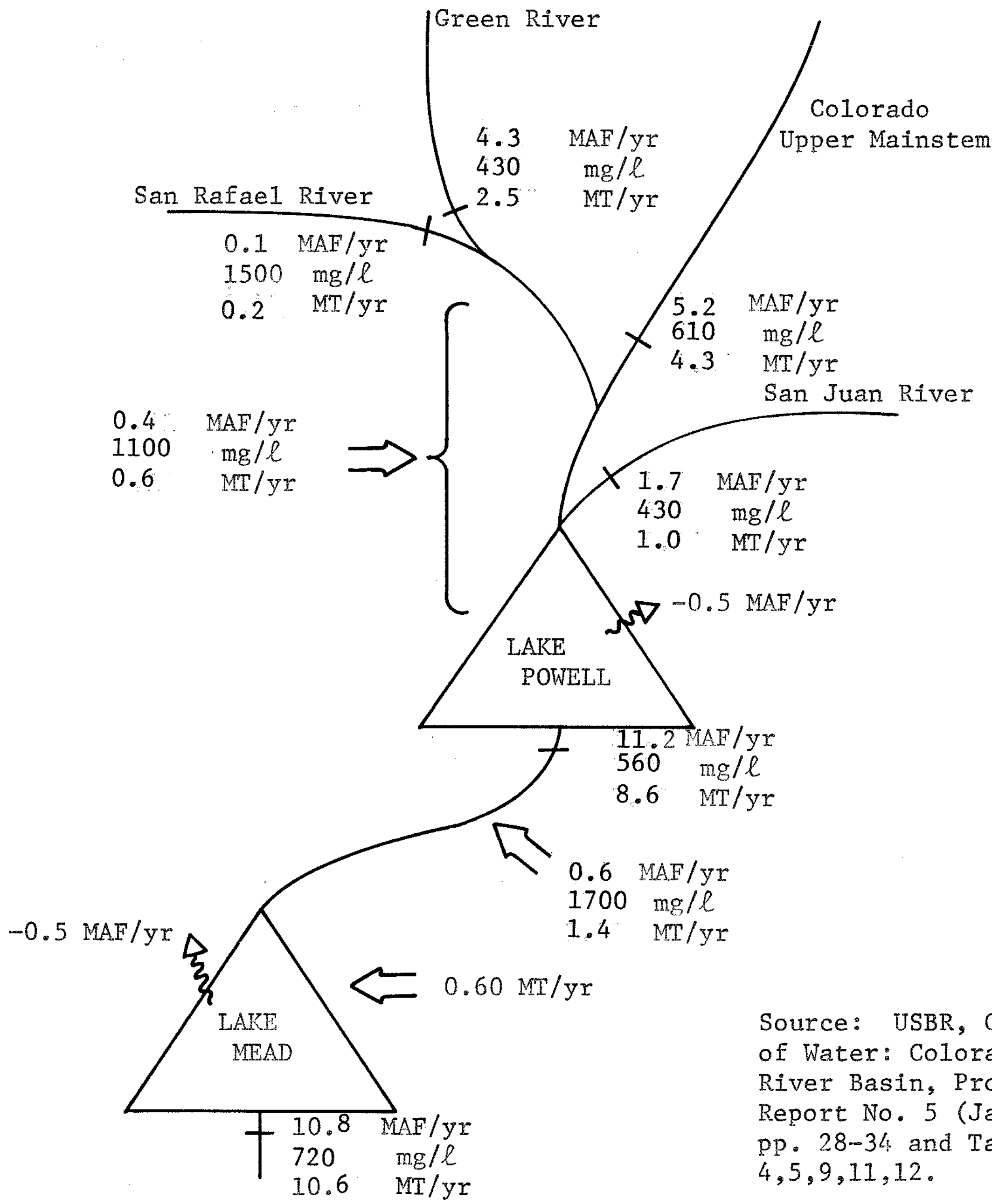
In order to study the operation of Lakes Powell and Mead and their effects upon salinity the model is terminated at a point just downstream of Hoover Dam on Lake Mead.

A time scale of one month was chosen for a number of reasons. Seasonal flow variations, reservoir detention and mixing times, and the desirability of examining monthly reservoir operation were factors in this decision. The streamflows of the wet season, April through July, are typically an order of magnitude greater than those of the dry season, September through February. Wet season flows are the result of snow melt and dry season flows are fed by subsurface water storage. Since these two different physical processes produce flows with different probability distributions, streamflows are synthesized on a monthly basis.

Reservoir detention times for both Lakes Powell and Mead are between two and four years, requiring that data at intervals of less

FIGURE 2.3

Colorado River Basin Water and Total Dissolved Solids Mass Flows (Average historical data, 1941 to 1968)



Source: USBR, Quality of Water: Colorado River Basin, Progress Report No. 5 (Jan., 1971) pp. 28-34 and Tables 4,5,9,11,12.

Note: 1 MAF = 1.233 km^3; 1 MT = 0.907 million metric tons than two years be used to represent mixing and dilution characteristics. Models of Lake Mead (Hendrick, 1973) have shown that monthly data are sufficient to describe the outflowing concentration of salts. Finally, reservoir evaporation in arid regions varies seasonally, suggesting the use of monthly evaporation data.

2.3.2.2 Hydrologic Model Elements

On the basis of the material presented above, the hydrologic model of the Colorado River Basin was formed as a sequence of elements as shown in Figure 2.4. The elements of the model are:

(1) a generator of synthetic tributary streamflows;

(2) a component which adjusts natural tributary flows in accordance with specified uses of water in each tributary basin;

(3) a component for including estimates of ungauged inflows above Lake Powell;

(4) a submodel for routing flows through Lake Powell, including inputs for specifying reservoir release policy;

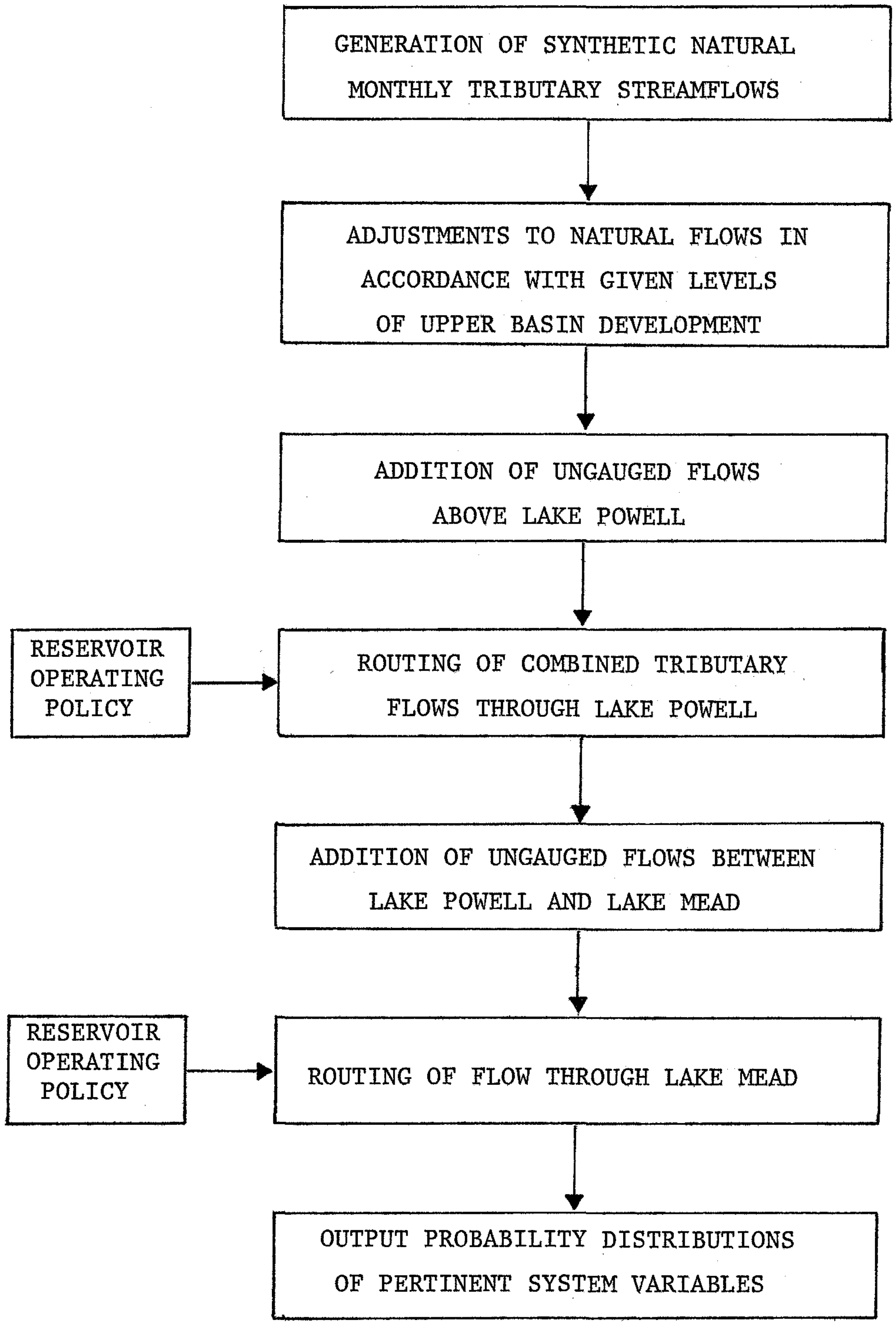
(5) a component for inputting estimates of ungauged inflows above Lake Mead;

(6) A submodel for routing flows through Lake Mead, using a specified release policy; and,

(7) a provision for obtaining information on the probability distributions of pertinent system variables.

FIGURE 2.4

Elements of the Colorado River Basin Hydrologic Model



The remainder of Chapter 2 presents the development of the snythetic flow generation submodel. The elements of the hydrologic model pertaining to Lakes Powell and Mead are developed in Chapter 4.

2.3.3 Preliminary Data Analysis

As stated in Section 2.2.1 it is usually necessary to analyze hydrologic records for trends and cycles which must be removed from the data prior to construction of a flow generation model.

2.3.3.1 Cycles

Hydrologists have long sought to prove the existence or absence of long-term cycles in the annual flows of the Colorado River. Yevdjevich (1961) and Jacoby and Anderson (1972; p. 54) have examined annual flow records of the Colorado River at Lees Ferry, Arizona from 1896 to the present, and found that no significant long period cycles could be detected. Linsley and Franzini (1972) support the finding that no significant cycles tend to exist in hydrologic data and further cite that one of the reasons cycles are hard to determine is that periods of records of hydrologic data are too short to allow definitive analysis. Bryson (1975) reported that significant fluctuations in climatic conditions may occur on a time scale of a few decades. However, he made no mention of cycles or periodicity in his discussion of climatic change.

While large variations in annual flow can be observed in the Colorado River data, no periodicity was observed over the period of record of this study, 1931 to 1968. No attempt was made to include long-term periodicity in the generation of synthetic streamflows.

2.3.3.2 Trends

The above researchers and the author found that the only significant trends in annual streamflows and monthly streamflows are due to water usage in the Upper Colorado River Basin for municipal, irrigation, export and other uses. Natural tributary flows, obtained by subtracting trends due to usage of water in the Upper Colorado Region, are used for determining the characteristics of the stationary flow probability distributions in each tributary. Ideally, trends due to upstream uses of water would be accounted for by using Equation (2.11).

$$(2.11)\qquad {}_tN_m^y = {}_tH_m^y + \sum_i {}_tDMI_m^y(i) + \sum_j {}_tEXP_m^y(j) + \sum_k [{}_tDIV_m^y(k) - {}_tRET_m^y(k)] + \sum_\ell [{}_t\Delta S_m^y(\ell) + {}_tE_m^y(\ell)]$$

where,

${}_tN_m^y$ = natural, undepleted flow in tributary t, for year y, and month m, as measured at a specified gauging station (MAF/yr);

${}_tH_m^y$ = the historically measured flow at the given gauge;

${}_tDMI_m^y(i)$ = the i^{th} depletion for municipal or industrial use upstream of the gauge, during year y, month m;

${}_tEXP_m^y(j)$ = the water exported from the basin at location j, upstream of the gauge;

${}_tDIV_m^y(k)$ = the k^{th} diversion of water for in-basin irrigation;

${}_tRET_m^y(k)$ = the return flow associated with irrigation at location k;

$_t\Delta S_m^y(\ell)$ = the change is storage during year y, month m, of upstream reservoir ℓ; and,

$_tE_m^y(\ell)$ = the net volume lost by evaporation at reservoir ℓ.

Use of this equation would have required complete knowledge of all depletions, irrigation returns, and losses, for each month and year of the study. Such data do not exist in most cases except as estimates on an annual basis. Exports have been measured by the USGS, but the majority of depletions and losses are ungauged. Annual net irrigation depletions (diversions minus returns), have been estimated by the USBR for the past years on the basis of irrigated acreage, type of crop, and rainfall (Willmore and Lazenby, 1973). These annual depletion estimates have then been distributed over the April to July growing season. Examination of streamflow depletion data revealed the following information:

(1) the total Upper Basin annual depletion rose slightly over the 1931-1968 period of record from 1.5 to 2.7 MAF/yr or from 10 to 20 percent of the average natural flow during that period;

(2) county, state, and Bureau of Reclamation estimates of irrigation depletions varied widely;

(3) depletions, including exports, occurred predominantly during the growing season, April to July;

(4) the fraction of the total Upper Basin depletion occurring in each tributary sub-basin remained roughly constant throughout the period of record.

These last two observations are summarized in the following tables:

TABLE 2.1

	Jan-Mar	Apr	May	Jun	Jly	Aug-Dec
Fraction of depletion occurring in each month, p_m	0.0	0.05	0.45	0.35	0.15	0.0

Table 2.2

	San Rafael	Green R.	Colo R.	San Juan
Fraction of total depletion occurring in each tributary, s_t	0.0	0.15	0.75	0.10

Monthly natural flows were then created using Equation (2.12).

$$(2.12) \qquad {}_tN_m^y = {}_tH_m^y + (p_m) \cdot (s_t) \cdot DPL_m^y$$

where p_m and s_t are given by Tables 2.1 and 2.2, and where ${}_tDPL_m^y$ equals the total Upper Basin depletion as estimated by the Bureau of Reclamation (1971a). These approximations result in annual flows which differ from USBR estimates by no more than 5% for each tributary. It should be noted here that the data from the Upper Basin gauging stations used here are considered accurate to within $\pm$ 10% (USGS Water Supply Paper 2125, 1973; Vol. 1, pp. 7, 514; Vol. 2, pp. 7, 435, 463, 605).

The resulting natural flows were analyzed to calibrate the synthetic streamflow generation model, and are graphically displayed in Appendix B.

2.3.4 The Synthetic Streamflow Generation Model

To re-emphasize, the purpose of generating synthetic streamflows is to provide long sequences of stochastic inputs to the basin simulation model. The simulation method requires that the synthetic flows be statistically indistinguishable from the historical sequence. To meet this requirement for flows of the Upper Colorado River Basin tributaries it is necessary to reproduce (a) the observed seasonal periodicity in average monthly flow, (b) the serial correlation between successive months, and (c) the cross-correlation between tributaries. The approach used in this study follows the method developed in Section 2.2. United States Geological Survey monthly streamflow data from the period 1931 to 1969 were used to calibrate the synthetic streamflow model.

The following sections will parallel the model development of Section 2.2. The residuals produced at each step are graphically displayed in Appendix B.

2.3.4.1 Removal of the Monthly Mean

In accordance with Equation (2.1) the mean monthly flows for each tributary were estimated and subtracted from the flow sequences. The mean flows, or average annual hydrographs, of each tributary are displayed in Table 2.3 and Figure 2.5. The residual, given by Equation (2.13),

$$(2.13) \qquad {}_t\varepsilon_m^y(1) = {}_tN_m^y - {}_t\overline{N}_m .$$

has zero mean, and variance equal to that of natural flow. (See Appendix A.)

TABLE 2.3

Monthly Average Flows of Upper Colorado River Basin Tributaries (MAF)
(Natural Flows, ${}_t\bar{N}_m$, 1931 - 1969)

Tributary	Month												Annual Total
	JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC	
Colorado Upper Mainstem, ${}_1\bar{N}_m$ (MAF/mo)	0.161	0.157	0.195	0.579	2.021	1.903	0.774	0.218	0.175	0.209	0.200	0.178	6.770
Green River, ${}_2\bar{N}_m$ (MAF/mo)	0.119	0.137	0.241	0.436	1.031	1.126	0.459	0.192	0.131	0.146	0.142	0.125	4.285
San Juan River, ${}_3\bar{N}_m$ (MAF/mo)	0.049	0.064	0.097	0.222	0.462	0.440	0.177	0.095	0.075	0.093	0.061	0.052	1.887
San Rafael River, ${}_4\bar{N}_m$ (MAF/mo)	0.003	0.004	0.005	0.006	0.020	0.031	0.007	0.007	0.003	0.003	0.003	0.003	0.095

Sources: U. S. Geological Survey, Water Supply Papers, (see the references at the end of this chapter for a complete list of Water Supply Papers used.)

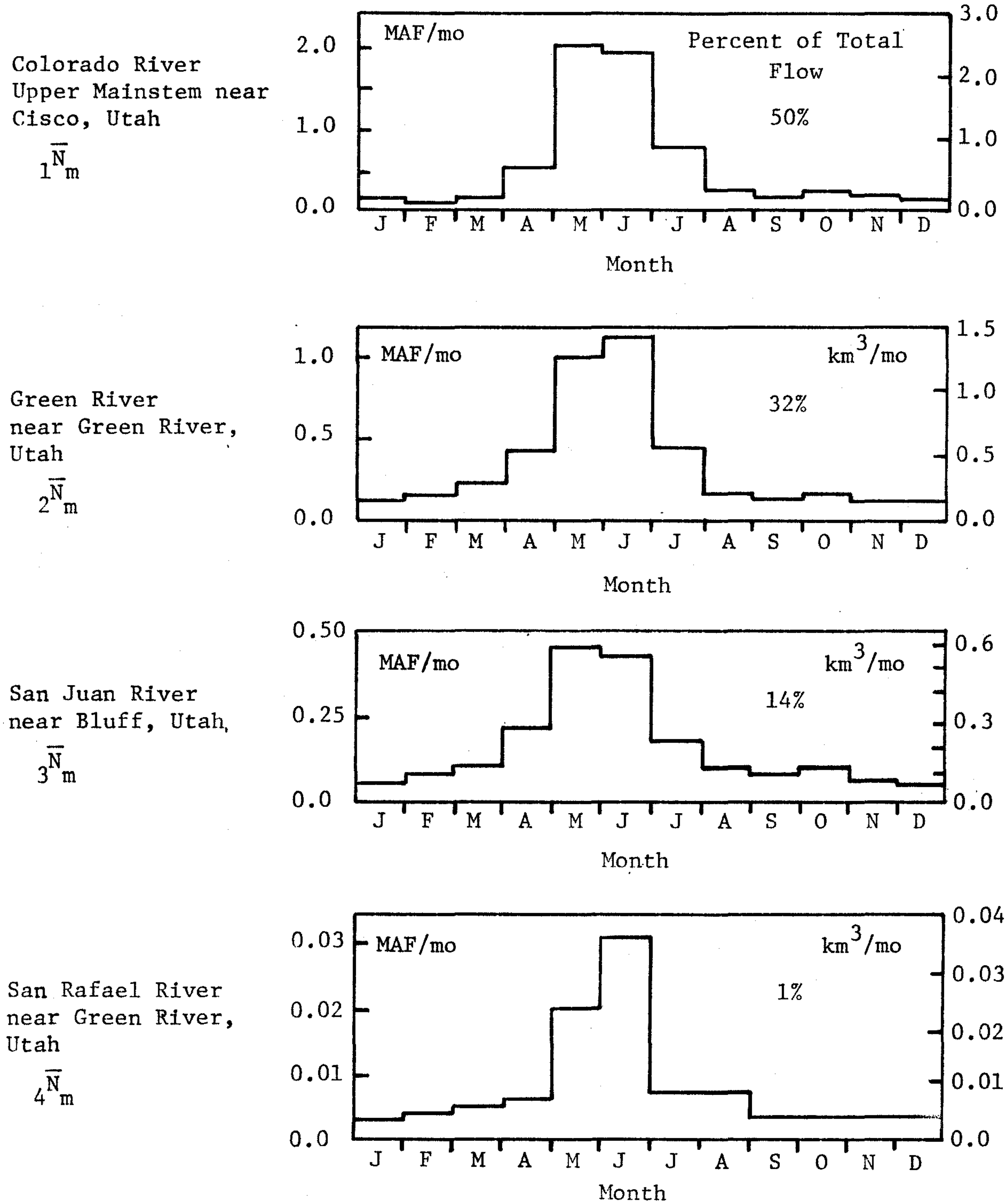
U. S. Bureau of Reclamation, "Computation of Virgin Flow...Colorado River at Lee Ferry," January, 1971.

Notes: Natural streamflows and streamflow statistics calculated using data from the above sources.

FIGURE 2.5

Average Hydrographs of Upper Colorado River Basin Tributaries

(Natural monthly flows, ${}_t\overline{N}_m$, 1931-1969)



Sources: See citations at bottom of Table 2.3.

2.3.4.2 Removal of Serial Correlation

The autocorrelation structure of the deterministic component of flow presented in Section 2.2.3 was decided upon following an examination of previous work on Colorado River flows and analysis of the data used in this study.

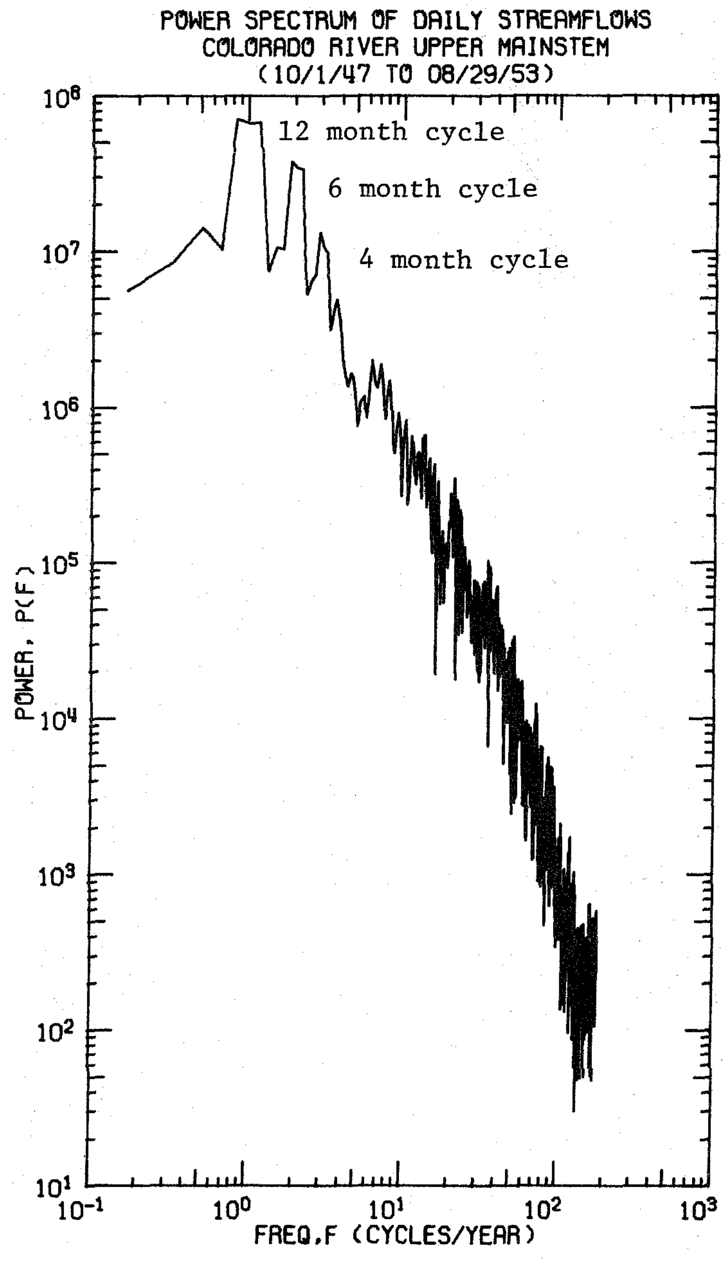
Leopold (1959) compared Lees Ferry annual flows to a random normal sequence and calculated the theoretical distribution characteristics. He also studied the effective persistence, or lag-one serial correlation, and the effect of storage on stream variability. He found that the annual flows closely resembled a normal sequence, with slight serial correlation. Later, Julian (1961) and Yevdjevich (1961), working on a project supported by the Upper Colorado River Commission, determined that there was little or no persistence between water years in the annual Lees Ferry flows.

The present analysis of streamflows between 1931 and 1969, a relatively dry period, also shows the lack of serial correlation between annual flows, but a high degree of serial correlation between monthly flows for some months.

To insure that there are no high frequency components of flow present which would invalidate the use of monthly data in estimating lag-one correlation coefficients, a spectral analysis was performed on six years of daily data for the Colorado Upper Mainstem. The analysis indicates peaks in the spectrum at periods of 365 days, 180 days, and 120 days. (See Figure 2.6)

The component with a period of 12 months represents the seasonal cycle in streamflows, as characterized in the present model by the

FIGURE 2.6



Sources: U.S. Geological Survey, <u>Water Supply Papers</u>, No. 119, 1149, 1179, 1213, 1243, 1283; records for steam gauge on the Colorado Upper Mainstem near Cisco, Utah.

monthly average flows. The spectral peaks at periods of 6 and 4 months represent harmonics of the 12 month cycle and are necessary to produce the shape of the annual hydrograph shown in Figure 2.5.

No cyclic components are encountered with frequencies greater than 0.016 cycles per day, corresponding to a period of 2 months. The sampling theorem defines this to be the folding frequency for monthly data. The absence of higher frequency components indicates that data samples at intervals of less than one month are not necessary to describe the autocorrelation between streamflows of consecutive months.

Correlograms of monthly flows for each tributary reveal that the only significant correlation present is of lag-one month. Typical correlograms giving $\rho^2_{m,m-\ell}$ for lags $\ell=0,1,\ldots,11$ are shown in Figure 2.7.

The adequacy of monthly streamflow data for modeling the autocorrelation structure of Colorado River tributary flows has been demonstrated using spectral analysis. Examination of streamflow correlograms indicates the significance of only lag-one month autocorrelation. These facts allow the application of Equation (2.5) in removing autocorrelation from the residuals of Equation (2.13). Equation (2.5) is reproduced below.

$$(2.14) \qquad {}_t\varepsilon^y_m(1) = ({}_ta_m) \cdot {}_t\varepsilon^y_{m-1}(1) + {}_t\varepsilon^y_m(2).$$

The regression coefficients, ${}_ta_m$, and the corresponding correlation coefficients, ${}_t\rho_m$, are given in Table 2.4. The regression coefficients are graphically displayed in Figure 2.8 for each month and tributary. (The step two residual, ${}_t\varepsilon^y_m(2)$, that results from this operation is displayed graphically in Appendix B.)

FIGURE 2.7

CORRELOGRAMS OF COLORADO RIVER
UPPER MAINSTEM NATURAL FLOWS
(1931-1968)

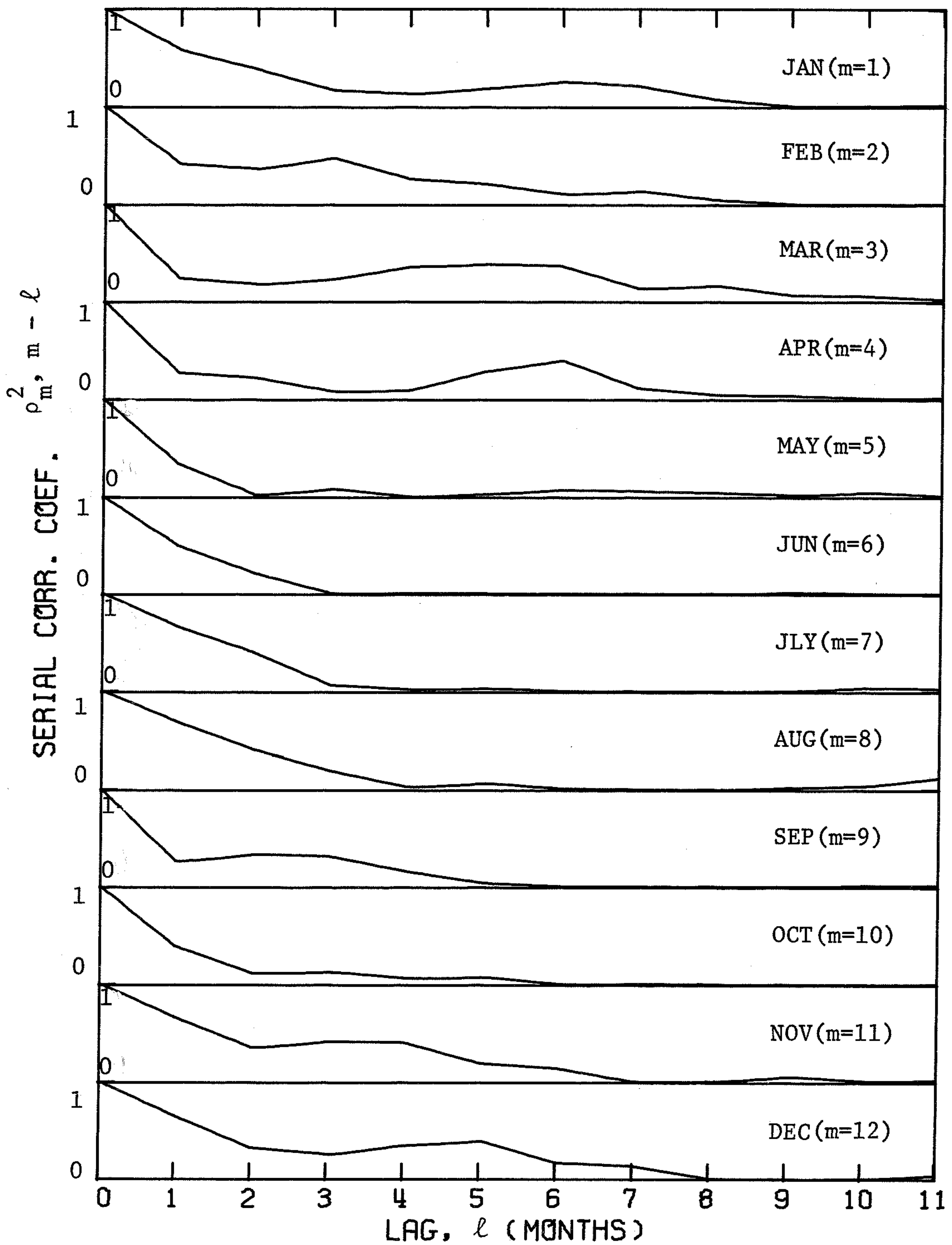


TABLE 2.4

Serial Regression Coefficients, ${}_{t}a_{m}$, and Correlation Coefficients, ${}_{t}\rho_{m}$, for Upper Colorado River Basin Tributaries*

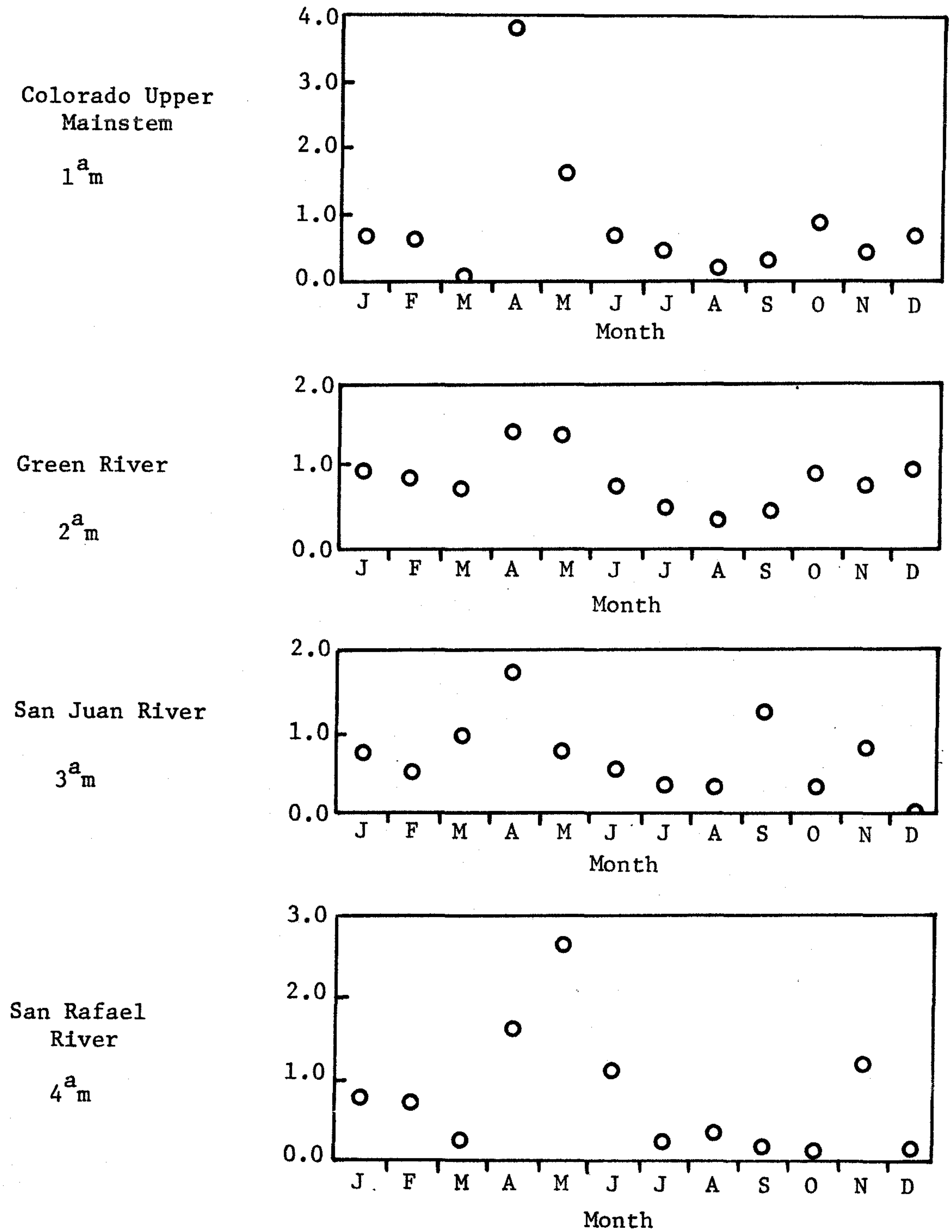
(Natural monthly flows, 1931 - 1969)

Tributary		Month											
		JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC
Colorado	${}_{1}a_{m}$	0.74	0.63	0.07	3.8	1.6	0.68	0.49	0.23	0.28	0.81	0.40	0.65
	${}_{1}\rho_{m}$	0.80	0.62	0.50	0.99	0.61	0.71	0.82	0.82	0.90	0.63	0.81	0.83
Green	${}_{2}a_{m}$	0.94	0.82	0.71	1.4	1.3	0.72	0.43	0.32	0.40	0.83	0.73	0.92
	${}_{2}\rho_{m}$	0.86	0.68	0.54	0.57	0.72	0.65	0.80	0.77	0.63	0.75	0.92	0.86
San Juan	${}_{3}a_{m}$	0.77	0.53	0.93	1.7	0.74	0.49	0.35	0.31	1.2	0.30	0.76	0.0
	${}_{3}\rho_{m}$	0.84	0.42	0.62	0.70	0.70	0.73	0.87	0.60	0.46	0.58	0.74	0.91
San Rafael	${}_{4}a_{m}$	0.80	0.71	0.27	1.6	2.6	1.1	0.21	0.31	0.15	0.11	1.1	0.17
	${}_{4}\rho_{m}$	0.66	0.51	0.17	0.73	0.74	0.72	0.76	0.52	0.22	0.16	0.70	0.58

*Figure 2.12 displays monthly regression coefficients and their 10% confidence intervals, together with typical values from a synthetic flow sequence.

FIGURE 2.8

Monthly Regression Coefficients, ${}_{t}a_{m}$, for Upper Colorado River Basin Tributary Flows



2.3.4.3 Removal of Cross-Correlation

A visual examination of the residuals, ${}_t\varepsilon_m^y(2)$ suggests the existence of cross-correlation between tributaries (see figures in Appendix B). The correlation coefficients, $\rho_{t\delta}$, between the various pairs of tributaries are shown in Table 2.5. The generally poor correlation between San Rafael River runoff and that of any other tributary may be understood in light of its geographic isolation and erratic runoff record.

TABLE 2.5

Correlation Coefficients, $\rho_{t\delta}$, from Cross-Correlation of Pairs of Tributary Residuals

	Colorado	Green	San Juan	San Rafael
Colorado	1.0	---	---	---
Green	0.5	1.0	---	---
San Juan	0.8	0.6	1.0	---
San Rafael	0.1	0.1	---	1.0

As explained in Section 2.2.3, since cross-correlated tributary flows cannot be generated simultaneously, it is necessary to establish a hierarchy of dependence. On the basis of correlation studies the following relationships were used: (1) the Colorado Upper Mainstem is prescribed to be the independent tributary; (2) the Green River flows are a function of Colorado tributary flow; (3) the San Juan River flows are a function of Green and Colorado flows; and, (4) the San Rafael River flows are a function of Green and Colorado flows.

These relationships are supported by the climatological patterns referred to previously. The largest storms enter the basin from the

Pacific Northwest in the late fall and winter. These storms produce rainfall runoff during October and November, and snow melt runoff in late spring and early summer (see Figure 2.9). Storms entering the basin during the summer and early fall originate in the Gulf of Mexico and most of their moisture is released over the San Juan and Colorado Upper Mainstem sub-basins. These weather patterns support the selection of the Colorado Upper Mainstem as the independent tributary, reflecting runoff conditions over the entire Upper Basin.

The relationships established above specify the elements of the set S in Equation (2.7), reproduced below:

$$(2.15) \qquad {}_t\varepsilon_m^y(2) = \sum_{\delta \in S} [(b_{t\delta}) \cdot {}_\delta\varepsilon_m^y(2)] + {}_t\varepsilon_m^y(3).$$

The values of the regression coefficients, $b_{t\delta}$, and the multiple correlation coefficients, R_t^2, are given in Table 2.6

TABLE 2.6

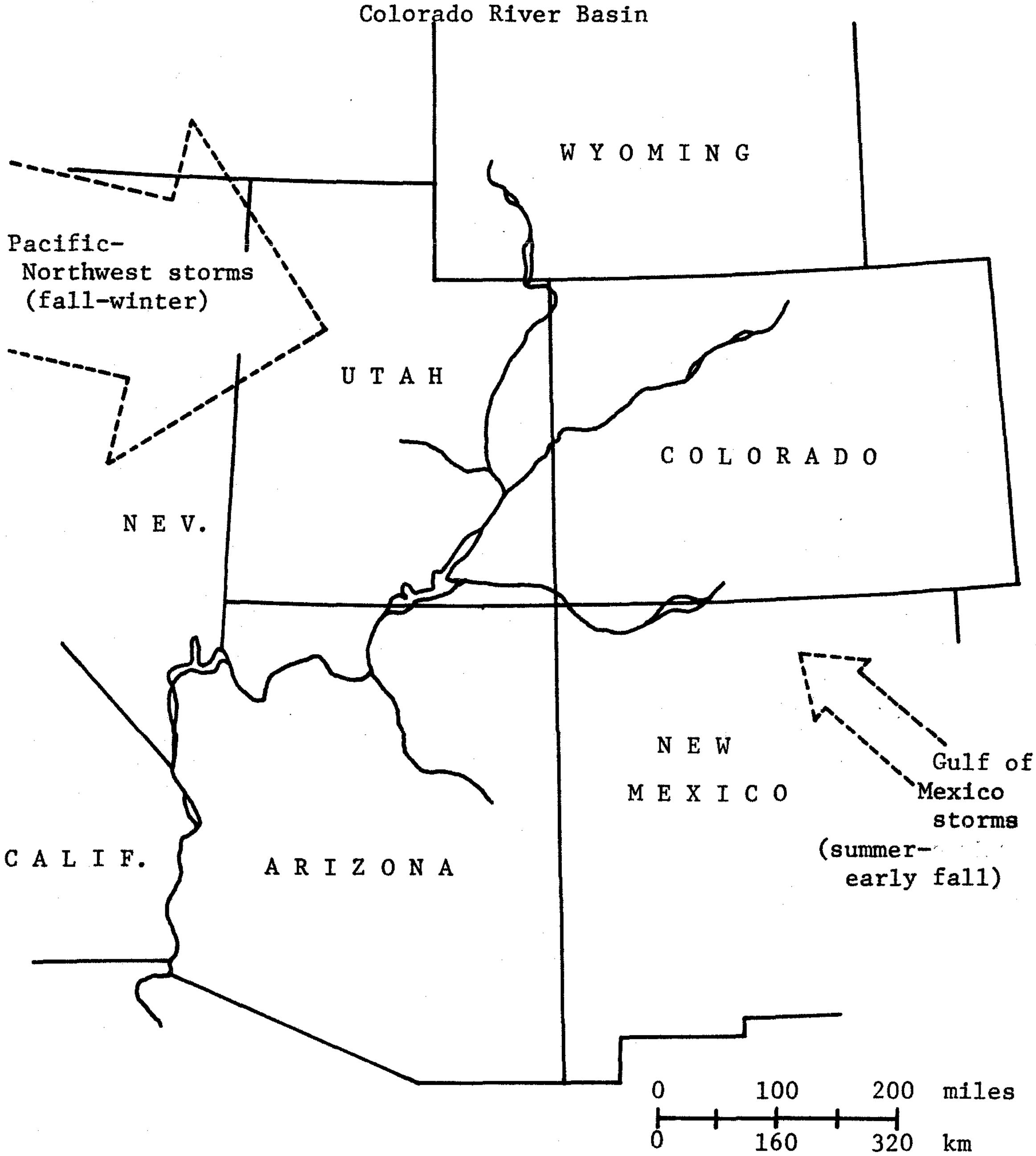
Regression Coefficients, $b_{t\delta}$, from Tributary Cross-Correlation, and Multiple Correlation Coefficient, R_t^2

	Colorado U.M. (δ= 1)	Green R. (δ= 2)	San Juan R. (δ= 3)	San Rafael R. (δ= 4)	R_t^2
Green River (t=2)	0.43	---	---	---	0.5
San Juan R (t=3)	2.1	1.2	---	---	0.6
San Rafael R(t=4)	0.00	0.00	---	---	0.01

It should be noted that the cross-correlation coefficients are independent of the month of the year. While weather patterns may suggest that cross-correlation would be a seasonal phenomenon, monthly cross-correlation analyses did not provide additional reductions in variance.

FIGURE 2.9

Major Weather Patterns Over the Colorado River Basin



Sources: U. S. Bureau of Reclamation, Quality of Water: Colorado River Basin, Progress Report No. 5 (1971a); page 9.

Reader's Digest Association, Reader's Digest Great World Atlas, (1963); p. 46.

The step three residuals, ${}_{t}\varepsilon_{m}^{y}(3)$, are graphically displayed in Appendix B.

2.3.4.4 Treatment of the Random Component of Flow

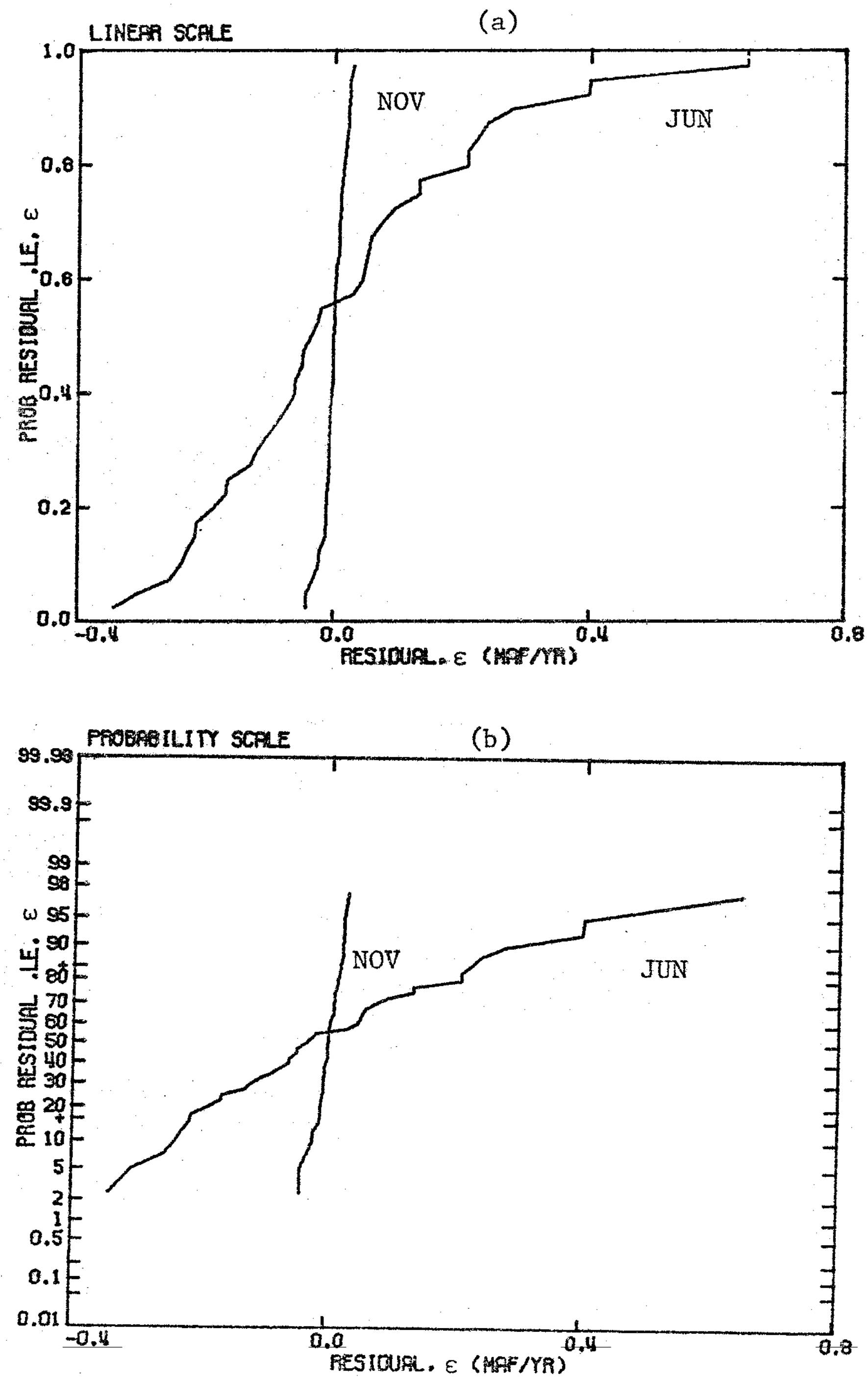
The method for modeling and generating random flow components is that described in Section 2.2.3 involving construction of cumulative probability distribution functions of the remaining residuals. This technique was chosen since the residuals for all twelve months for all tributaries do not appear to match any single theoretical distribution, and separate treatments for each of the 48 cases was deemed impractical.

A typical C.D.F. for a high runoff and a low runoff month is displayed in Figure 2.10a using a linear scale and again in Figure 2.10b using a probability scale.

During streamflow synthesis the selection of random flow components proceeds as follows: (1) a sequence of random integers having a uniform distribution on the interval (o,n+1) are generated, where n is the number of points in the cumulative distribution function (see Section 2.2.3.3). In the application to Colorado River tributaries n is equal to 39. (2) Each random number is associated with the corresponding value of the step three flow residual. The C.D.F.'s are truncated at their extreme entries, as shown by dotted lines in Figure 2.10a,b. The truncation at the tails of each C.D.F. affects the selection of 5% of the random flow components. It should be noted that this truncation does not directly limit the magnitudes of the synthesized flows since the serial and cross-correlated components of flow can produce magnitudes higher or lower than those observed historically.

FIGURE 2.10(a,b)

Cumulative Probability Distribution of Green River Residuals, ${}_2\varepsilon_m^y(3)$



Because the generation of Colorado Upper Mainstem flows does not involve cross-correlation, the C.D.F. for this tributary is formed from the second step residuals, $\varepsilon_m^y(2)$.

2.3.4.5 Synthetic Streamflow Generation Procedure

Flow synthesis retraces the sequence of operations presented above as follows:

(1) specify average flows, correlation coefficients, and the starting position of the random number generator used to select random components, ${}_tR_m^y$, from C.D.F.'s;

(2) set flows at time period y = 0, m = 12 to arbitrary values, in this case the averages;

(3) proceeding by year, month, and tributary:

   (a) select random flow components, ${}_tR_m^y$;

   (b) calculate cross-correlation component

   $$\sum_{s \in S} ({}_{}b_{ts}) \cdot {}_sR_m^y;$$

   (c) calculate serial correlation component

   $$({}_ta_m) \cdot ({}_tQ_{m-1}^y - {}_t\overline{N}_{m-1});$$

   (d) construct flow for year y, month m, tributary t using Equation (2.16).

$$(2.16) \qquad {}_tQ_m^y = {}_t\overline{N}_m + ({}_ta_m) \cdot ({}_tQ_{m-1}^y - {}_t\overline{N}_{m-1}) + \sum_{s \in S} (b_{ts}) \cdot {}_sR_m^y + {}_tR_m^y$$

As stated in Section 2.2.3.5, generation of negative flows is possible using this formulation, and care should be taken in selecting a method for their removal from the sequence so as not to distort the distribution of flows. Two strategies were tested with regard to the elimination of negative flows: (1) setting the flow arbitrarily equal to zero, and (2) taking the absolute value. Neither method affects the first or second moments of the generated flows, probably due to the infrequent occurrence of negative flow generation. The method adopted is that of taking absolute values. The extent to which the tails of the flow distributions are altered by this technique is included in an assessment of the entire generation procedure in Section 2.3.5.

2.3.5 Evaluation of the Synthetic Streamflow Model

The two major questions concerning the generation of synthetic tributary flows are (1) how well do the synthetic flows statistically resemble the historical flows, and (2) how well do the historical flows serve as a data base for model calibration?

The question of statistical resemblance was answered by (1) making comparison tests between the probability distributions of synthetic and historical streamflows, and (2) by checking that model input parameters (averages and regression coefficients) are faithfully reproduced. These tests and their results are described in Section 2.3.5.1.

The second question, which concerns the adequacy of model calibration data, may be restated as follows: *Do the synthetic streamflows create conditions which might reasonably be expected to occur in the future?* Aspects of this question are addressed in Section 2.3.5.2 and again in Chapter 7.

2.3.5.1 Statistical Evaluation of Synthetic Streamflows

The previously stated requirement imposed on the synthetic streamflows was that they be statistically indistinguishable from the historical natural flows. To see if this requirement is fulfilled a test was made of the hypothesis that a sample of synthetic flows and a sample of the historical flows come from the same probability distribution. The Kolmogorov-Smirnov distribution test was used (Benjamin and Cornell, 1970; pp. 509-510).

To check that flow averages, standard deviations, and correlation coefficients are faithfully reproduced by the model, two samples of synthetic flows were subjected to the statistical analysis of the preceding section. The parameter estimates obtained were then compared to those of the historical flow sequence.

The Kolmogorov-Smirnov (K-S) distribution test is performed using the test statistic given by

$$D_{n_1 n_2} = \max\,[\,|F_1(x) - F_2(x)|\,], \tag{2.17}$$

where $D_{n_1 n_2}$ is the maximum value of the difference between $F_1(x)$ and $F_2(x)$, the cumulative distribution histograms of the two samples. The cumulative distribution histograms are formed using Equation 2.9. The samples from which the C.D.F.'s are constructed are not required to be of equal size, although each should have $n > 12$.

A theoretical approximation of $D_{n_1 n_2}$ at the α level of significance is given by Equation (2.18).

$$(2.18) \qquad D_{n_1 n_2}(\alpha) = a(\alpha) \cdot \left(\frac{n_1 + n_2}{n_1 \cdot n_2}\right)^{1/2} ,$$

where a(α) is given by Table 2.7 for various values of α.

If $D_{n_1 n_2} > D_{n_1 n_2}(\alpha)$, then the hypothesis that the two samples are drawn from the same distribution must be rejected at the α level of significance. This statement is equivalent to saying that α is the probability that the maximum difference between the C.D.F.'s of two samples taken from the same distribution would be greater than $D_{n_1 n_2}(\alpha)$.

This test was carried out for the following sets of flows:

(1) the flows for each month of each tributary,

(2) the annual flows of each tributary,

(3) the combined monthly tributary flows versus the monthly flows at Lees Ferry, and

(4) the annual combined flows versus the annual flows at Lees Ferry.

Two synthetic flow samples of 200 years were tested against the 39 year historical sample in each case. The San Rafael historical sample contains only 28 years of data. The results of the tests are shown in Table 2.8 and in Figures 2.11(a-e).

In general it was found that the stated hypothesis can not be rejected at or near the 0.10 level of significance for all annual flow distributions and for the distributions of months of high runoff.

TABLE 2.7

Values of the Coefficient $a(\alpha)$ for the Kolmogorov-Smirnov Distribution Test

	Significance Level, α		
	0.10	0.50	0.01
Test Coefficient $a(\alpha)$	1.22	1.36	1.63

Source: Benjamin, Jack R. and C. Allin Cornell, Probability, Statistics, and Decisions for Civil Engineers (McGraw-Hill, New York, 1970) p. 667.

TABLE 2.8

Kolmogorov-Smirnov Streamflow Distribution Test Results
For Two Flow Sequences

Sequence	Gauge station and streamflow sequence	Test Statistic, $D_{n_1 n_2}$, for Monthly and Annual Flows													$D_{n_1 n_2}$ (α), α =		
		JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC	YEAR	0.10	0.05	0.01
Sequence N9991	Colorado Upper Mainstem	0.14	0.18	0.11	0.13	0.15	0.08	0.15	0.13	0.15	0.18	0.18	0.12	0.11	0.22	0.24	0.29
	Green River	0.24	0.23	0.15	0.15	0.13	0.15	0.10	0.17	0.09	0.11	0.11	0.16	0.09	0.22	0.24	0.29
	San Juan River	0.35	0.23	0.18	0.21	0.14	0.26	0.22	0.17	0.16	0.21	0.22	0.43	0.23	0.22	0.24	0.29
	San Rafael River	0.34	0.21	0.20	0.36	0.22	0.17	0.22	0.20	0.20	0.15	0.26	0.28	0.26	0.25	0.27	0.33
	Lees Ferry	0.32	0.33	0.22	0.22	0.17	0.14	0.08	0.16	0.21	0.25	0.21	0.25	0.21	0.22	0.24	0.29
Sequence N3177	Colorado Upper Mainstem	0.10	0.15	0.11	0.10	0.13	0.09	0.12	0.15	0.12	0.10	0.15	0.10	0.08	0.22	0.24	0.29
	Green River	0.26	0.21	0.11	0.14	0.10	0.11	0.11	0.19	0.15	0.14	0.15	0.17	0.12	0.22	0.24	0.29
	San Juan River	0.26	0.24	0.19	0.18	0.14	0.23	0.24	0.16	0.15	0.19	0.21	0.45	0.22	0.22	0.24	0.29
	San Rafael River	0.38	0.21	0.18	0.31	0.23	0.26	0.27	0.20	0.17	0.14	0.27	0.33	0.29	0.25	0.27	0.33
	Lees Ferry	0.31	0.26	0.22	0.17	0.18	0.14	0.12	0.14	0.22	0.26	0.22	0.23	0.21	0.22	0.24	0.29

Note: If $D_{n_1 n_2} > D_{n_1 n_2}(\alpha)$ then the hypothesis that the two samples are drawn from the same distribution must be rejected, at the α level of significance.

FIGURE 2.11 (a) - (d)

Kolmogorov-Smirnov Streamflow Distribution Test Results

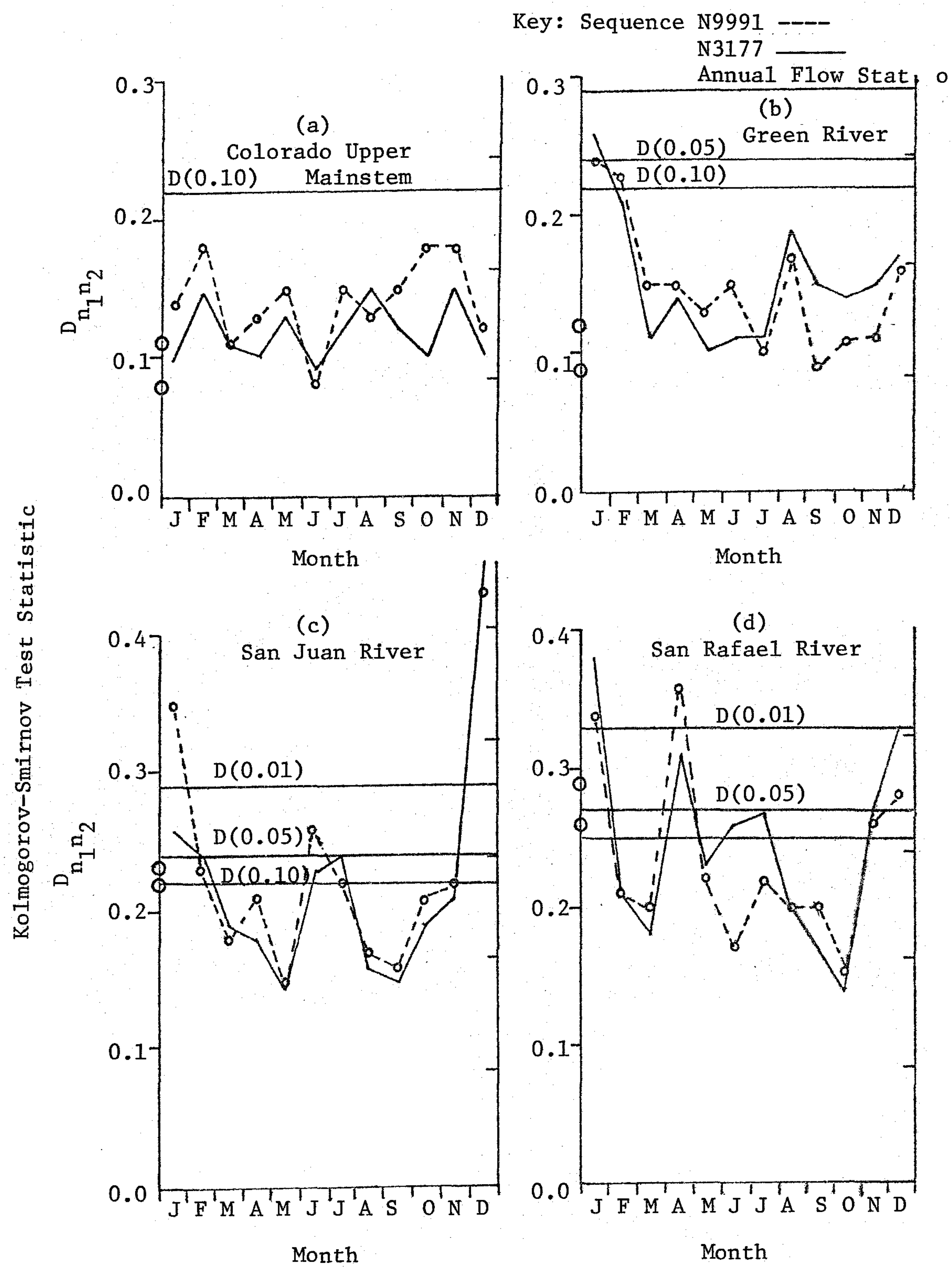
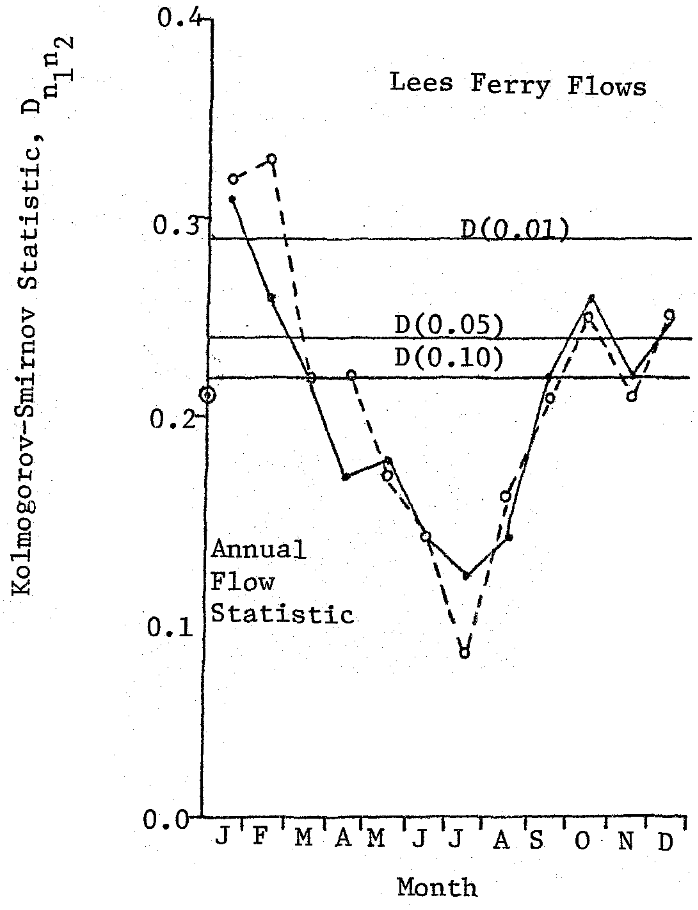


FIGURE 2.11 (e)

Kolmogorov-Smirnov Streamflow Distribution Test Results



Agreement at a 0.05 or higher level of significance is generally considered to be acceptable for applications of the K-S test (Benjamin and Cornell, 1970; p. 468).

Test results are generally poorest for the flow distributions of winter months, periods of low runoff, possibly due to the cross-correlative structure of the model. It may be that December, January and February represent months in which runoff is affected by freezing conditions, disrupting the cross-correlation exhibited during the remainder of the year.

In testing the combined synthetic flows against the historical natural sequence measured at Lees Ferry it is necessary to add ungauged side inflows between the four tributary gauges and the gauge at Lees Ferry to the total synthetic flow. The magnitude of the ungauged flows was estimated from model validation and U. S. Bureau of Reclamation estimates (USBR, 1971b). (Model validation is discussed in Chapter 5.) The K-S test of Lees Ferry flow distributions gives the best results during months of high runoff. The tests of annual flow distributions show that the stated hypothesis can not be rejected at the 0.10 level of significance.

From the results of the K-S distribution tests it was concluded that the synthetic streamflows generated adequately resemble the historical natural flows of the basin.

The two synthetic flow sequences used in the above distribution tests were subjected to a statistical analysis to determine monthly averages, standard deviations, and regression coefficients. The results are displayed graphically in Figure 2.12.

The parameter estimates from the synthetic sequences are found to lie well within the confidence intervals of the historic flow parameters (see Figure 2.12).

On the basis of Kolmogorov-Smirnov distribution tests between historical and synthetic streamflow sequences and the preservation of model input parameters the synthetic streamflows are judged statistically indistinguishable from the calibration data.

2.3.5.2 Discussion of the Adequacy of the Data Base

The second question posed at the beginning of Section 2.3.5 asks whether a model calibrated with thirty-nine years of historical data can provide useful information for planning and determining management practices. The question is important given the typical lifetimes (150 to 200 years) of river management structures and the reported time variation of the earth's climate.

As noted in Section 2.3.3.1 the state of the art of climate modeling is not capable of providing predictions of future climatic conditions. Moreover, significant climatic fluctuations over a period of a few decades are reported to have occurred in the past (Bryson, 1975).

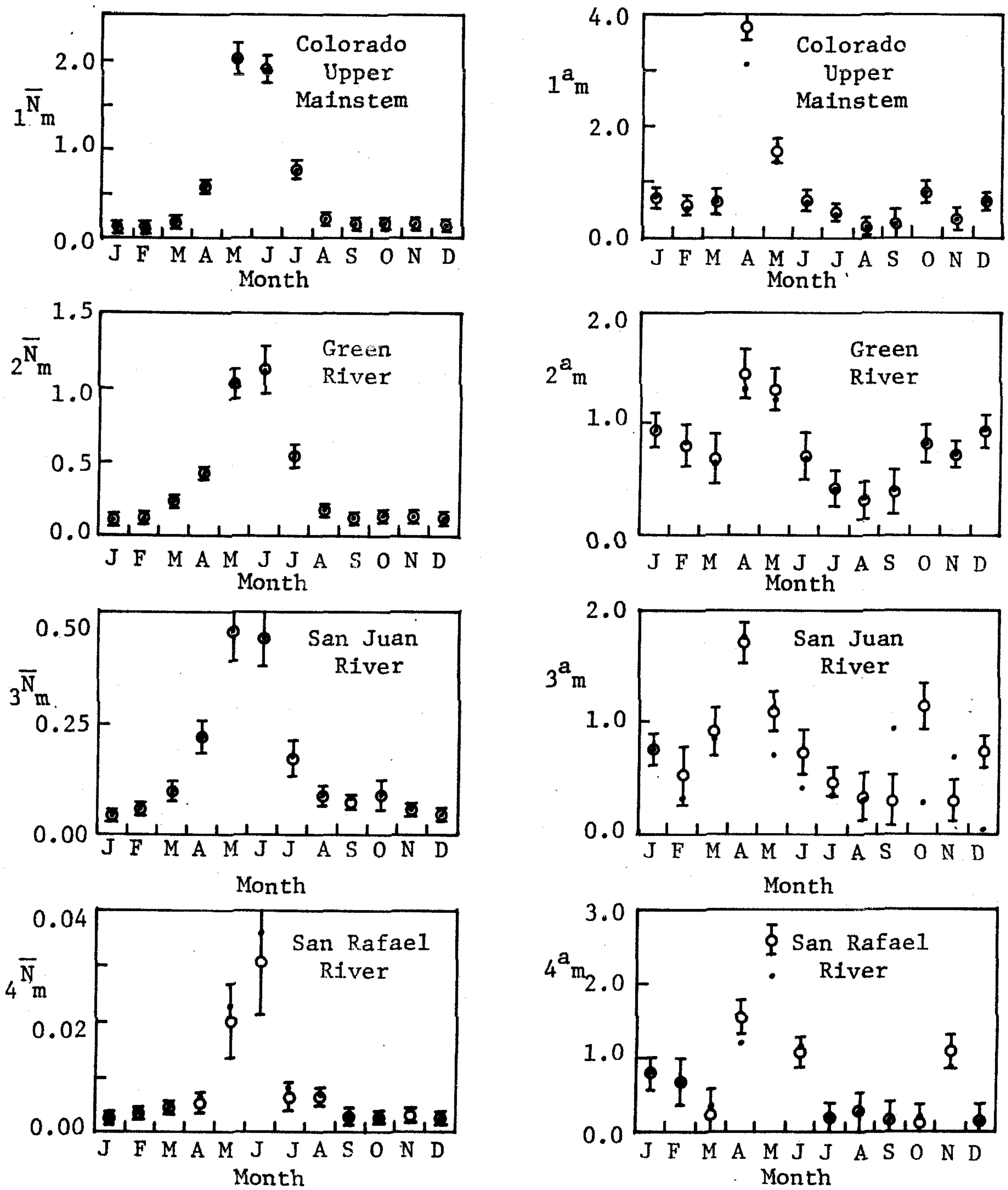
In the absence of predictive climate models management decisions can only be made on the basis of available historical records, as in the study presented here. The purpose of addressing the question is to generate some awareness of how hydrologic simulation should be interpreted.

The thirty-nine year period of streamflow records (1930-1968) used to calibrate the model was selected on the basis of availability

FIGURE 2.12

Natural Flow Averages, ${}_t\overline{N}_m$, and Lag-1 Month Serial Correlation Coefficients, ${}_ta_m$, from Historical and Synthetic Data

Estimate and 90% confidence interval-historical data.
• Estimate-synthetic data.



of data at the stream gauges incorporated in the model. This set of data may be compared to those used by other investigators.

Traditionally, persons responsible for regulating or utilizing the flows of the Colorado River have based decisions about future management on studies employing various historical periods of high or low streamflow (for example, see USBR, 1969). Average annual natural flows at Lees Ferry, Arizona for selected periods range from 12.9 MAF/yr (1931-1964) to 15.6 MAF/yr (1914-1945). The record at this gauging station extends back to 1896, and this 1896 to 1972 annual average natural flow is 14.8 MAF/yr.

The downward trend in natural flow has led to the use of 13.8 MAF/yr as an estimate of the reliable yield of the river (Weisbecker, 1974).

The period of record used in the study presented in this paper provides an average Lees Ferry flow of 13.6 MAF/yr. This figure is in agreement with that used in the Weisbecker study. The average flow values presented show that the calibration data employed are representative of a period of relatively low streamflows and thereby provide a "worst case" for the study of basin management. As more streamflow and flow depletion data become available the model may be updated.

2.4 Summary

The purpose of the Colorado River Basin model is to model the outstanding hydrologic features of the basin. A major element of the model is the synthetic streamflow generator.

Methods of generating synthetic streamflows for studies of hydrologic systems have been advanced over the last two decades. Section 2.2.3 has traced the development of a Thomas-Fiering synthetic flow model of serially and cross-correlated monthly streamflows.

Application of hydrologic modeling to the Colorado River Basin consisted of selecting appropriate time scales and spatial resolution of streamflow data and the generation of synthetic tributary flow sequences. The flows of the four major tributaries of the Upper Colorado River Basin were chosen as the inputs to the river basin model. Historical monthly records were corrected for trends introduced by upstream water usage. The natural tributary flows thus obtained were used to estimate the parameters required by the synthetic flow generating scheme developed in Section 2.2.3.

The synthetic sequences generated were tested and found to be statistically indistinguishable from the historical flow record, using the Kolmogorov-Smirnov test.

CHAPTER 3

THE STEAM SALINITY MODEL

3.1 Introduction

The purpose of the stream salinity model is to supply water quality inputs to the Colorado River Basin model in the form of total dissolved solids (TDS) concentrations. The flow of total dissolved solids through the river system is then modeled so that the effects of various management configurations upon water quality can be studied. Monthly TDS concentrations are generated for each tributary by relating concentration to stream discharge.

The total dissolved solids concentration, C, also referred to as salinity, is expressed in units of milligrams per liter (mg/ℓ), parts per million by weight (ppm), or tons per acre foot (T/AF). For the small concentrations observed in the Colorado River system the concentration in ppm is very nearly equivalent to the value in mg/ℓ (Holburt and Valentine, 1972). In this report concentration is expressed in mg/ℓ. Total dissolved solids flows, T, are commonly expressed in millions of tons (1 ton = 2000 pounds) passing a given point on the river per unit of time, MT/yr or MT/mo (1 MT = 0.9 metric tons). In this report TDS flows are expressed in units of MT/yr or MT/mo.

The impact of increasing salinity upon irrigated agriculture in both the Lower Colorado Basin and Mexico has made total dissolved solids concentration a relevant measure of water quality in the basin. While agricultural outputs are dependent upon other water quality characteristics such as the sodium absorption ratio, the concentration of boron, and the presence or absence of certain trace elements, the high concentration of salts has been recognized as the dominant problem of agricultural efficiency in the Colorado Basin (Valentine, 1974). The average annual salinity at Lees Ferry, Arizona, has increased from 514 mg/ℓ in 1941 to 655 mg/ℓ in 1969, and had been projected to reach 800 mg/ℓ by the year 2000 if adequate salinity control measures are not taken (Holburt and Valentine, 1972). A variety of salinity control measures are presently being studied to determine ways to keep concentrations from rising above present levels (CRBC, 1974; Flack and Howe, 1974; Ribbens and Wilson, 1973).

The concentration of total dissolved solids in any natural water system is the result of many geochemical, hydrological, and man-related processes. One factor found to be of particular significance in determining the TDS concentration is river discharge. This observation has lead to the development of a variety of dissolved solids-discharge models and a variety of model applications. Pinder and Jones (1969) derived a model which they used to estimate the ground water component of peak river discharge. Other models have been suggested for use in estimating runoff, but the most common application encountered is the estimation of dissolved solids concentrations from discharge data

(Ledbetter and Gloyna, 1964; Johnson et al., 1969; Hyatt et al., 1970). These models employ time bases of days, months or years, and have been applied to both large and small river basins.

Relationships between dissolved solids concentrations and river discharge have been formulated in a variety of ways. Some methods are based strictly upon statistical correlation while others have been derived from a knowledge of geochemical conditions and a body of assumptions appropriate to a given river system. Hall (1970) presented derivations for several stream salinity models based upon mass balances and mixing models. He showed that when certain assumptions were applicable, the models he had derived would reduce to statistical relationships, thereby providing a phenomenological basis for formerly empirical analyses.

A particular stream salinity model was chosen and applied to the four major Upper Colorado River Basin tributaries. The relationships established are used to generate synthetic sequences of monthly TDS concentrations associated with the synthetic streamflows for each tributary. The flow of salts through Lakes Powell and Mead is modeled, as described in Chapter 4.

3.2 Stream Salinity in the Colorado River Basin

3.2.1 Sources of Salinity in the Colorado River Basin

To model the flow of salts into and through the river system it was necessary to make some accounting of sources of salts and the processes which effect salinity. Processes which elevate the concentration of

TDS in the Upper Basin, in order of their effect, are (1) flow from natural diffuse or point sources, (2) irrigation, (3) reservoir evaporation, (4) out-of-basin export, and (5) municipal and industrial practices (Maletic, 1974).

The average salt mass leaving the Upper Basin at the present time is roughly 8.6 MT/yr. Estimates of the impact of irrigation upon the salt flow vary widely. Iorns et al. (1965) report that 3 MT/yr of salts are contributed by agricultural return flows. Hyatt et al. (1970), however, estimate the agricultural contribution to be only 1.5 MT/yr. Assuming the natural salt flow to be 5.1 MT/yr, Holburt and Valentine (1972) report that 4.2 MT/yr are from natural diffuse sources, and 0.9 MT/yr are from natural point sources. Natural point sources are springs or seeps.

Table 3.1 shows the contributions by each tributary to the total salt flow at Lees Ferry (see also Figure 2.3). Because the effect that Lake Powell has upon TDS flow is still uncertain, only data from the period prior to the formation of the lake are shown (see Chapter 4 for a discussion of reservoir discharge salinity modeling).

Between Lees Ferry, Arizona, and Hoover Dam, an average of 2.0 MT/yr enters the river. Of this amount, approximately 60% is derived from diffuse sources and 40% from point sources (USBR, 1971).

3.2.2. Data

The stream salinity model developed for this study has a time base of one month. Total monthly streamflow and monthly average TDS concentration data were used to calibrate the model. USGS data for

TABLE 3.1

Contributions to the Historical Total Dissolved Solids Flow at Lees Ferry, Arizona (Historical Averages, 1941-1962)[1]

Source	TDS Flow (MT/yr)	% of TDS Flow at Lees Ferry, Arizona	Streamflow (MAF/yr)	Concentration (mg/ℓ)
Colorado Upper Mainstem	4.25	50	5.21	610
Green River	2.54	30	4.25	430
San Juan River	0.97	11	1.72	430
San Rafael River	0.21	2	0.10	1500
Other [2]	0.60	7	0.40	1100
Colorado River at Lees Ferry, Arizona	8.57	100	11.7	540

Source: USBR, Quality of Water: Colorado River Basin, Progress Report No. 5, (Jan., 1971).

[1] The period 1941 to 1962 covers the data available prior to the formation of Lake Powell, just upstream of Lees Ferry, Arizona.

[2] Estimates of ungauged side inflows between the tributary gauges and the gauge at Lees Ferry, Arizona.

the period 1941 to 1968 were obtained from the U. S. Bureau of Reclamation (USBR, 1971).

The monthly average concentrations are the flow weighted averages of daily data, given by Equation (3.1):

$$(3.1) \qquad {}_tC^y_m = \frac{\sum_i {}_tC^y_{i,m} \cdot {}_tQ^y_{i,m}}{\sum_i {}_tQ^y_{i,m}} ,$$

where

${}_tC^y_m$ = the monthly average concentration in month m, hereafter denoted C;

${}_tC^y_{i,m}$ = the concentration measured on the i^{th} day of month m;

${}_tQ^y_{i,m}$ = the total streamflow during the i^{th} day;

and the summation is over all of the days in month m. For the remainder of this report, the value, ${}_tC^y_m$, or C, is called the <u>concentration</u> for a given month m, year y, and tributary t. The average concentration observed in month m, ${}_t\overline{C}_m$, is called the <u>monthly average concentration</u>, and is given by Equation (3.2):

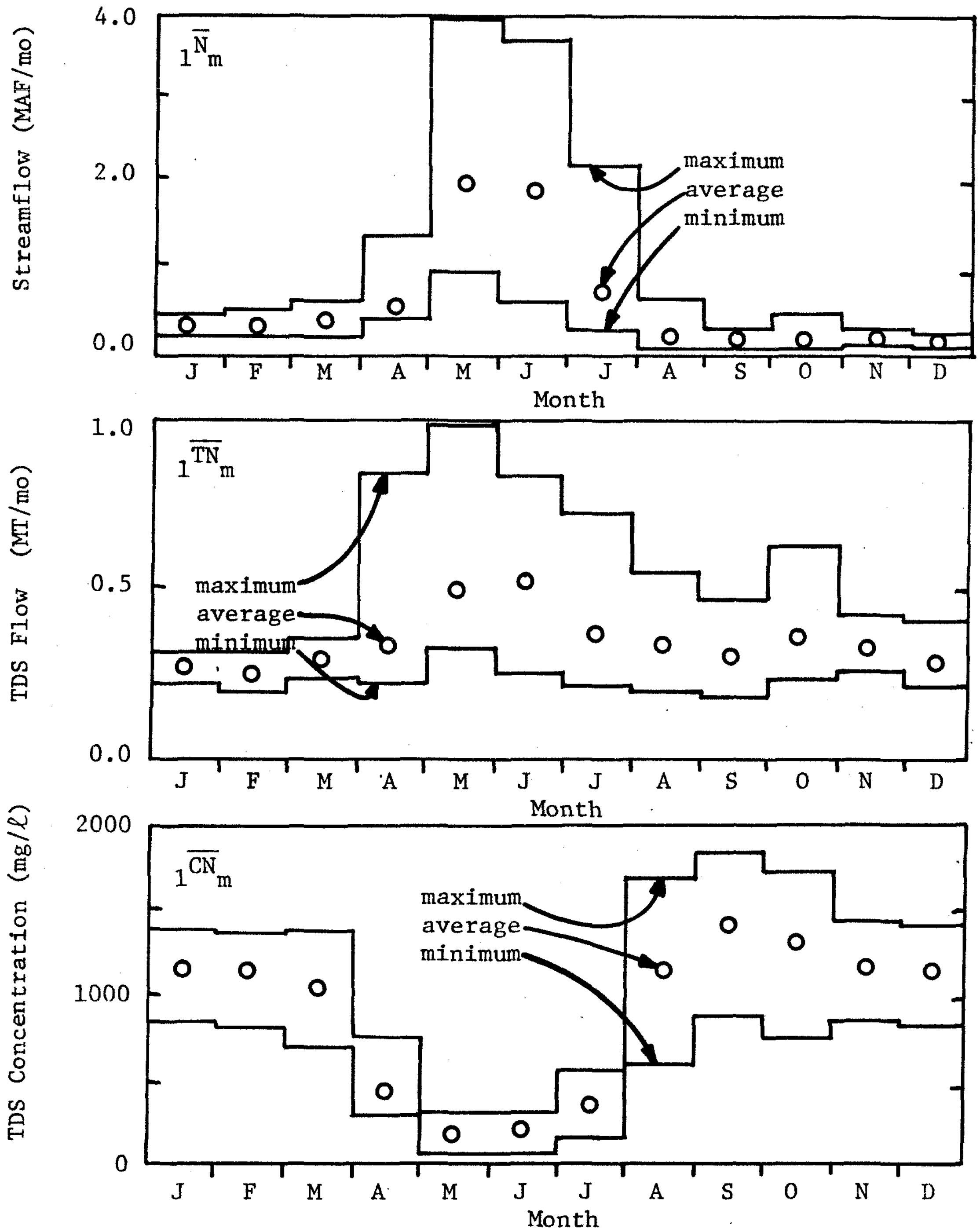
$$(3.2) \qquad {}_t\overline{C}_m = \frac{1}{n} \sum_{y=1}^{n} {}_tC^y_m .$$

Figure 3.1 displays the relationships between the average monthly streamflows, TDS flows, and TDS concentrations measured at the Colorado River Upper Mainstem, Cisco, Utah gauge. The maxima and minima of each quantity are also displayed. The data shown represent natural conditions for the period 1941 to 1968 (adjustments of salinity data to natural conditions are described in Section 3.4.1).

FIGURE 3.1

Monthly Average Streamflow, TDS Flow, and TDS Concentration with Observed Extremes

(Colorado Upper Mainstem Near Cisco, Utah. 1941-1968 recorded data adjusted to natural conditions)

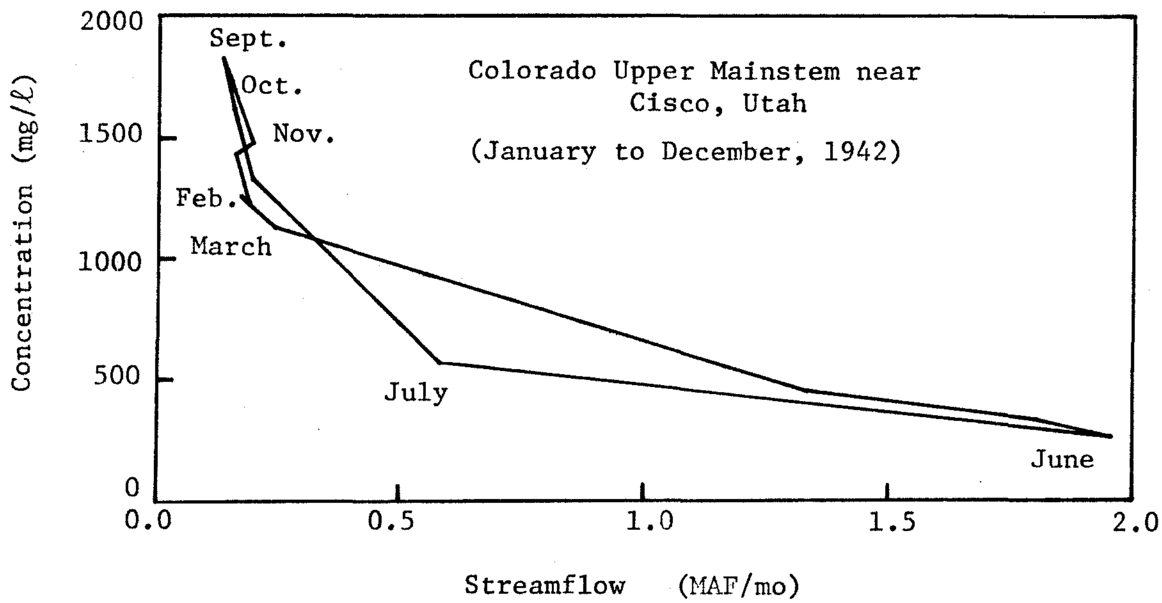


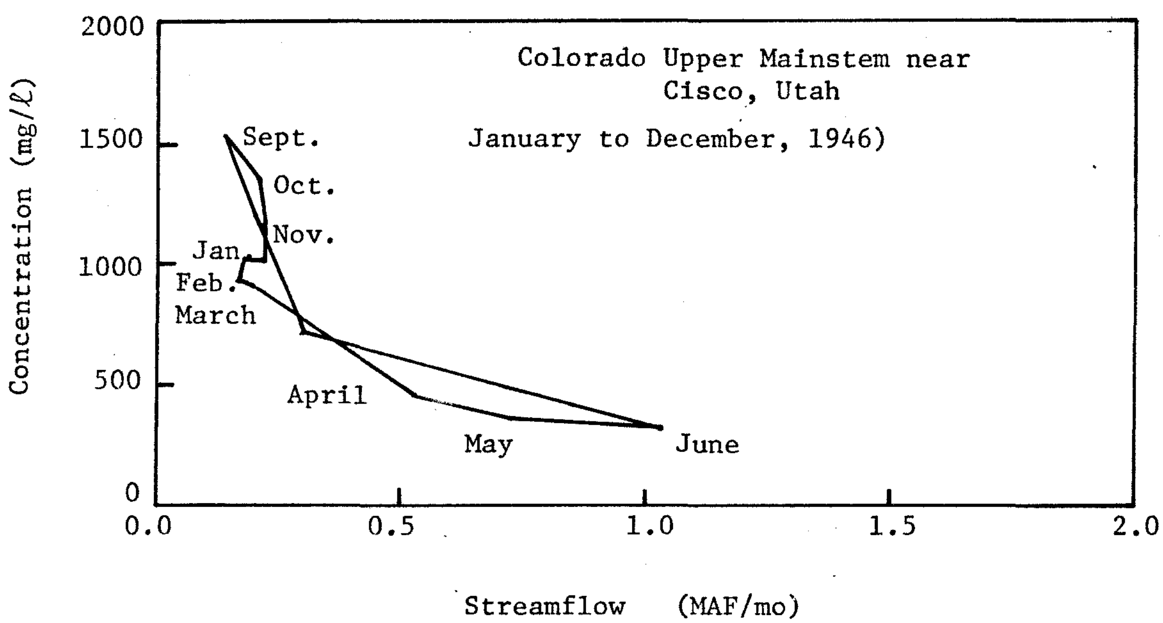
The inverse relationship between streamflow and TDS concentration is typical for snow melt streams like those of the Colorado Basin. Just as the streamflow of spring and fall are the results of two different processes, (Section 2.3.2.1), so are the salt flows. During the late spring snow melt, the dissolved solids are predominantly calcium and bicarbonate, picked up as the runoff passes over rocks on its way to the streams. Beginning in late summer the groundwater begins to contribute a larger fraction of the total runoff than in the spring, and the dissolved solids include sodium, magnesium, calcium, potassium, chloride and sulfate ions (Iorns _et al._, 1965).

The changing contribution to total flow from groundwater also affects the concentration of _total_ dissolved solids. In Figure 3.2, the total dissolved solids concentration is plotted as a function of streamflow using recorded monthly data from the years 1942 and 1946. It is observed that for a given value of streamflow, the concentration is higher during the falling limb of the hydrograph, September through November, than during the rising limb of the hydrograph, January through March. This hysteresis results from the depletion of groundwater storage during the fall, and ground water recharge during early spring. These observations are important with regard to the development of a stream salinity model. For the relationship to incorporate the multivalued character of concentration as a function of streamflow, a monthly model must be used.

FIGURE 3.2

The Monthly Dependence of Total Dissolved Solids Concentration Upon Streamflow (Recorded data)





3.3 Development of the Stream Salinity Model

The primary requirements of the dissolved solids-discharge model are that the total mass of salts entering the modeled portion of the river system preserve the following observed characteristics: (1) seasonal periodicity, (2) average salt load, and (3) average concentration. Principal assumptions in the formation of the dissolved solids model are (1) that the ionic composition of total dissolved solids is constant over all months and all tributaries, or that no chemical reactions or precipitation occur (i.e., TDS is taken to be a conservative substance), and (2) the dissolved solids output of each tributary basin can be adequately modeled using streamflow and TDS data recorded at the outflow gauging station of each sub-basin.

The derivation of the stream salinity model is based upon the use of natural TDS concentration and streamflow data for model calibration. The natural data are obtained from the recorded data by making suitable adjustments (Section 3.4.1). The model synthesizes natural TDS concentrations.

3.3.1 Derivation of the Model

The model formulated below relies heavily on work performed by O'Connor (1974).

Consider the total runoff, Q_T, to be the sum of a contribution from groundwater, Q_g, and a contribution from surface runoff, Q_s.

$$Q_T = Q_g + Q_s. \tag{3.3}$$

Denoting the groundwater and surface runoff TDS concentrations by C_g and C_s, respectively, and the concentration in the stream by C, the following mass balance equation can be formed:

$$(3.4) \qquad C \cdot Q_T = C_g \cdot Q_g + C_s \cdot Q_s .$$

The stream TDS concentration is then,

$$(3.5) \qquad C = C_g \cdot \frac{Q_g}{Q_T} + C_s \cdot \frac{Q_s}{Q_T} .$$

Let the ratio of the groundwater component of flow to the total runoff be written,

$$(3.6) \qquad r = \frac{Q_g}{Q_T} .$$

Combining Equations (3.3) and (3.6) gives

$$(3.7) \qquad (1 - r) = \frac{Q_s}{Q_T} .$$

Upon substitution, Equation (3.5) becomes

$$(3.8) \qquad C = r \cdot C_g + (1 - r) \cdot C_s .$$

The observation was made in Section 3.2.2 that the ratio, r, affects the relationship between TDS concentration and streamflow. This ratio was observed to depend upon the magnitude of the total flow, Q_T. During periods of low flow, r tends toward unity and total flow has a significant groundwater contribution. During periods of high flow, r tends toward zero and the surface runoff component increases. The ratio r, will exhibit a seasonal periodicity. Its maximum value will be observed at a total river flow denoted by $Q_T = Q_o$, at which time the groundwater component is greatest. For the snowmelt streams of the Colorado River Basin it can be assumed that from late summer to late fall the total runoff is derived entirely from groundwater flow. The quantity, Q_o, defines two flow regimes,

$$(3.9) \qquad Q_g = Q_T, \quad \text{or} \quad r = 1, \quad \text{for } Q_T \leq Q_o;$$

and

$$(3.10) \qquad Q_g = r \cdot Q_T, \quad \text{or} \quad r = \frac{Q_g}{Q_T}, \quad \text{for } Q_T > Q_o.$$

Any number of functional forms may be assumed to specify the dependence of r upon Q_T, resulting in the simplification of Equation (3.8). O'Connor (1974) suggests taking

$$(3.11) \qquad Q_g = \gamma \cdot Q_T^n ,$$

when $Q_T > Q_o$. This relationship specifies that

$$(3.12) \qquad r = \frac{\gamma}{Q_T^{1-n}} , \quad \text{for } Q_T > Q_o,$$

To insure the continuity of Q_g at $Q_T = Q_o$, the value of γ must be given by,

$$(3.13) \qquad 1 = \frac{\gamma}{Q_o^{1-n}} ,$$

or

$$\gamma = Q_o^{1-n} .$$

For the two flow regimes, Equation (3.8) becomes

$$C = C_g, \qquad \text{for } Q_T \leq Q_o \tag{3.15}$$

and

$$C = C_s + \left(\frac{Q_o}{Q_T}\right)^{1-n} \cdot (C_g - C_s), \qquad \text{for } Q_T > Q_o. \tag{3.16}$$

The value of n is typically less than one with the result that the groundwater flow component becomes a smaller fraction of the total flow as Q_T increases.

The derivation has assumed that the ratio of the groundwater flow component to the total flow is a function of only the total flow. If this assumption is made the hysteresis effect shown in Figure 3.2 would not be reproduced by the model. The model can be made to incorporate the hysteresis phenomenon by making the ratio, r, a function of Q_T and the month of the year. The exponent, n, and the quantity, Q_o, are determined by statistical correlation in this study. Performing separate correlations with the data from each month of the year causes the values of n and Q_o, and therefore the ratio, r, to take on the necessary monthly dependence.

A further simplification to the model can be made if C_s can be assumed to be zero. If this assumption is valid, Equations (3.15) and (3.16) become,

$$C = C_g \qquad \text{for } Q_T \leq Q_o\ , \tag{3.17}$$

and

$$C = C_g \cdot \left(\frac{Q_T}{Q_o}\right)^{\beta}, \qquad \text{for } Q_T > Q_o\ , \tag{3.18}$$

where β = n-1. The value of β will typically lie between -1.0 and 0.0 (see Table 3.2)

TABLE 3.2

Stream Salinity Model Parameters

Tributary		Month											
		JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC
Colorado	$Q_o/\overline{N}$	0.52	0.19	0.33	0.03	---	---	0.04	0.36	0.50	0.48	0.52	0.51
Upper	K	0.51	0.36	0.59	0.47	0.34	0.35	0.41	0.72	0.82	0.79	0.54	0.54
Main-	β	-0.64	-0.53	-0.53	-0.40	-0.47	-0.39	-0.51	-0.49	-0.46	-0.50	-0.68	-0.64
stem	ρ	0.69	0.75	0.73	0.77	0.60	0.63	0.82	0.95	0.89	0.88	0.82	0.73
C_g=1840 mg/ℓ													
Green	$Q_o/\overline{N}$	0.04	---	---	---	---	---	---	---	---	0.02	0.06	0.02
River	K	0.61	0.68	0.79	0.62	0.35	0.32	0.44	0.71	0.87	0.73	0.65	0.74
	β	-0.22	-0.16	-0.11	0.09	0.15	0.10	0.04	-0.10	-0.04	-0.17	-0.23	-0.17
	ρ	0.62	0.53	0.49	0.26	0.25	0.25	0.11	0.23	0.10	0.56	0.63	0.51
C_g=1470 mg/ℓ													
San Juan	$Q_o/\overline{N}$	0.24	0.14	0.05	0.17	---	---	---	---	0.01	0.04	0.20	0.23
River	K	0.34	0.39	0.50	0.36	0.27	0.23	0.28	0.70	0.62	0.51	0.27	0.30
	β	-0.40	-0.35	-0.26	-0.21	0.00	-0.10	-0.22	-0.13	-0.16	-0.25	-0.46	-0.43
	ρ	0.88	0.85	0.80	0.72	0.01	0.29	0.51	0.43	0.73	0.77	0.94	0.93
C_g=1470 mg/ℓ													
San Rafael	$Q_o/\overline{N}$	0.12	0.01	0.07	0.04	0.02	---	---	---	---	0.06	0.04	0.14
River	K	0.39	1.20	0.80	0.55	0.29	0.39	0.95	3.00	1.80	1.10	1.30	0.66
	β	-0.38	-0.19	-0.29	-0.33	-0.49	-0.36	-0.22	-0.01	-0.14	-0.23	-0.21	-0.32
	ρ	0.79	0.65	0.80	0.84	0.94	0.94	0.72	0.06	0.68	0.73	0.76	0.66
C_g=5880 mg/ℓ													

An examination of a plot of C versus Q_T will indicate whether $C_s = 0$ is a valid assumption. Equation (3.16) shows that C_s will be the limiting value of C for large values of Q_T. For the major tributaries in the Colorado River Basin, plots similar to Figure 3.2 reveal no tendency for C_s to attain a limiting value greater than zero.

Finally, the value of C_g was set equal to the highest concentration recorded for each tributary. In theory, the values of both C_g and Q_o could be established on the basis of field data. The latter form of calibration is possible for small water basins. However, for the large tributary basins modeled in this study, the graphical approach was adopted.

Application of the above model to the study region is discussed in Section 3.4.

3.3.2 Comparison to Other Models

Several models have been formulated using relationships similar to Equation (3.18) (Hall, 1970; Hall, 1971; Hyatt et al., 1970; Ledbetter and Gloyna, 1964). The time bases for these models range from days to years. The application of Equation (3.18) to the Colorado River Basin data produced exponents with values in the range from -0.68 to 0.15 (see Section 3.4). By comparison, Hall (1971) found a value of -0.18 for a watershed in Vermont, and Hyatt et al., (1970) found values ranging from -0.04 to -1.00 for the tributaries in the Upper Colorado Basin.

Except for the model derived by Ledbetter and Gloyna (1964), none of these models incorporate the dependency of the coefficients upon the month of the year. They modified Equation (3.18) by making the flow exponent a function of flow in the present and preceeding time periods. Their expression for β is given by

$$\beta = f + g \log \sum_{i=1}^{m} \frac{Q_i}{m} + hQ^n, \tag{3.19}$$

where f, g, h, and n are regression coefficients, and where the second term represents the logarithm of the average streamflow during preceding time periods.

All of the models of the form $C = KQ^{\beta}$ produce unrealistically high concentrations at low streamflow values unless accompanied by Equation (3.17) and the appropriate condition on total flow.

Other models described in the literature are based upon the mixing of surface and subsurface flows, and take the general form:

$$C = C_o + \frac{a}{b+c\cdot Q^n}, \quad (n > 0), \tag{3.20}$$

where the values of the constants are assigned from field data and statistical correlation (Langbein and Dawdy, 1964; Johnson <u>et al.</u>, 1969; Hall, 1970; Ribbens and Wilson, 1973). If used in the form given above, this equation is capable of producing realistic concentrations at the extremes of high and low streamflow. The desired monthly dependence of the coefficients can be attained by calibrating Equation (3.20) for each month individually.

The model presented in Section 3.3.1 was selected, on the basis of its simplicity, for application to the Colorado River Basin tributaries. The model was found to give good results, as shown in the next section.

3.4 Application of the Model

For modeling purposes, the salt inflows to the basin are divided into constant flows from ungauged sources and variable flows associated with the streamflows of the four major Upper Basin tributaries.

The division of the total salt load into variable and constant components is practical for several reasons. As noted above, many of the salt sources are ungauged, or gauged infrequently, like those between Glen Canyon Dam and Hoover Dam. Having insufficient streamflow and salt flow data for these sources makes correlation to other river basin streamflows infeasible. However, since these ungauged sources are largely springs whose flows are relatively constant, and since they contribute only twenty percent of the total salt load measured at Hoover Dam, they are represented as constant sources of dissolved solids. The magnitude of the salt load issuing from these constant sources is established using USBR estimates and confirmed during validation of the river basin model (see Chapter 5).

The remaining salt inputs to the basin are associated with the tributary streamflows. Modeling the salt outflow of each sub-basin in this manner involves many assumptions regarding the effects of man's activities upon the measurements taken at the gauging stations. Implicit are temporal and spatial integrations over all of the geochemical and hydrological processes occurring upstream of each gauge, including man's interventions.

3.4.1 Preparation of Data

An equation similar to the one proposed for adjusting streamflows to natural conditions, Equation (2.11) was proposed for adjusting dissolved solids flows to natural conditions:

$$(3.21)\qquad {}_tTN_m^y = {}_tTH_m^y + \sum_i [{}_tTD_m^y(i) - {}_tTDR_m^y(i)] + \sum_j [{}_tTEX_m^y(j)]$$

$$+ \sum_k [{}_tTDIV_m^y(k) - {}_tTRET_m^y(k)] + \sum_\ell [{}_t\Delta TS_m^y(\ell)]$$

where,

${}_tTN_m^y$ = natural, unaltered salt flow in tributary t, for year y, and month m, as measured at a specific gauging station (MT/yr);

${}_tTH_m^y$ = the recorded salt flow at the given gauge;

${}_tTD_m^y(i)$ = the salt removed from the tributary t, by the i^{th} depletion for municipal and industrial use;

${}_tTDR_m^y(i)$ = the salt returned to tributary t, by the i^{th} municipal and industrial use;

${}_tTEX_m^y(j)$ = the salt removed from tributary t, by the j^{th} export of water;

${}_tTDIV_m^y(k)$ = the salt removed from tributary t, by the k^{th} diversion for in-basin irrigation;

${}_tTRET_m^y(k)$ = the salt returned to the river from the k^{th} irrigation diversion;

${}_t\Delta TS_m^y(\ell)$ = the change in the mass of salt stored in the ℓ^{th} upstream reservoir.

Available data are not sufficient for making even the simplistic adjustments defined by Equation (3.21).

The assumptions made in deriving calibration data for the stream salinity model presented here are as follows: (1) over the period of record used for model calibration the average annual flow of salts (mass flow) has remained constant; and (2) increased consumption of water over this period is responsible for the observed increase in dissolved solids concentration. These assumptions are supported by recorded salinity data and information pertaining to the effects of water consumption.

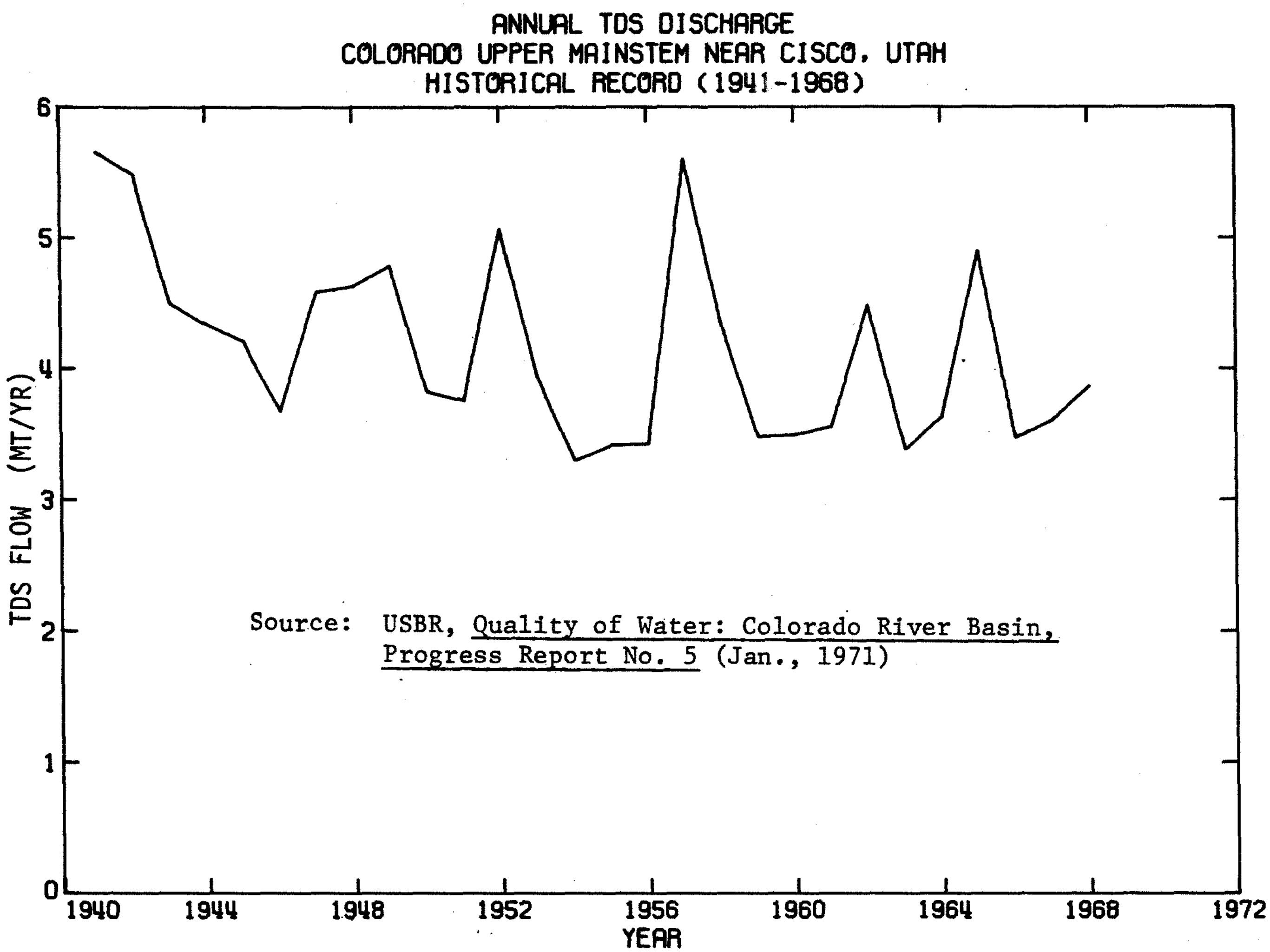
Figures 3.3 and 3.4 display the historical annual TDS flows and annual streamflows, respectively, for the years 1941 through 1968. These data are for the Colorado Upper Mainstem, gauged at Cisco, Utah. Figure 3.5 displays the corresponding average annual TDS concentrations.

The annual mass flow of total dissolved solids is observed to follow the fluctuations in annual streamflow, as expected on the basis of the discussion in Section 3.3. The average annual streamflow is observed to decrease during the period shown. This decline in average annual flow is the result of increasing upstream depletions. However, the average annual dissolved solids flow is seen to remain relatively constant during the same period. This observation can be understood given the nature of the increased depletions.

Irrigated acreage in the Upper Basin has changed very little during the 1941 to 1968 period (Iorns, 1965; USBR, 1971, pp. 12-13). Although salinity control measures may force the adoption of new irrigation methods in the future, there has been no incentive to change irrigation practices in the past. On the basis of this information the contribution to the TDS flow from agricultural lands can be assumed to be unchanged over the period of record shown.

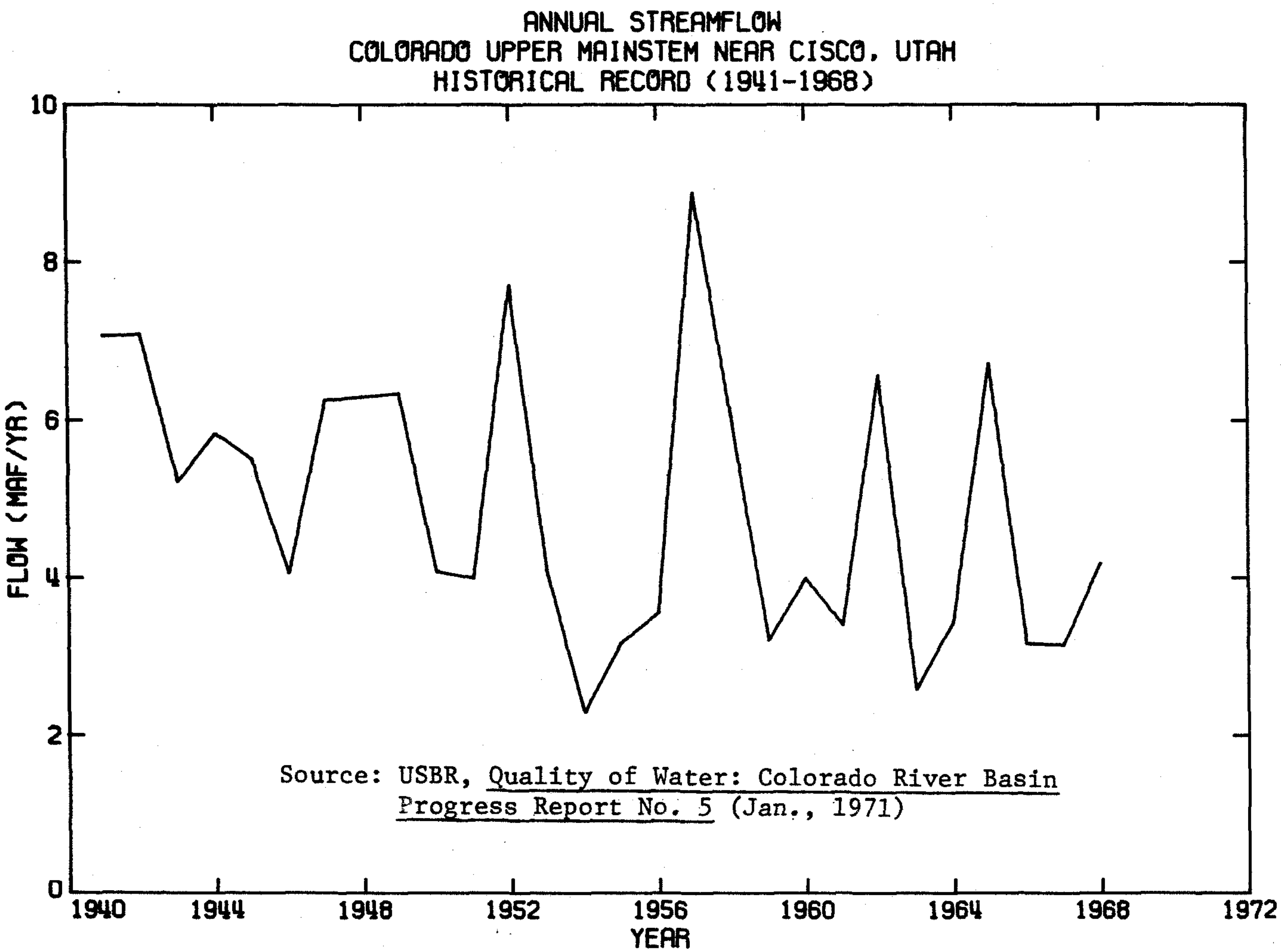
The impact of municipal and industrial diversions and returns upon the mass flow of salts is small. Municipal and industrial discharges are estimated to produce a net change of only 1% in the flow of salts

FIGURE 3.3



Source: USBR, Quality of Water: Colorado River Basin, Progress Report No. 5 (Jan., 1971)

FIGURE 3.4



Source: USBR, Quality of Water: Colorado River Basin Progress Report No. 5 (Jan., 1971)

(USBR, 1971). Exports of water to other river basins occur near the headwaters of the Upper Basin tributaries. The TDS concentrations in these regions are low, resulting in a small exportation of salts. For example, exports from the Colorado Upper Mainstem increased from 0.17 MAF/yr to 0.50 MAF/yr during the 1941 to 1968 period. A typical headwater TDS concentration of 90 mg/ℓ would indicate a decrease of only 0.04 MT/yr in the annual flow of salt from this tributary.

Although the increased depletions have affected the average salt flow very little, the impact on average TDS concentration has been significant (Figure 3.5). The increased consumption of water has served to concentrate the salts flowing in the river.

On the basis of the above arguments, the average salt flow in the basin was taken to be constant over the period of record used for model calibration. Recorded concentrations were adjusted for the effects of streamflow depletions by taking

$$(3.22) \qquad {}_tCN_m^y = {}_tCH_m^y \cdot \frac{{}_tH_m^y}{{}_tN_m^y} ,$$

where ${}_tCN_m^y$ = the adjusted concentration;

${}_tCH_m^y$ = the historical, or recorded concentration;

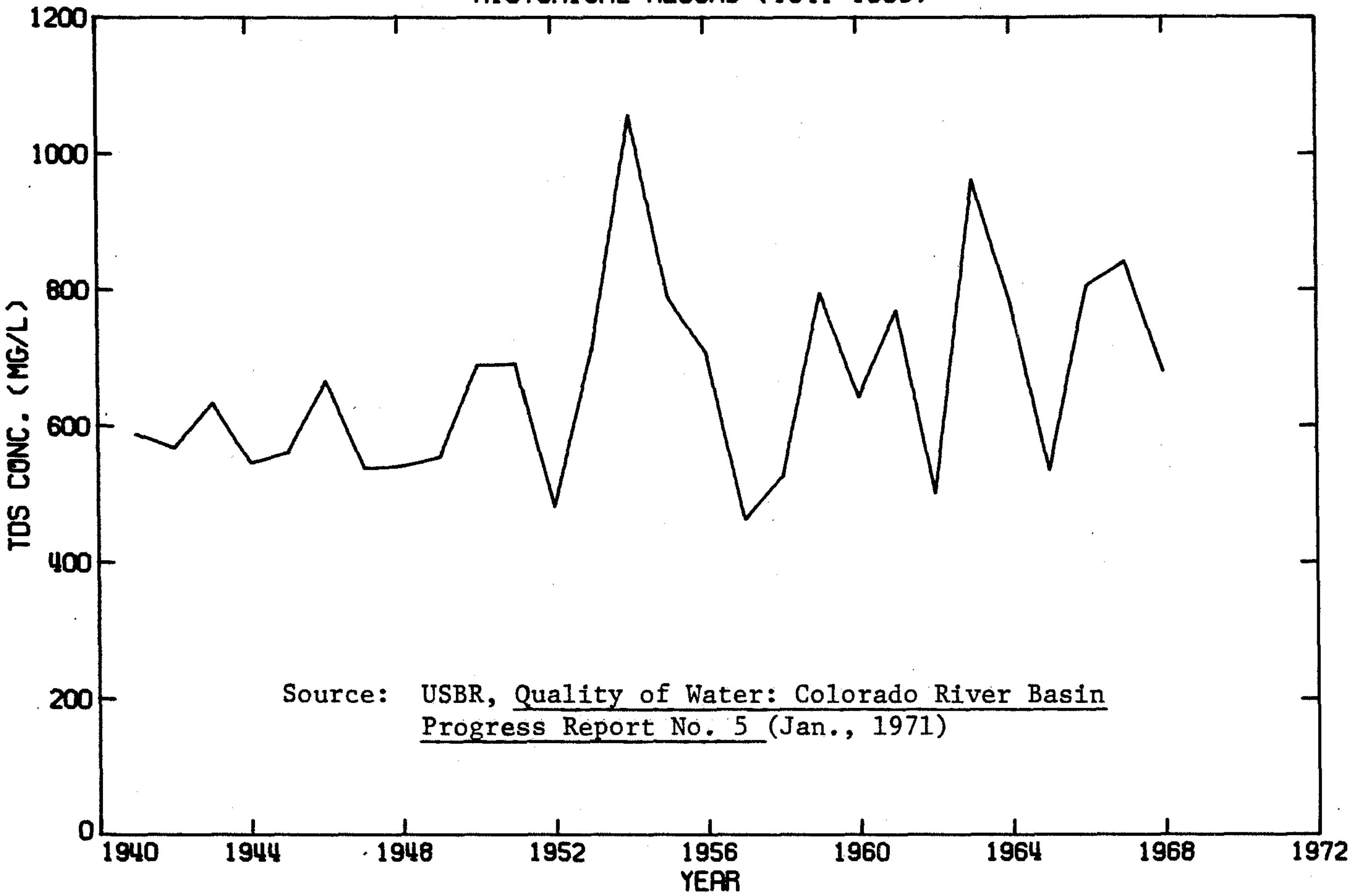
and ${}_tH_m^y$ and ${}_tN_m^y$ are the historical and natural streamflows, respectively (see Equation (2.12)).

These adjusted concentrations, CN, and the natural streamflows, N, were used to determine Q_o and β in Equation (3.18).

The TDS concentrations, CN, and the associated TDS flows, TN are referred to as "natural" quantities throughout this report. This terminology has been adopted so that CN and TN will be associated with

FIGURE 3.5

ANNUAL AVERAGE TDS CONCENTRATION
COLORADO UPPER MAINSTEM NEAR CISCO, UTAH
HISTORICAL RECORD (1941-1968)



Source: USBR, Quality of Water: Colorado River Basin Progress Report No. 5 (Jan., 1971) the corresponding natural streamflows, N, introduced in Chapter 2. The actual natural values of both CN and TN would be lower than the values produced by the model, since the constant flow of salt from agricultural return flows, TRET, has not been removed. Depending upon the estimate of TRET used, CN and TN could be lower by factors of 0.82 to 0.65. Since consistent estimates of TRET could not be obtained, no adjustment for this contribution was attempted.

The use of CN in calibrating the stream salinity model yields synthetic salt flows that are higher than natural flows by an amount equal to the constant agricultural salt contribution. In making adjustments to salt flows for the effects of streamflow depletions, the simulation model only increases agricultural salt pick-up in accordance with increases in irrigated acreage over the 1941 to 1968 levels. Salinity adjustments for exports and agricultural, municipal, and industrial depletions are discussed further in Section 5.2.2.

3.4.2 Model Calibration and Evaluation

As stated in Section 3.3.1, the value of C_g for each tributary was taken as a constant equal to the highest recorded TDS concentration. The values of Q_o and β in Equation (3.18) were found by statistical correlation using Equation (3.23).

$$(3.23) \qquad {}_t CN_m^y = {}_t K_m \cdot ({}_t N_m^y)^{{}_t\beta_m} .$$

The value of ${}_t Q_{om}$ is then given by

$$(3.24) \qquad {}_t Q_{om} = \left(\frac{{}_t C_g}{{}_t K_m \cdot 735} \right)^{1/{}_t\beta_m}$$

Table 3.2 displays the values for C_g, K, and β for each tributary and month. The corresponding correlation coefficients, ρ, are also shown. The values for ${}_tQ_{om}$ are shown in each case as the ratio of Q_o to the monthly average natural streamflow, $\overline{N}$. For several months these ratios are too small to be noted, indicating that flows in these months are never low enough to produce concentrations near $C = C_g$. It is also seen that in some instances the value of β is greater than or equal to zero. In these cases salinity is relatively independent of streamflow, as shown in the upper graph of Figure 3.6. The lower graph in Figure 3.6 displays the worst and best fits to the data.

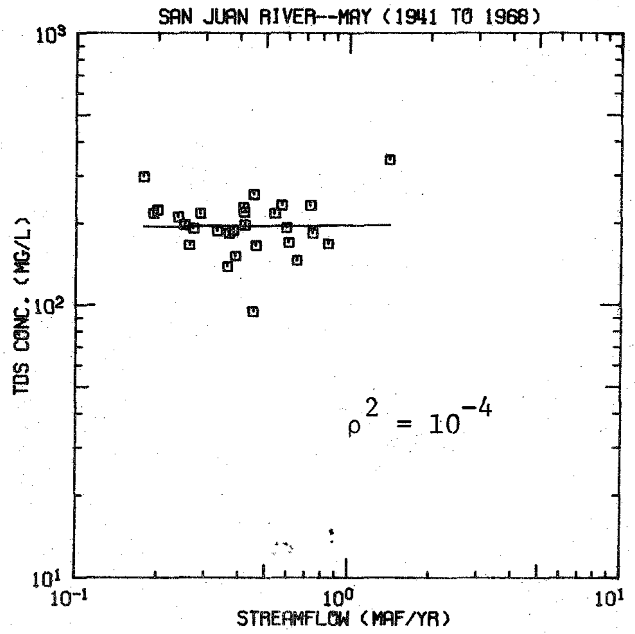
The simulation model uses Equation (3.23) to generate synthetic salinities. The condition expressed in Equation (3.17) is imposed by restricting concentration to be less than the specified value of C_g.

Figure 3.7 displays the averages, $\overline{TN}$, and standard deviations, s_{TN}, of the recorded salt flows and of synthetic sequence. Also shown are the averages, $\overline{CN}$, maxima, and minima of the calibration TDS concentrations and of a synthetic sequence.

The statistical parameters for salt flows and the average concentrations are seen to be well preserved by the model. The extremes of TDS concentration for the synthetic data are seen to differ dramatically from those of the calibration data. The occurrence of high synthetic concentrations during the months of low streamflow indicates that the streamflow model is producing some flows that are lower than any recorded for those months. Table 3.2 shows that these extremes of concentration occur in months for which Q_o is a substantial fraction of the average flow.

FIGURE 3.6

Correlation of Concentration With Streamflow: Worst and Best Cases



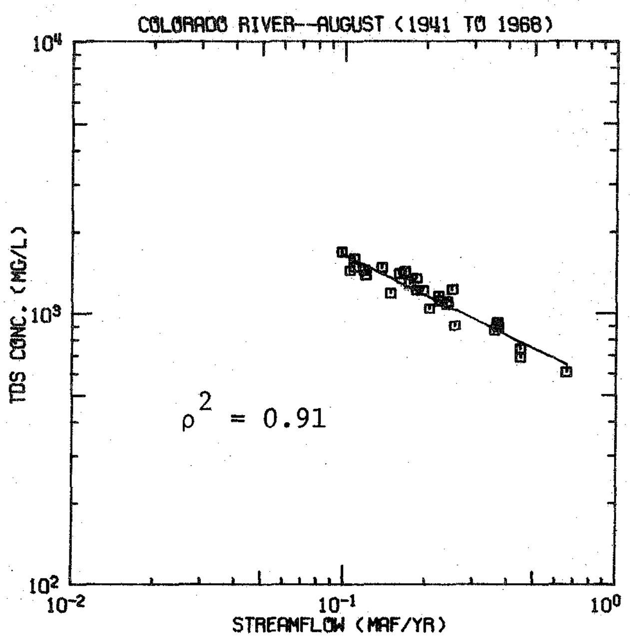
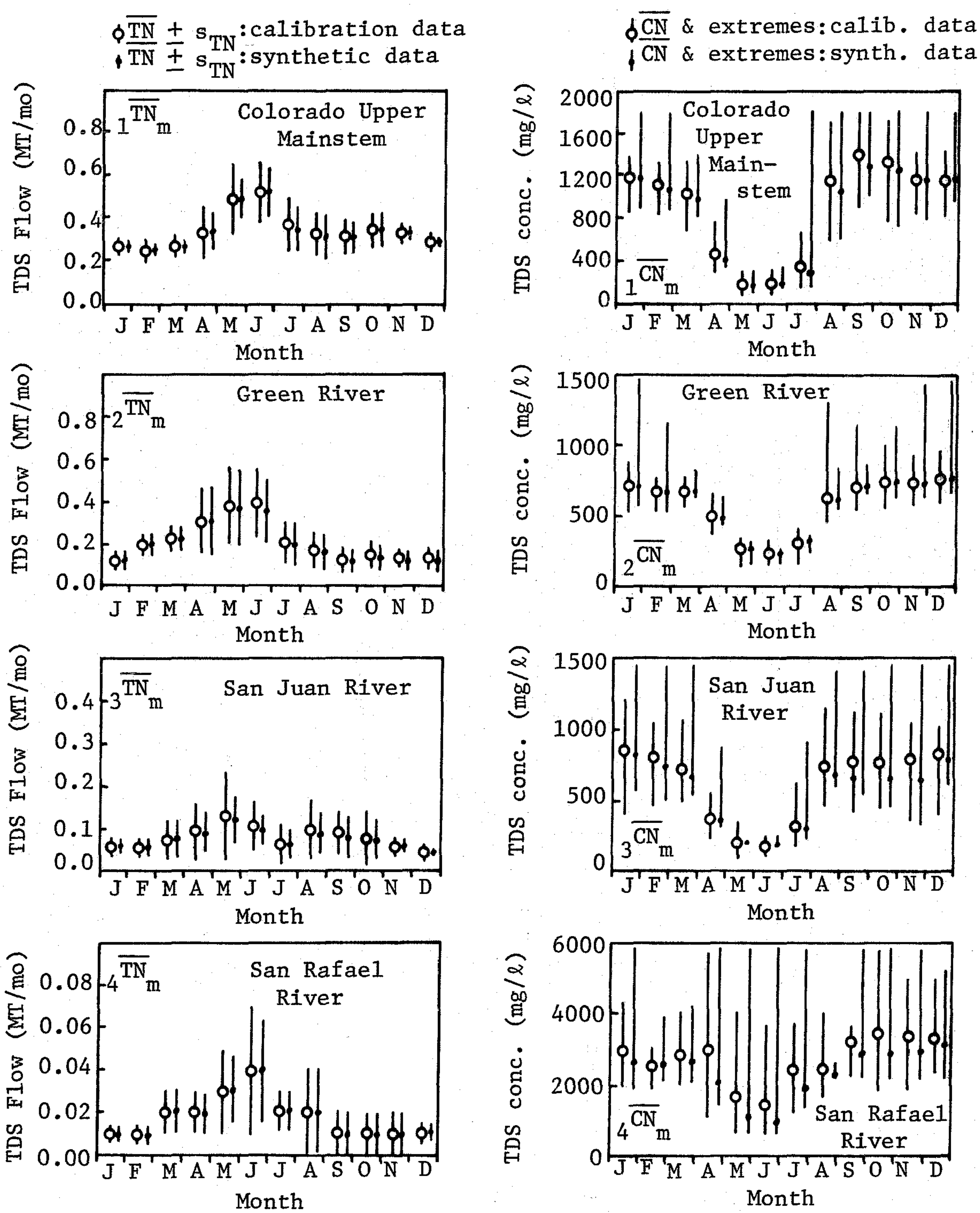


FIGURE 3.7

Comparison Between Stream Salinity Calibration Data and Synthesized Salinity Data



Because streamflows during these months contribute only a small fraction of the annual salt flow, the extreme concentrations produced by the model are considered tolerable.

The very approximate nature of the natural salt data, the implicit integration of geochemical processes over the area of each sub-basin, and the simple discharge relationship employed contribute to the poor results obtained for certain months.

As discussed in Chapters 4 and 7, reservoir mixing serves to smooth out the fluctuations in inflowing salinity. With regard to average downstream salinities, the preservation of the average salt flows into Lake Powell is the most important function of the stream salinity model.

3.5 Summary

The Colorado River Basin simulation model is intended to produce average (annual and monthly) information about the salinity of the tributary flows and reservoir discharges. Synthetic total dissolved solids inputs are generated by the stream salinity model presented in this chapter.

Insufficient data are available for making detailed estimates of natural dissolved solids concentrations from recorded data. The assumptions made in generating natural salinity data are that the increase in concentration over the period of record has been the result of water depletions rather than an increase in salt loading.

A relationship expressing natural dissolved solids concentration as a function of stream discharge is developed and applied to the monthly data for each tributary.

The salinity model preserves the average TDS concentrations and the average and variance of TDS mass flows for each tributary.

The broad assumptions employed in generating the dissolved solids-discharge relationships and the quality of data used to calibrate the relationships require that the outputs of river basin simulation pertaining to dissolved solids concentrations be interpreted carefully.

CHAPTER 4

RESERVOIR MODELS

4.1 Introduction

The purpose of the models of Lakes Powell and Mead is to describe the passage of water and dissolved solids through each reservoir. Reservoir releases, changes in storage, and significant losses of water are modeled. Reservoir mixing characteristics and significant sources and sinks of dissolved solids are included in the modeling of discharge salinity.

An important consideration in modeling the flow of water through reservoirs like Lake Powell and Lake Mead in the southwestern United States is the possible loss of water to bank storage and evaporation. Water readily enters the sandstone canyon walls which contain Lake Powell behind Glen Canyon Dam. The fate of bank inflows has not been well established. Evaporative losses from reservoirs in this arid region are significant. The average annual net evaporation from Lake Mead is 6.5 ft/year (1.95 m/yr). With both Lakes Powell and Mead full, the net annual evaporation from the two reservoirs would equal more than 10% of the average flow of the Colorado River, gauged at Lees Ferry, Arizona.

Impoundments may affect downstream dissolved solids concentrations by containing sources or sinks of dissolved solids. Sources may take the form of springs, seeps, and side inflows, or dissolution and leaching of salts from substrate soils. Precipitation of salts followed by deposition on the floor of the reservoir may serve as a sink of dissolved solids. Reservoir stratification and circulation affect discharge salinity by controlling the mixing of waters of varying concentration.

A brief discussion of modeling reservoir hydrology is followed by descriptions of the models used for Lakes Powell and Mead in Section 4.2. Factors influencing discharge salinity and the model of salinity adopted are presented in Section 4.3. Section 4.4 describes the method used to model the scheduling of releases from both reservoirs. Finally, Section 4.5 summarizes the chapter.

4.2 Reservoir Hydrology

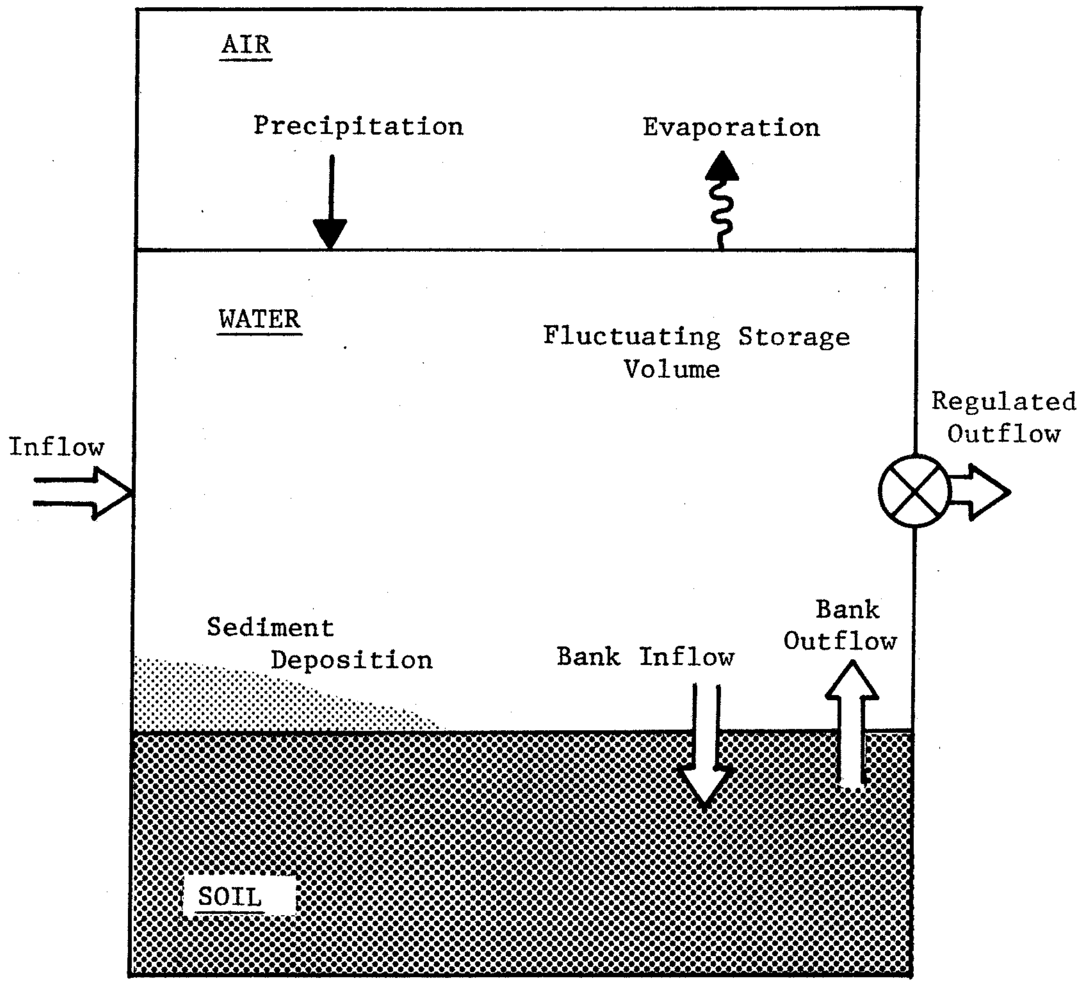
The flow through a reservoir may be affected by losses of water through evaporation, bank inflow, and loss of storage due to sediment encroachment. Figure 4.1 shows a simple hydrologic system for a reservoir.

4.2.1 Models of Reservoir Losses

Evaporation from lakes and reservoirs has been modeled as a function of humidity, temperature, wind speed, solar radiation, and other climatic parameters (Hutchinson, 1957). Alternatively, mass balance or pan evaporation studies can be used to construct tables of average net evaporation rates as a function of reservoir area or volume. These tables may be used to estimate reservoir evaporation when average climatic conditions are assumed.

FIGURE 4.1

Reservoir Hydrologic System



Investigations into the nature of bank inflow and changes in bank storage have largely been carried out using data from Lake Mead. The complicated nature of the surrounding geologic formations has caused people to favor a mass balance description of the process over a physical description using estimates of permeability and hydro-static forces. The mass balance technique involves forming a budget for water using recorded and estimated inflows, discharges, and evaporative losses from the reservoir. Any remaining imbalance between reservoir inputs and outputs is attributed to changes in bank storage. For modeling purposes, these mass balance residuals may be correlated with changes in reservoir surface storage or elevation. Both the physical and mass balance models for bank storage have been examined by Hendrick (1973) whose work is reviewed in Section (4.2.2).

The rate of sediment encroachment upon a reservoir's storage may be estimated from the difference in sediment mass flux into and out of an impoundment. The storage loss rates so determined can be verified by periodic surveys of reservoir storage and elevation.

4.2.2 Hydrologic Models of Lakes Powell and Mead

Refinement of a general hydrologic reservoir model was performed using historical data for Lake Mead since a long period of record is available. Lake Powell began forming when Glen Canyon Dam was completed in 1963. The short period of record, and great losses to bankstorage during the initial filling period, made Lake Powell data undesirable for model calibration. Because both Lake Powell and Lake Mead have porous underlying soils, high surface evaporation rates, and length to width ratios of the same order, the same form of hydrologic and mixing models developed for Lake Mead are also applied to Lake Powell.

4.2.2.1 Physical Dimensions

The physical dimensions of Lakes Powell and Mead are compiled from a variety of sources. Area versus capacity, and capacity versus elevation tables were obtained from the Bureau of Reclamation (1966, 1967). The elevations and volumes associated with dead storage, total storage, and storages at minimum and rated power are given in Table 4.1.

4.2.2.2 Evaporation

Net evaporation from Lakes Powell and Mead has been estimated using pan evaporation and mass balance studies. Monthly values of evaporation from Lake Mead are published in the USGS Water Supply Papers.

From average values of pan evaporation the Bureau of Reclamation has constructed tables of net evaporation versus elevation and month-of-the-year for each reservoir (USBR, 1963; and Feeny, 1975). These tables are used in the river basin model to simulate reservoir evaporation. Average annual evaporation versus storage is displayed in Figure 4.2 a and b.

4.2.2.3 Bank Storage

Since the construction of Hoover Dam in 1935, efforts have been made to determine the volume of water held in bank storage and to develop relationships for predicting changes in bank storage. Similar

Table 4.1

Physical Dimensions of Glen Canyon and Hoover Dams

		Elevation above m.s.l.		Total Capacity	
		feet	meters	MAF	km^3
GLEN CANYON DAM					
Top of dam	(1)	3711	1132	28.821	35.536
Top of flood control	(1)	3700	1129	27.000	33.291
Top of spillway gates	(2)	3700	1129	27.000	33.291
Spillway crest	(2)	3648	1113	19.532	24.083
Rated head (900 MW)	(2)	3570	1089	11.426	14.088
Min. power pool	(1)	3490	1064	6.124	7.551
Dead storage	(1)	3370	1028	1.998	2.464
Dam base	(1)	3015	920	0.0	0.0
HOOVER DAM					
Top of dam	(3)	1232	376	---	---
Top of flood control	(3)	1229	375	29.755	36.688
Top of spillway gates	(3)	1221	372	28.537	35.186
Spillway crest	(3)	1205	368	26.086	32.164
Rated head (1328 MW)	(4)	1123	343	16.031	19.766
Min. power pool	(3)	1083	330	12.402	15.292
Dead storage	(3)	895	273	2.378	2.932
Dam base	(3)	640	195	0.0	0.0

		Maximum Penstock Outlet Capacity			
		MAF/yr	MAF/mo	km^3/yr	km^3/mo
Glen Canyon Dam	(5)	28.2	2.35	34.8	2.9
Hoover Dam	(5)	85.8	7.15	106.0	8.8

(1) USBR, Colorado River Storage Project, Glen Canyon Unit: Lake Powell Area and Capacity Tables (April 1, 1963), p. 120.

(2) USBR, Glen Canyon Dam and Powerplant: Technical Record of Design and Construction (Denver, Colorado: December, 1970), p. 10.

(3) U.S. Army Corps of Engineers, Report on Reservoir Regulation for Flood-Control Storage at Hoover Dam and Lake Mead (U.S. Army Engineer District, Los Angeles: September, 1955; revised November, 1968), p. iii.

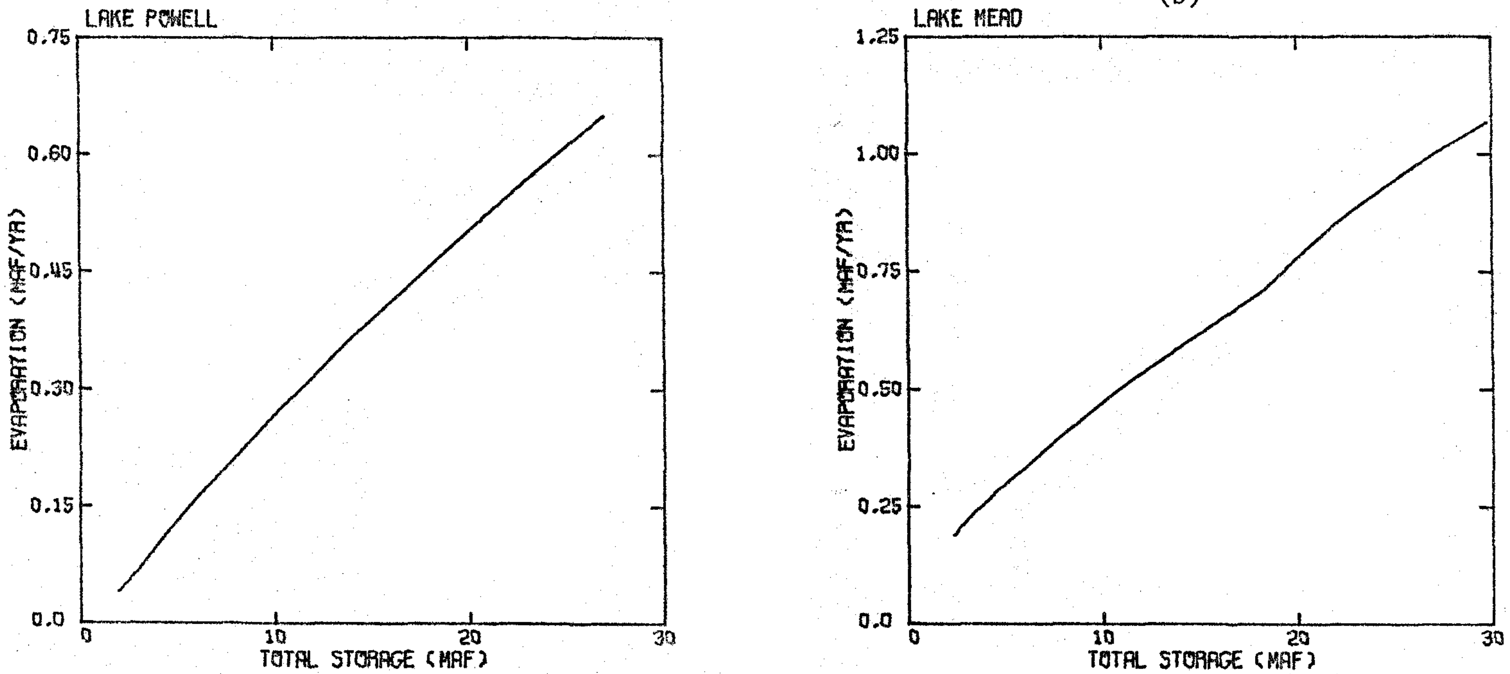
(4) USBR, Boulder Canyon Project, Arizona-Nevada: Lake Mead Area and Capacity Tables (April, 1967), p. 127.

(5) Ribbens, Richard W. and Robert F. Wilson, Application of a River Network Model to Water Quality Investigations for the Colorado River (Denver, Colorado: USBR Engineering and Reserach Center, September, 1973), Table I.

FIGURE 4.2(a,b)

Average Annual Evaporation Versus Storage for Lake Powell and Mead

(a) (b)



Sources: U. S. Bureau of Reclamation (1963a)
U. S. Bureau of Reclamation (1967)
Feeny, C. (1975). (Lake Mead evaporation rates).

determinations for Lake Powell are made more difficult by the small amount of data now available for mass balance studies, and because the reservoir has only recently completed filling.

Early examinations of the bank storage of Lake Mead were performed by Langbein (1960) and Harbeck (1958), both working for the USGS. Rechard (1965) improved upon their work, and developed a relationship between the change in bankstorage and the change in surface storage, given by Equation (4.1):

$$\Delta BS = (0.065) \cdot \Delta S, \tag{4.1}$$

where, ΔBS is the annual change in bank storage,

ΔS is the annual change in surface storage.

The relationship is still used by the Bureau of Reclamation to assist in rescheduling releases and regulating the storage of Lake Mead (Feeny, 1975). A comparable result was obtained by Hendrick (1973), expressed in terms of changes in surface storage elevation. His relationship, given by Equation (4.2), is interesting in that it contains a constant loss term, and was developed using linear regression of monthly data ($r^2 = 0.33$).

$$\Delta BS = 1.19 + (3.65) \cdot h, \tag{4.2}$$

where, ΔBS is the monthly bank storage change,

Δh is the change in surface storage elevation since the last month, and the constant term has units of thousand of acre-feet per month.

The author's attempt to model bankstorage changes employs the mass balance equation

$$(4.3) \qquad I_m^y + S_{m-1}^y = E_m^y + D_m^y + S_m^y + R_m^y ,$$

where, I_m^y = measured reservoir inflow, year y, month m,

S_m^y = recorded surface storage,

E_m^y = estimated evaporation from tables,

D_m^y = measured outflow,

R_m^y = residual or imbalance in the budget for year y and month m.

No attempt is made to estimate small side inflows to the reservoir. The residuals of this calculation are linearly regressed to the changes in surface storage, or to the changes in surface storage elevation. Both attempts lead to poor results with correlation coefficients on the order of 0.1.

Bureau of Reclamation estimates of the change in bankstorage of Lake Powell are of a form similar to the one specified by Equation (4.1) for Lake Mead.

$$(4.4) \qquad \Delta BS = (a) \cdot \Delta S,$$

where the proportionality coefficient, a, lies between 0.05 (Clinton, 1970) and 0.1 (Ribbens and Wilson, 1973).

Equations (4.1) and (4.4) contain no constant loss term. The implicit assumption is that all water entering the bank remains within the river basin, and that none is lost through deep percolation. Bureau of Reclamation use of these relationships does not incorporate a lag time between changes in surface storage and changes in bank storage.

Thus, bank storage in this sense is equivalent to surface storage which is essentially free from evaporation, and effectively increases the total effective storage of each reservoir.

To determine the river system's sensitivity to bank storage modeled in this manner, simulations were made using the relationships in Equations (4.1) and (4.4) and also with $\Delta BS = 0.0$ for both reservoirs. No differences in long-run statistics were observed, and further simulations were made with no accounting of bank storage (see Section 6.3).

4.2.2.4 Reservoir Sedimentation

The surveys of Lake Mead taken in 1948-1949 and 1968-1969 indicate that between the closing of Hoover Dam, in 1935, and the closing of Glen Canyon Dam, in 1963, the loss of usable storage in Lake Mead amounted to less than 1 MAF (1.2 km^3). The loss in dead storage was also less than 1 MAF. Prior to the formation of Lake Powell, behind Glen Canyon Dam, the sediment discharge at Lees Ferry varied between 20 and 143 MT/yr. Following the formation of Lake Powell, sediment discharge recordings at Lees Ferry were terminated because measurements were consistently less than 6 MT/yr (USBR, 1971).

Lake Powell exhibits a sedimentation rate of about 0.04 MAF/yr (0.05 km^3/yr) (USBR, 1971). If this rate remains unaffected by upstream developments, the reduction in storage by the year 2000 will equal approximately 1 MAF (1.2 km^3).

The effects of sedimentation over the period studied in this report, 1980 to 2000, were considered to be of second order. No adjustments for future sedimentation were made in the model.

4.3 Reservoir Discharge Salinity

The purpose of the reservoir salinity model is to predict, for given monthly reservoir inputs, the concentration of total dissolved solids in the outflow. Three processes capable of influencing the outflow concentration are examined: (1) loss or gain of dissolved solids due to precipitation in the reservoir, (2) dissolution and leaching of dissolved solids from the substrate soils, and (3) mixing or stratification of waters of high and low salinity, and (4) evaporation.

4.3.1 Reservoir Water Quality Models

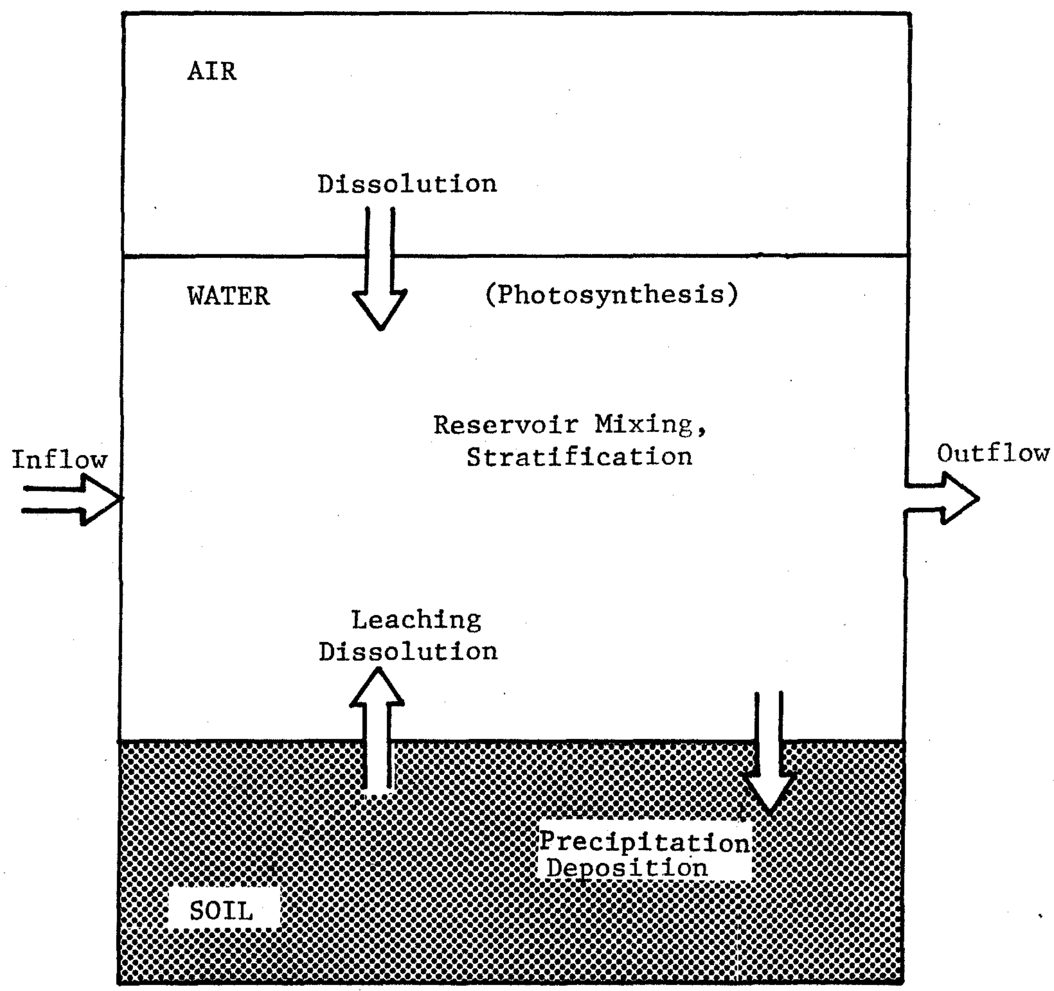
A simple schematic diagram of the flow of a non-conservative substance through a reservoir is shown in Figure 4.3. If dissolution and precipitation reactions involving the substance are found to be negligible, the substance may be modeled as a conservative material, subject only to the effects of reservoir mixing and additional sources.

Modeling of the fate of non-conservative substances in lakes and reservoirs usually involves three steps: (1) defining the relevant interactions between the air, water, soil, and biological phases of the reservoir; (2) adopting differential equations to describe the interactions over time; and (3) applying these equations to volumes of water considered to be completely stirred reactors (e.g. Hutchinson, 1957; O'Connor and Mueller, 1970; O'Melia, 1971).

An examination of reservoir hydrodynamics helps to define the mixing volumes within a reservoir. Monomictic reservoirs, like Lakes Powell and Mead, are stratified during the late spring and summer, and become fully mixed in a vertical direction in the fall. Stratification occurs because of density differences due to temperature, salinity, or

FIGURE 4.3

Reservoir Chemistry System



suspended silt. Orlob and Selna (1970), Ryan and Harleman (1971), and Rahman and Marcotte (1974) have created mathematical models for describing the seasonal changes in reservoir stratification. Longitudinal circulation may also be significant, and the division of the reservoir into successive cells may be necessary (Varga and Falls, 1972).

Sources of salinity from ungauged inflows may be estimated from field data or mass balance studies and entered as constants. Leaching from substrate soils is thought to be significant only during initial reservoir filling, and when required, may be modeled by a differential equation describing a decay process (Hendrick, 1973).

4.3.2 Application of Reservoir Salinity Modeling to Lakes Powell and Mead

Several investigations of the sources and fates of dissolved solids entering Lakes Powell and Mead have been made (Howard, 1949; Iorns *et al.*, 1965; USBR, 1967, 1971; Irelan, 1971; Hendrick, 1973; Reynolds and Johnson, 1974). The earlier studies are accountings of the gauged and ungauged inflows of either total dissolved solids or of the individual ionic species. Attempts to quantify the extent to which precipitation and dissolution of salts occurs have been undertaken by Irelan (1971) for Lake Mead and Reynolds and Johnson (1974) for Lake Powell. Hendrick (1973) proposed several models for the flow of total dissolved solids through Lake Mead, one of which was adopted for the present study.

4.3.2.1 Precipitation and Dissolution of Salts

As stated in Chapter 1, one of the concerns of this research has been to estimate the effect of alternative reservoir operating policies upon downstream total dissolved solids concentrations. Reductions in maximum reservoir storage and subsequent reductions in evaporation may result in decreases of TDS concentrations. If precipitation of salts within the reservoir is a function of reservoir surface area, then the effects of reduced evaporation may be offset by reduced precipitation. Mass balances for the ionic species entering and leaving Lake Mead have provided numerical evidence for the precipitation and dissolution of salts within the reservoir (Irelan, 1971). Irelan was forced to make several assumptions regarding the chemical composition and volume of ungauged inflows and the total mass of each species stored within the reservoir at any particular time in forming these mass balances. His results indicate that significant dissolution of calcium sulfate ($CaSO_4$) occurred following the initial storage of water in Lake Mead (Irelan, 1971; p. E18). The rate of $CaSO_4$ dissolution has declined since that time. At present, the rate of $CaSO_4$ dissolution is offset by the rate of precipitation of calcium carbonate ($CaCO_3$). The result is that a change in composition but no net change in the mass of total dissolved solids occurs as water passes through the reservoir.

Similar mass balance examinations for Lake Powell indicate that precipitation of $CaCO_3$ is the dominant process for this reservoir (Reynolds and Johnson, 1974). This result is supported by the absence of significant quantities of $CaSO_4$ in the geologic formations at the Lake Powell site (Reynolds, 1975; Shoemaker, 1975).

Reynolds and Johnson report that conditions favor the precipitation of calcium carbonate during the summer months, and propose the following mechanism. Briefly, photosynthesis in the epilimnion cause a rise in pH and super-saturation with respect to calcium carbonate, as shown below:

$$(4.5) \qquad nCO_2 + nH_2O \underset{\text{resp.}}{\overset{\text{photo}}{\rightleftharpoons}} (CH_2O)_n + nO_2 \; ;$$

$$(4.6) \qquad Ca^{2+} + 2\,HCO_3^- \rightleftharpoons CaCO_3(s) + CO_2 + H_2O \; .$$

These processes result in a decrease in both bicarbonate ion and calcium ion masses between reservoir inflow and outflow.

Using data collected before and during the filling of Lake Powell, Reynolds and Johnson have performed a bicarbonate mass balance for the reservoir site. Although the calculation is affected by the increase in storage over this period, they observed a reduction in bicarbonate mass attributable to $CaCO_3$ precipitation. Further, they estimate that at normal operating storages, the presence of the reservoir may account for a decrease of 20 to 30 mg/ℓ in the annual average TDS concentration measured downstream of Lake Powell (Reynolds and Johnson, 1974; p. 10).

To estimate the mass of salt that would need to be precipitated to create a change in concentration of 20 to 30 mg/ℓ, consider the following equation for the average Lake Powell discharge concentration:

$$(4.7) \qquad C = 735 \cdot \left(\frac{T-TP}{I-E}\right),$$

where T = the mass inflow of TDS (MT/yr);

TP = the net mass of TDS precipitated (MT/yr);

I = the volume inflow to the reservoir (MAF/yr);

E = the reservoir evaporation (MAF/yr);

and 735 is the conversion factor from tons per acre-foot to mg/ℓ .

The change in TDS concentration due to the presence of the lake is then given by Equation (4.8),

$$\Delta C = 735 \cdot \left[\frac{T}{I} - \frac{T-TP}{I-E}\right] \quad . \tag{4.8}$$

Solving Equation (4.8) for TP gives

$$TP = T + (I-E) \cdot \left(\frac{\Delta C}{735} - \frac{T}{I}\right) \quad . \tag{4.9}$$

Under normal operating conditions E will range from 0.4 to 0.6 MAF/yr. Substituting the values of ΔC given above, and the Lees Ferry values of T and I given in Table 3.1, Equation (4.9) gives

$$0.6 \text{ MT/yr} \leq TP \leq 0.9 \text{ MT/yr} \quad . \tag{4.10}$$

This range for TP indicates that the presence of Lake Powell causes a 4 to 5 percent reduction in the average concentration and a 7 to 10 percent reduction in the average TDS discharge, measured at Lees Ferry, Arizona.

As stated previously, one goal of this research is to estimate the effect that reducing maximum Lake Powell storage has upon the downstream TDS concentration. This task requires a lake chemistry model that expresses the mass of TDS precipitated as a function of reservoir storage. The precipitation of $CaCO_3$ in Lake Powell is also a function of reservoir hydrodynamics and biological activity. Construction of a model that incorporates all of these processes requires information which is not currently available (Reynolds, 1975).

In the absence of more complete information, the following heuristic model of precipitation as a function of reservoir storage is proposed. This model is used to predict annual average discharge TDS concentrations.

To first order, let TP be proportional to the reservoir surface area, A, and the detention time, S/(I-E), where S equals the volume of storage. In the range of storage between half-maximum to full storage, the surface area is approximately linear with respect to volume.

Then

$$TP \propto A \cdot S/(I - E) \ , \tag{4.11}$$

or

$$TP \propto S^2/(I - E) \ . \tag{4.12}$$

At maximum storage, S_{max},

$$TP_{max} = K \cdot S^2_{max}/(I - E_{max}) \ . \tag{4.13}$$

The constant of proportionality may be determined using known values for S_{max}, E_{max}, and the estimates of TP given in Equation (4.10). Solving for K gives

$$K = \frac{TP_{max}}{S^2_{max}} \cdot (I - E_{max}) \ . \tag{4.14}$$

Substituting the expressions for TP and K into Equation (4.7) yields

$$C = 735 \cdot \left[\frac{T - TP_{max} \cdot \left(\frac{I-E_{max}}{S^2_{max}} \right) \cdot \left(\frac{S^2}{I - E} \right)}{(I - E)} \right] . \tag{4.12}$$

Finally, expressing the storage and evaporation as a fraction, r, of their maximum values and simplifying,

$$C(r) = 735 \cdot \left[\frac{T}{(I-r \cdot E_{max})} - TP_{max} \cdot r^2 \cdot \frac{(I-E_{max})}{(I \cdot r \cdot E_{max})^2} \right] . \tag{4.13}$$

For zero storage, r = 0, and Equation (4.13) reduces to the inflow concentration, T/I.

Figure 4.4 displays Lake Powell discharge TDS concentration as a function of r for TP_{max} = 0.6 MT/yr and TP_{max} = 0.9 MT/yr. The concentrations predicted when TP = 0, a conserved mass model, and TP $\propto$ S/(I-E) are shown for comparison. The inflow TDS concentration and inflow values used are typical for the period 1968 to 1970.

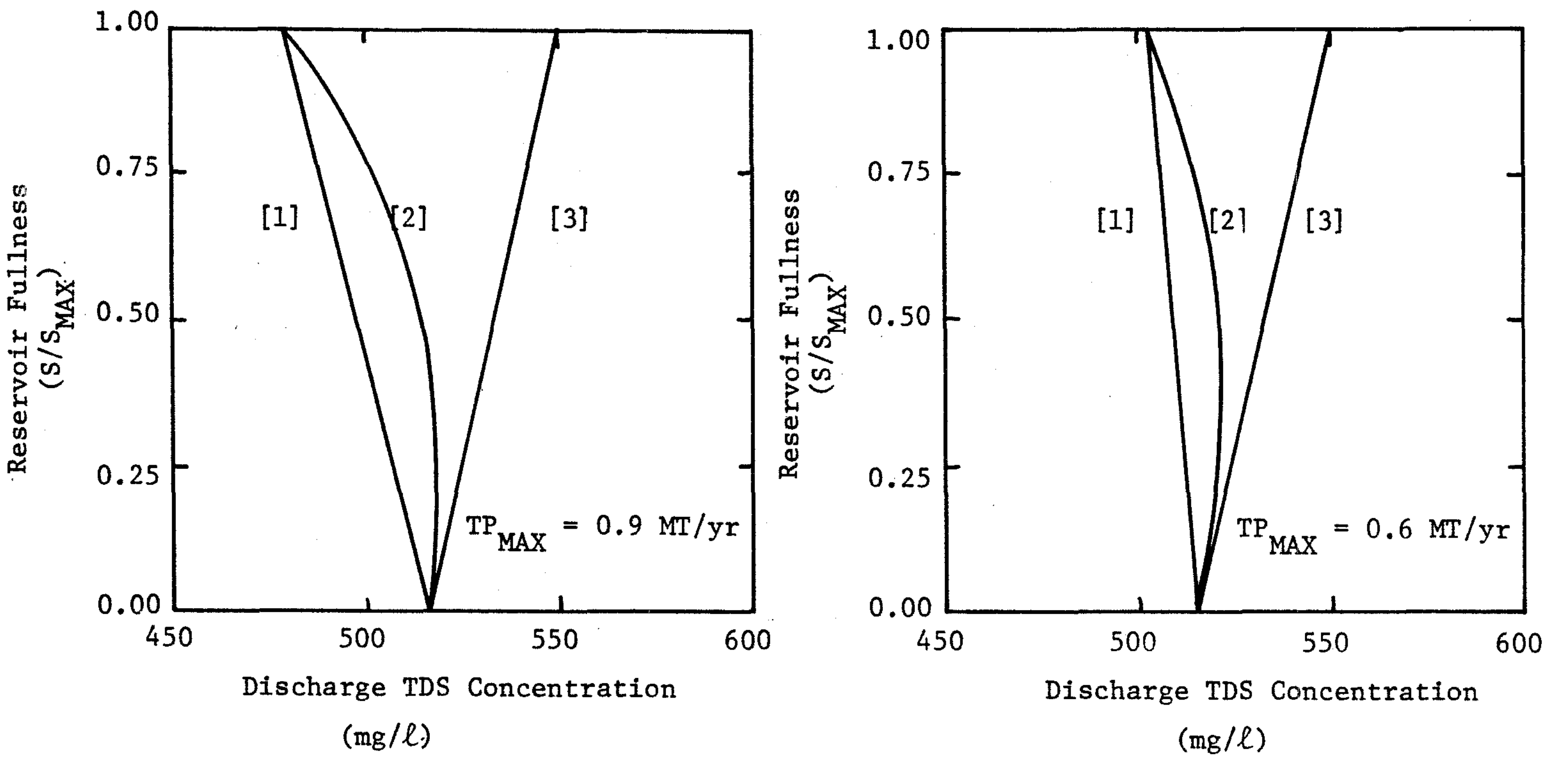
The important features of the model are the effects upon discharge concentration by reductions in average storage. As shown in Figure 4.4, the conservative model, TP = 0, produces a reduction in concentration with storage reduction. The model developed above, TP $\propto$ S^2/(I-E), predicts an increase in concentration as storage is reduced.

FIGURE 4.4

Three Possible Models for the Effect of Precipitation as a Function of Storage Upon Lake Powell Discharge TDS Concentration

Curve [1]: $TP \propto S/(I-E)$ Curve [2]: $TP \propto S^2/(I-E)$ Curve [3]: $TP = 0$

where: TP = precipitated mass of TDS (MT/yr),
S = storage (MAF),
I = inflow (MAF/yr),
E = evaporation (MAF/yr).



It has been speculated that photosynthetic activity in shallow bays, which exist when Lake Powell storage is near maximum, may control the precipitation chemistry of the reservoir (Reynolds, 1973; p. 56). If this speculation is correct it is possible that the mass of TDS precipitated is large only when the lake is nearly full. The value of TP may be relatively constant for all storages below the elevation of these shallow bays. In this case, the discharge TDS concentration may be modeled using a conserved mass model, providing that the constant loss of TDS is subtracted from the inflow to the reservoir.

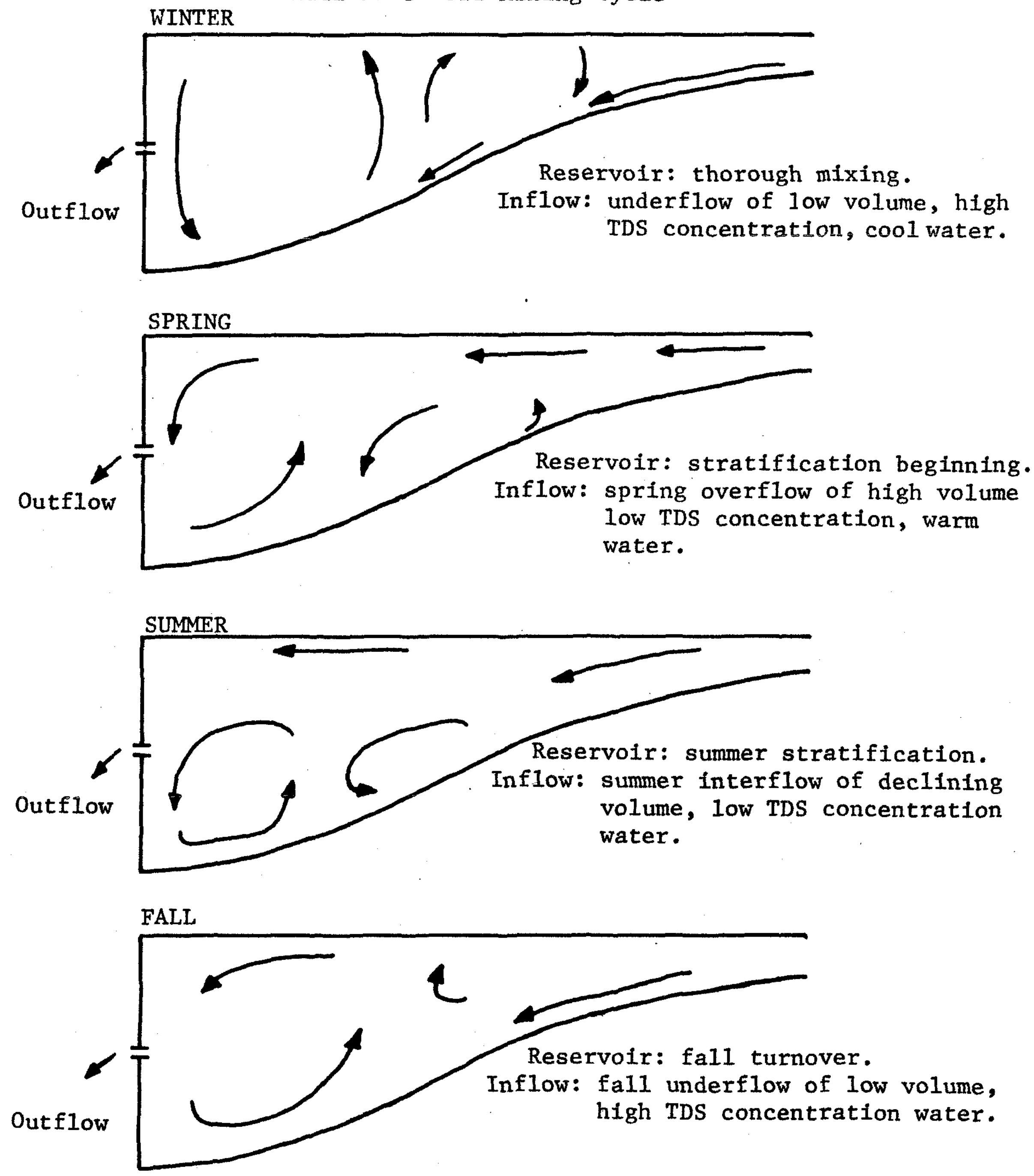
The conserved mass model developed by Hendrick (1973) for predicting the average monthly TDS concentration in Lake Mead discharge is presented in Section 4.3.2.2. The Colorado River simulation program employs this latter model for both Lakes Powell and Mead. The average TDS concentrations predicted by the precipitation model are calculated using Equation (4.13) and outputs from the simulation program. The results from both models are discussed in Chapter 7.

4.3.2.2 Reservoir Mixing

The hydrodynamics of Lakes Powell and Mead are similar, and the annual cycle is portrayed in Figure 4.5. Hendrick (1973) has shown that the best model for predicting monthly Lake Mead discharge salinity, when monthly inflow and outflow data are employed, is one in which the reservoir is taken to be a completely stirred tank reactor. The mass of total dissolved solids entering the reservoir is assumed to be conserved. The outflow concentration specified by this model for period i may be written:

FIGURE 4.5

Annual Lake Mead Mixing Cycle



Source: Hendrick, John, Techniques for Modeling Reservoir Salinity, Hydrology Paper No. 62 (Fort Collins, Colorado; Colorado State University, August, 1975), p. 6.

$$C_o(i) = \frac{C_I(i) \cdot I(i) + C_o(i-1) \cdot S(i-1)}{S(i) + D(i)} \quad (4.14)$$

where,

$C_o(i)$ = the outflow TDS concentration for period i,

$C_I(i)$ = the inflow TDS concentration,

$S(i)$ = the total storage at the end of the i^{th} period, and

$D(i)$ = the discharge during period i (assumed released at the end of the period).

Magnitudes of ungauged side inflows of water and salt were obtained from USBR estimates for each reservoir and average values are used in the model (see Figure 2.3). Evaporation is implicitly included in this model by specifying S(i), S(i-1), I(i) and D(i).

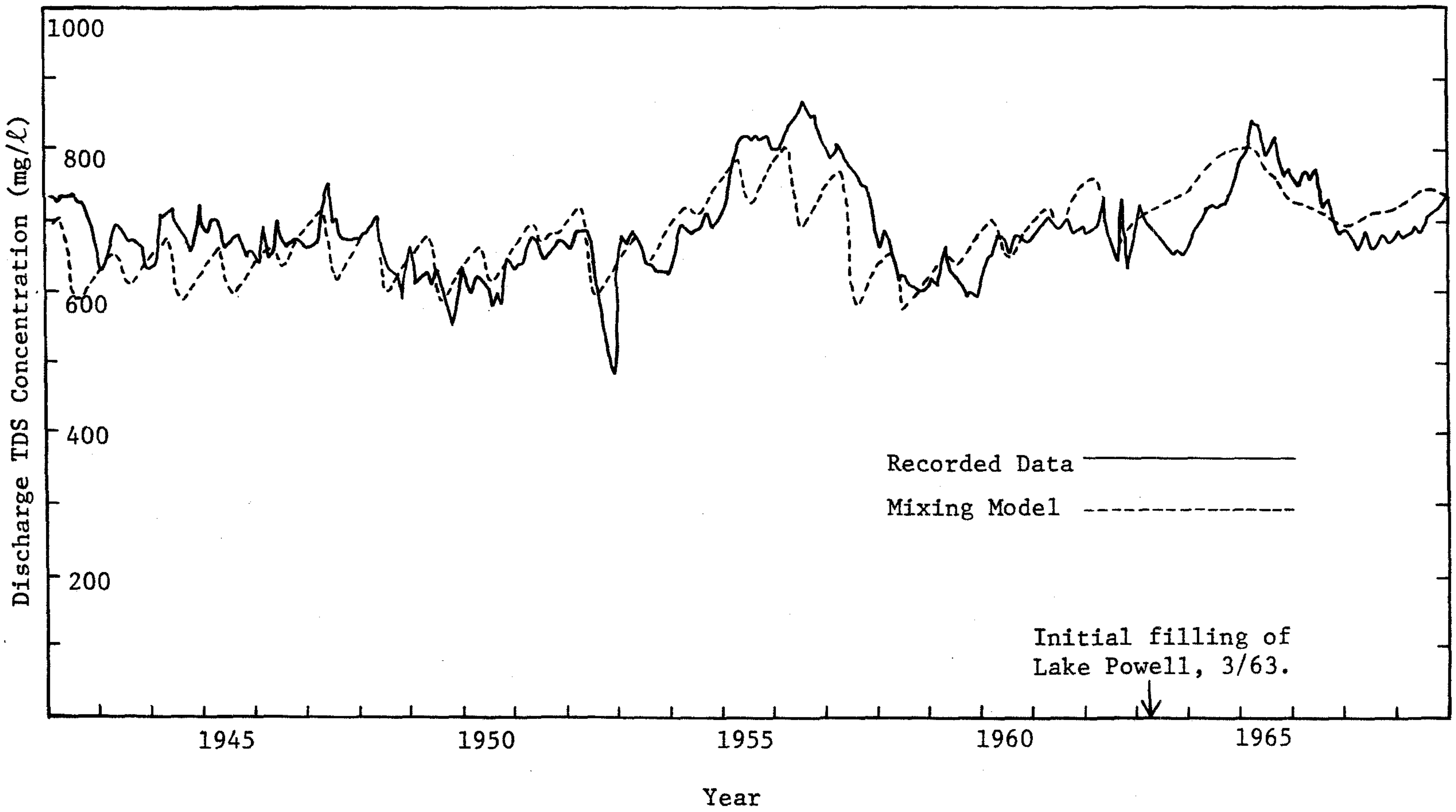
This mixing model was used to estimate historic outflow concentrations from Lake Mead given recorded inputs. The results were correlated with recorded outflow concentrations giving a coefficient of correlation $\rho^2 = 0.6$ (see Figure 4.6). The same model applied to Lake Powell data gave $\rho^2 = 0.77$.

4.4 Reservoir Discharge Scheduling

Releases of water from controlled reservoirs are scheduled on the basis of some prescribed set of rules. In general the volume of water released in a particular time period may depend upon storage, inflow, water quality, downstream water demand, power demand, and other conditions. The release rule specifies the relationship between these conditions and the scheduled release.

FIGURE 4.6

Recorded and Modeled Total Dissolved Solids Concentration of Lake Mead Discharge



Common reservoir release, or operating rules, are (1) the linear release rule, (2) the space rule, (3) the pack rule, and (4) the hedging rule (Bower et al., 1962). Each of these rules minimizes economic losses associated with failure to supply water to downstream users. The rules differ according to the type of downstream water use. A variety of mathematical programming techniques for finding optimal rules or mixes of rules appear in the literature (Beard, 1967; Hall et al., 1969; Mejia et al., 1974; Vemuri, 1974).

The linear release rule is used in the simulation model. This rule satisfies the basic requirements of Lake Powell and Lake Mead operation.

The demands and legal constraints imposed on the operation of Lakes Powell and Mead are presented in Section 4.4.1 which follows. The linear release rule and its application to Lakes Powell and Mead are discussed in Section 4.4.2. The other release rules mentioned above are briefly described and compared to the linear rule toward the end of Section 4.4.2.

4.4.1 Discharge Scheduling Requirements of Lakes Powell and Mead

This study requires that the modeling of reservoir discharges provides a realistic picture of the long-run storage capabilities of Lakes Powell and Mead. It was desirable to retain the existing management of these reservoirs as well as incorporate a capability for imposing alternative operating procedures.

The scheduling of releases from Colorado River storage reservoirs is presently the responsibility of the U.S. Bureau of Reclamation. Short-term, daily and monthly reservoir releases from Lakes Powell and

Mead are made in accordance with hydroelectric power demands and monthly downstream water demands. The water demand below Lake Powell is primarily established by the institutional flow requirements imposed below Glen Canyon Dam. Short-term water demands below Lake Mead are met primarily by releases from smaller downstream reservoirs (see Figure 1.1).

The long-term discharge requirements of Powell and Mead are specified by the Coordinated Long-Range Operating Criteria (see Section 1.2.3). These Criteria require of both reservoirs that adequate storage be maintained for meeting specified discharges and flood control storage. Also, that as nearly as practicable, storage volumes in Lakes Powell and Mead be equalized at the end of each water year. The specified water demands imposed at Lake Powell are (1) 8.23 MAF/yr whenever possible, and (2) an average of not less than 7.5 MAF/yr in any ten-year period. The water demand imposed at Lake Mead is that volume of water necessary to provide 1.5 MAF/yr to Mexico and the consumption of 7.5 MAF/yr in the lower Basin (specific quantities used in this study are given in Table 5.11).

4.4.2 Application of the Linear Discharge Rule

Discharges from Lakes Powell and Mead are modeled using the linear discharge or release rule. Releases in each time period are dependent upon the inflow to the reservoir during that period, the storage remaining at the end of the previous period, and a specified target discharge. The linear rule states that the target discharge will be met whenever possible. When inflow plus storage is not sufficient to meet the demand target, all available water is released, lowering reservoir storage to the minimum allowed. Finally, if the calculated storage following release of the target discharge exceeds the maximum allowed reservoir storage, the surplus volume is also released. The decision structure for the linear rule is shown in the flow chart of Figure 4.7 and graphically in Figure 4.8.

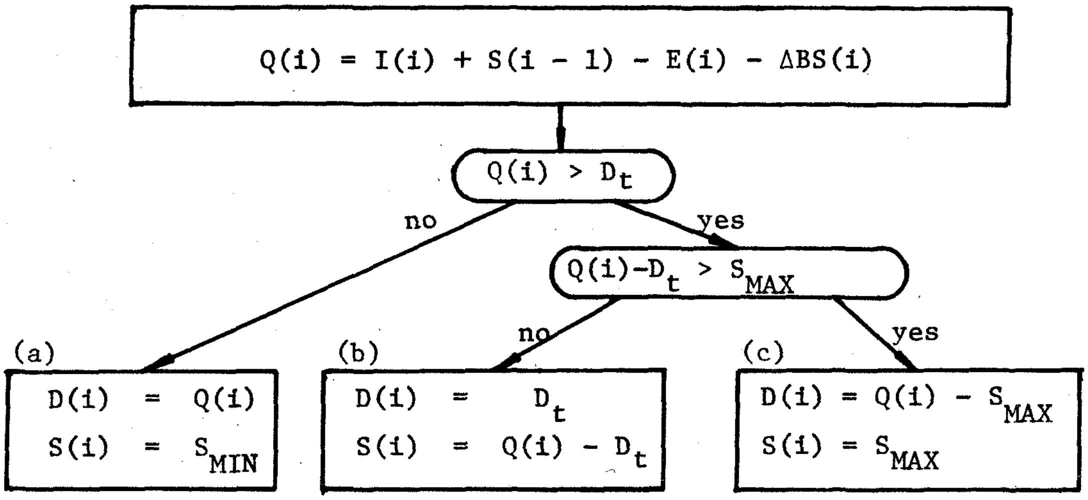
Reservoir evaporation and bank storage changes may be included in the linear discharge rule as shown in Figures 4.7 and 4.8. Withdrawals from the reservoir for use in the immediate area may also be included as an addition to the target discharge.

Application of the linear rule to model releases from Lakes Powell and Mead involves several assumptions. In the model the reservoirs are operated independently without regard to equalizing year-end storage or other possible costs incurred by independent operation. While the potential demand satisfying capabilities of the system can not be explored under independent operation, the capability of each reservoir in meeting its specified target discharge can be examined.

A second assumption regards the maintenance of a 10-year average discharge of 7.5 MAF/yr from Lake Powell. In practice this constraint <u>may</u> require increased releases following a year with discharge less than 7.5 MAF/yr. (If previous discharges have exceeded 7.5 MAF/yr, maintenance of the average requirement may not require increased releases.) The linear release rule, as applied, does not attempt to make up discharge deficits from previous time periods. Rather, since the reservoir is at minimum storage following failure to meet target

FIGURE 4.7

The Linear Reservoir Release Rule Logic Flow Chart



$D(i)$ = release during period i.

D_t = target release for downstream uses.

$Q(i)$ = volume of water available for release.

$I(i)$ = inflow during period i.

$S(i)$ = storage at the end of period i.

$E(i)$ = evaporation during period i.

$\Delta BS(i)$ = increase in bankstorage during period i.

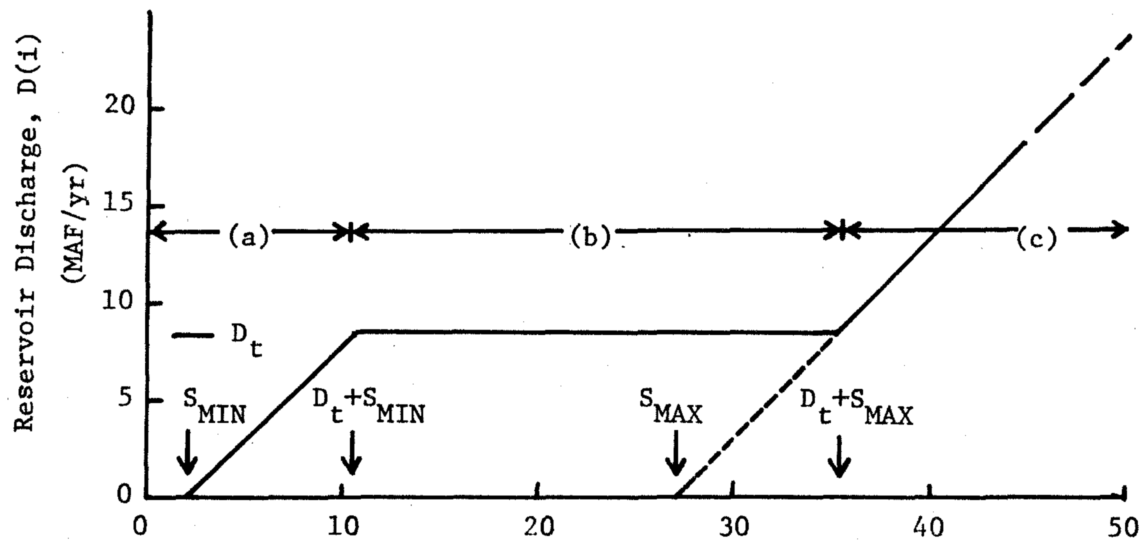
S_{MIN} = minimum allowed reservoir storage.

S_{MAX} = maximum allowed reservoir storage.

FIGURE 4.8

The Linear Reservoir Release Rule

(Numbers shown correspond to the application of the linear release rule to Lake Powell)



Water Available for Discharge in Period i, Q(i)
(MAF)

$$Q(i) = I(i) + S(i-1) - E(i) - \Delta BS(i)$$

D_t	=	the annual target discharge.
S_{MIN}	=	the minimum active storage.
S_{MAX}	=	the maximum total storage.
Q(i)	=	the volume of water available for discharge.
I(i)	=	the reservoir inflow during period i.
S(i-1)	=	the reservoir storage at the end of period i-1.
E(i)	=	the reservoir evaporation during period i.
ΔBS(i)	=	the increase in bankstorage during period i.

discharge, surplus water in succeeding time periods is used to replenish storage, providing insurance against future flow deficits. This latter form of operation is typical for reservoirs where economic losses from water shortage cannot be made up by excess releases in following periods.

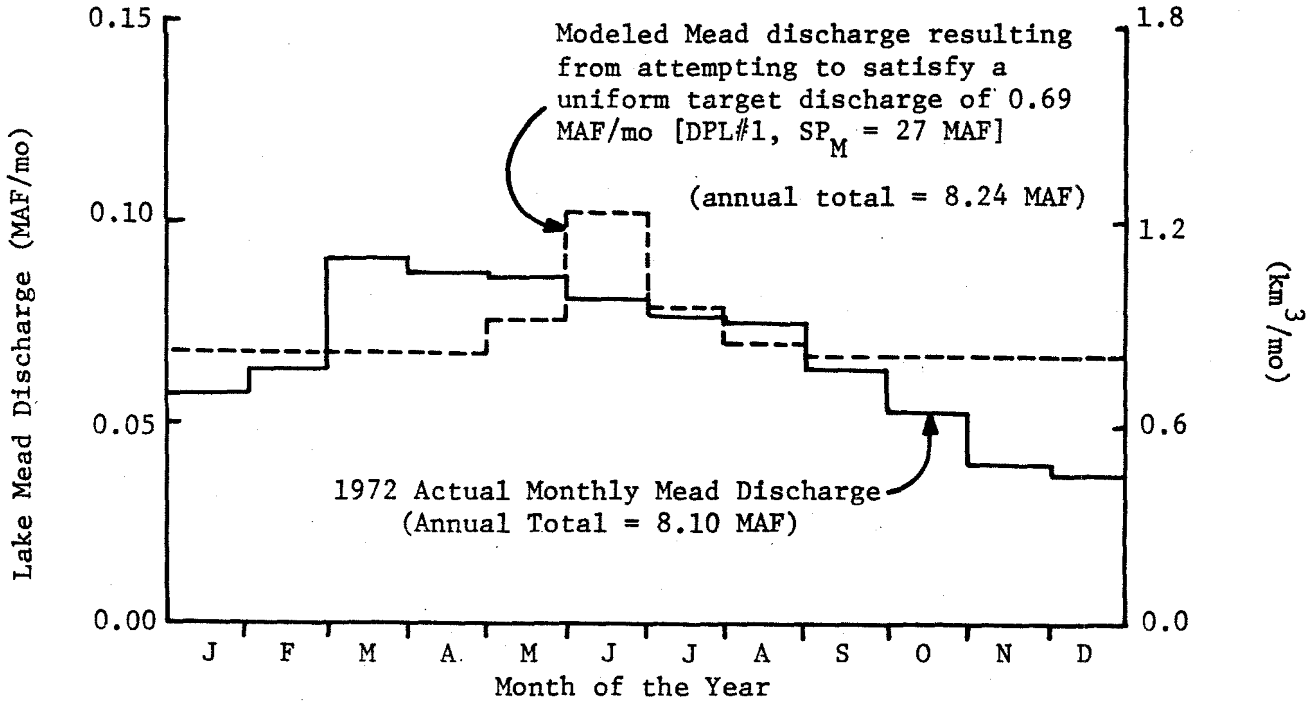
The 10-year average flow requirement was originally intended to prevent long-term deviations from the annual target flow. To check whether modeled reservoir discharges satisfied this flow requirement, a 10-year running average of annual discharge was performed. The number of deficit years can be easily read from cumulative probability functions of the 10-year average values. Because discharges below 7.5 MAF/yr are not compensated in succeeding time periods by the linear rule, more years of deficit flow are recorded than under the actual operating policy. The linear rule therefore provides more stringent conditions for studying the frequency or probability with which the 10-year average flow requirement is not met.

Finally, in the simulations performed for this study, the annual target discharge was divided equally throughout the months of the year. Actual reservoir operation is dependent upon stream-flow forecasting for providing flood control storage and the satisfaction of hydroelectric power demands. These considerations represent slight perturbations to operation under the linear rule, as shown in Figure 4.9, and are considered to have little effect upon the system response examined in this study.

The linear rule may be contrasted to the other rules mentioned at the beginning of Section 4.4.

FIGURE 4.9

Comparison of Modeled and Actual Monthly
Lake Mead Discharge



Source: United States Bureau of Reclamation, <u>Quality of Water: Colorado River Basin Progress Report No. 6</u> (January, 1973), Table 15.

The space rule is used to schedule releases from linked, either parallel or series, reservoirs (Bower *et al.*, 1962; Mejia *et al.*, 1974). The space rule defines releases from each reservoir in the system to provide the target discharge and distributes the remaining storage in the system between the reservoirs in proportion to the economic value of storage in each reservoir. The economic value of storage is assigned in accordance with recreational, power, flow augmentation, and flood control benefits for each reservoir. Mejia, *et al.* produced a mathematical programming solution to this scheduling problem and examined the value of streamflow forecasts with varying degrees of reliability. For application of the space rule the form of the economic loss functions used must be estimated or assumed, value functions for recreational and other benefits supplied, and a method of flow forecasting adopted. The space rule is a flexible rule in which the values of the control variables are adjusted to maximize net benefits.

The Operating Criteria established for the Colorado River reservoirs most closely resemble the space rule with equal economic value assigned to Lake Powell and Lake Mead storage.

The pack and hedging rules for the operation of individual reservoirs also rely upon forecasts of future inflows. The pack rule causes releases above the target value prior to high runoff periods to provide storage for accommodating future inflows. The pack rule is applicable when value can be derived from excess discharge, by power generation, for instance. Both the space and pack rules can also be used to provide flood control storage. The hedging rule, in contrast, releases less than the target amount during some periods in order to insure against larger flow deficits in subsequent periods. The hedging rule is applicable when economic losses increase with the magnitude of flow deficit, as, for example, in the supply of irrigation water.

The application of any but the fixed linear rule requires (1) forecasting of future streamflows, in practice over a six to twelve month period; (2) economic information of the absolute and marginal values of water stored, discharged, and used downstream; and (3) optimization with respect to the benefits derived from different release rules.

A detailed economic analysis of the Colorado River Basin was not an objective of this research. The present river basin model does not provide forecasts of future inflows. Either of these conditions prevents application of the space, pack, or hedging rules except in some arbitrary, fixed form.

4.5 Summary

Modeling the passage of water through Lakes Powell and Mead required examining the possible effects of evaporation, changes in bank storage, and loss of storage through sedimentation.

Evaporation is modeled on the basis of U.S. Bureau of Reclamation tables of evaporation as a function of storage elevation and the month of the year.

Changes in bank storage are not modeled because they were found to have no influence on the long-run statistics generated for this study.

Sediment encroachment is considered of secondary importance in the context of this study and was not included in the models of either Lake Powell or Lake Mead.

A simple, complete mixing model was found to provide a good representation of the flow of total dissolved solids through the reservoirs. The possible influence of chemical precipitation and dissolution of salts upon discharge salinity was examined. In Lake Mead dissolution of calcium sulfate offsets precipitation of calcium carbonate, resulting in a net change in composition but not mass of total dissolved solids. The absence of significant deposits of calcium sulfate in the geologic formations at the Lake Powell site results in a net loss of total dissolved solids through calcium carbonate precipitation.

Existing data are not sufficient for constructing an accurate model of precipitation as a function of reservoir storage. A range of estimates for the net reduction in TDS is reported, and a simple model of discharge concentration versus reservoir storage is developed.

In modeling the discharge TDS concentrations for both Lakes Powell and Mead, the mass of total dissolved solids is assumed to be conserved. The presentation of simulation results reported in Chapter 7 includes a discussion of the effects of employing the precipitation model developed in this chapter.

Reservoir discharges are modeled using a linear release rule. The linear rule attempts to meet target discharges whenever possible. This type of operation provides an approximation to existing long-term reservoir operating policies and is easily modified for examinations of alternate policies. The linear rule is compared to other possible discharge rules which have data requirements beyond the scope of this research.

CHAPTER 5

THE COLORADO RIVER BASIN MODEL

5.1 Introduction

The Colorado River Basin Model was constructed using the submodels developed in Chapters 2 through 4 as its major elements. The completed model is of a form that can be used in simulation studies in the manner outlined in Section 1.3. Each operation and relationship is coded for use on a digital computer, operations being modularized as subroutines for efficiency of computation and to facilitate modification.

Submodels corresponding to streamflow generation, stream salinity generation, and reservoir modeling have been validated as described in Chapters 2, 3, and 4 respectively to insure reproduction of the major characteristics of the actual river system. Validation of the complete basin model was performed to ensure that the mass balance of water and total dissolved salts would be maintained over the portion of the river system modeled.

The conceptual structure of the river basin model is presented in Section 5.2. Validation of the river basin model is discussed in Section 5.3, and a summary of program inputs is included in Section

5.4. Section 5.5 contains the values and sources of all control variables used in subsequent simulations.

5.2 Simulation Program Structure and Operation

Figure 5.1 displays a flow diagram of the Colorado River Basin computer model. The model performs synthetic streamflow generation, stream salinity generation, routing of water and total dissolved solids through Lakes Powell and Mead, and other tasks in a downstream direction. The subroutines corresponding to submodels of these various basin processes are indicated in the margin of the figure.

The simulation program, which initializes and operates the river basin model, is displayed in Figure 5.2. The structure of the program allows simulation studies to be carried out in the manner indicated previously in Figure 1.4.

Program operation proceeds twelve months at a time in a downstream fashion. On the first year of simulation each subroutine reads from disk storage or data cards all of the parameters, initial conditions, or other information necessary for its specific task. Statistical information on the first and second moments of each variable on a monthly and annual basis is accumulated in each subroutine and printed out at the conclusion of the simulation run. The simulation program includes a capability for rejecting the first M years of simulation as a transient time. If M is non-zero, statistics are reinitialized and accumulated on the next N years of simulation. Initial and final conditions corresponding to reservoir storage of water and dissolved solids are also printed out.

FIGURE 5.1

Colorado River Basin Model Structure

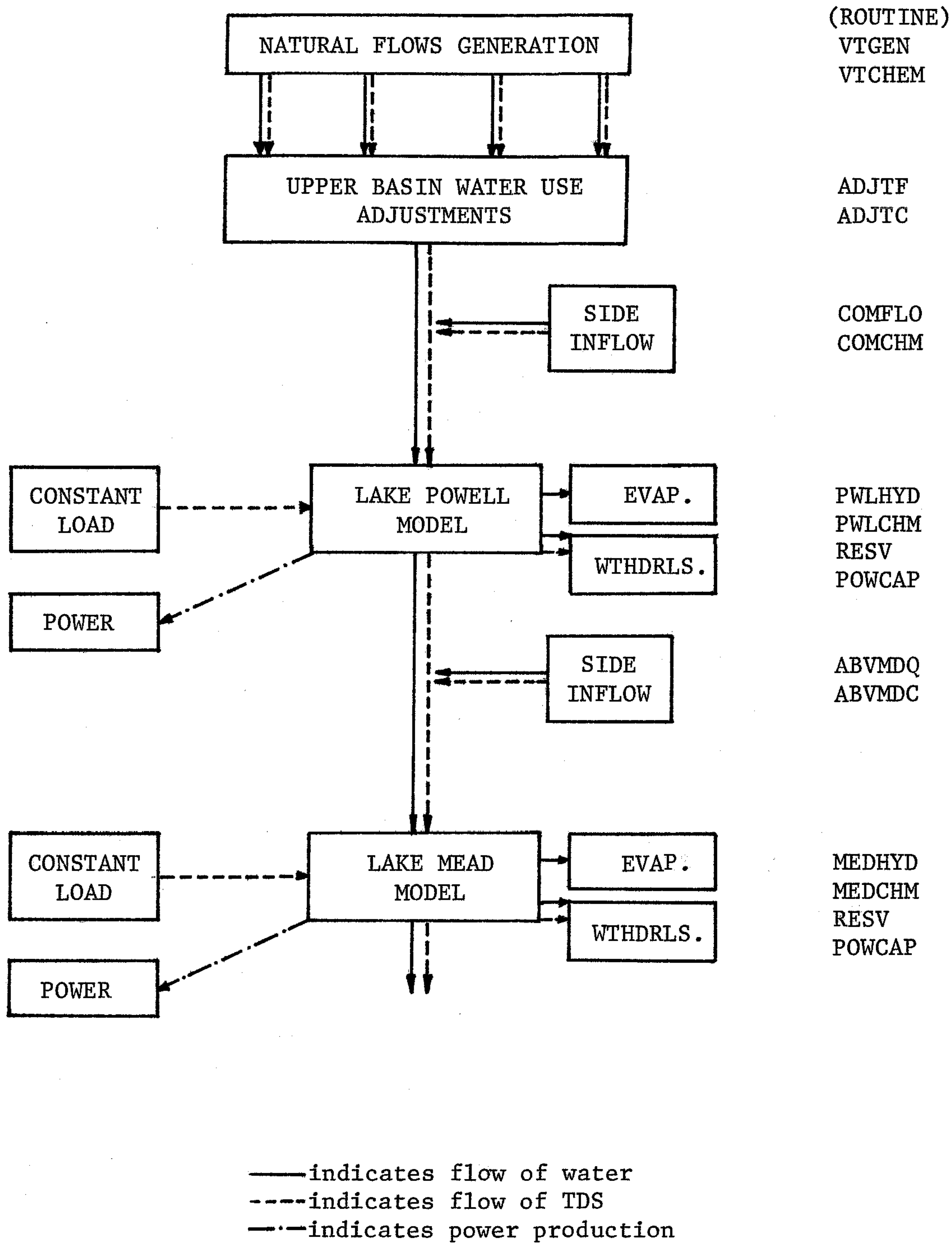
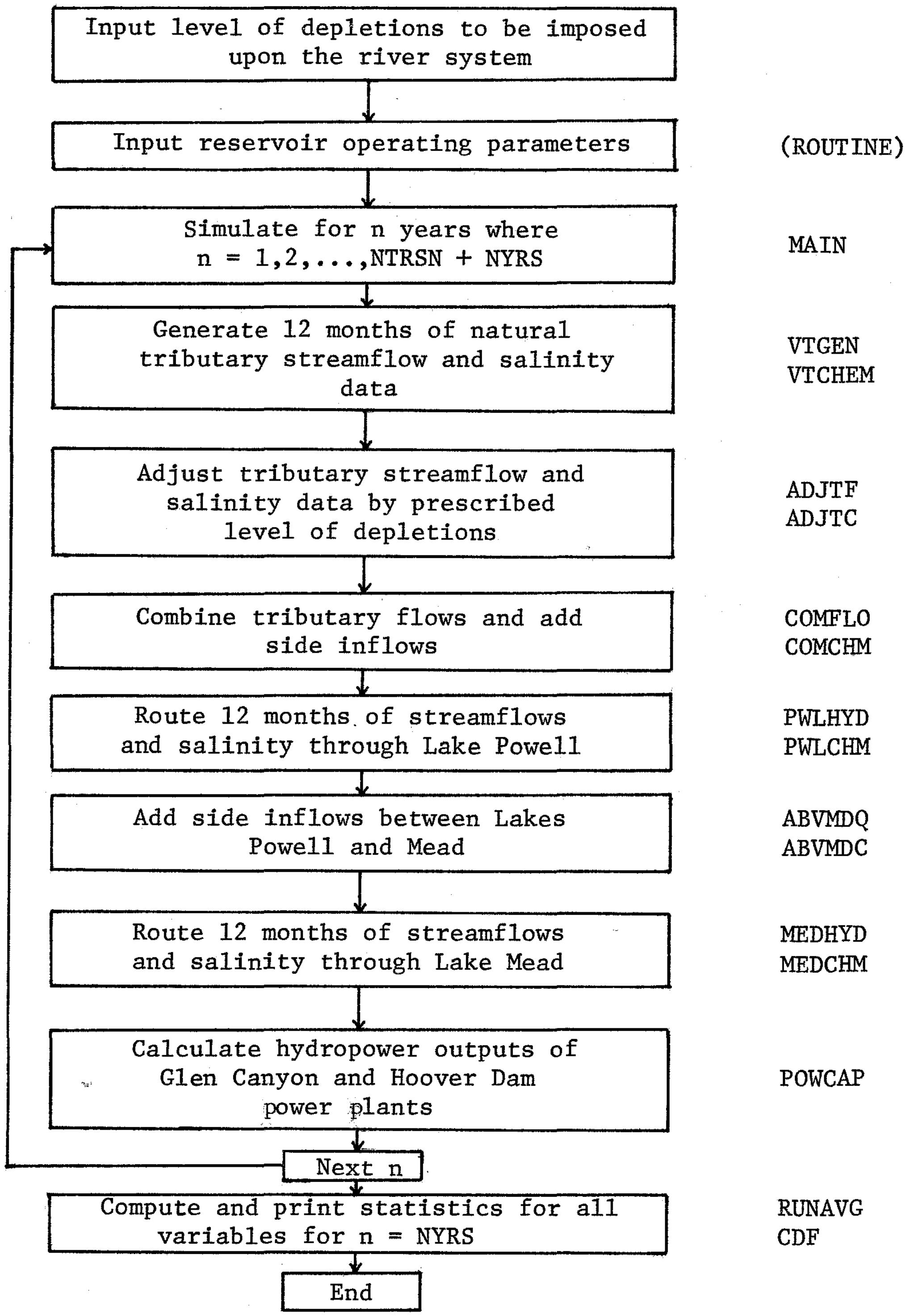


FIGURE 5.2

Colorado River Basin Simulation Program



In addition to the statistical information routinely printed out, the main program may be instructed to perform running averages and produce distribution plots of any desired system variable.

The theory and limitations of the algorithms used to model streamflows, stream salinity, and reservoir routing have been presented in Chapters 2 through 4.

The methods used to model streamflow adjustments for depletions upstream of Lake Powell and the corresponding effects upon stream salinity are important in regard to the interpretation of system response. Subroutines corresponding to these operations are described in the sections which follow.

5.2.1 ADJTF: Flow Depletion Adjustments

This subroutine adjusts the synthetic monthly tributary flows for depletions occurring in each tributary sub-basin. Constant monthly values for exported water, water depleted within the basin for municipal and industrial uses, and water consumed by irrigated agriculture are inputs to the subroutine. Depletions are subtracted from the streamflow for each month and any remaining flows routed downstream. If demand exceeds streamflow, the entire flow is consumed and the sub-basin outflow for that month is zero.

These depletion adjustments are summarized by Equation (5.1).

(5.1) $${}_tQ_m^y = {}_tN_m^y - {}_tDPL_m - {}_tEXP_m - {}_tAGI_m,$$

where: ${}_tQ_m^y$ = the adjusted flow in tributary t, year y, and month m;

${}_{t}N^{y}_{m}$ = the (synthetic) natural flow;

${}_{t}DPL_{m}$ = the total depletion for municipal and industrial use in the tributary t sub-basin, for month m;

${}_{t}EXP_{m}$ = the total volume exported from tributary t; and

${}_{t}AGI_{m}$ = the total irrigated agriculture consumptive use, including evaporation from supply reservoirs.

Several assumptions are implied by this construction; (1) that the Upper Basin demand is always met, if possible, regardless of conditions elsewhere in the basin; (2) that Upper Basin demand is independent of streamflow. These two assumptions effectively place the worst case demands upon downstream reservoirs, i.e. can the reservoirs supply downstream users without forcing reductions in upstream use. These are the strictest constaints that can be placed upon the system when examining the required storage problem. (3) The assumption is also made that the operation of upstream reservoirs serves only to provide over year storage for the purpose of meeting Upper Basin water demands. In practice this is only partially true. During operation of the river basin model no change in upstream reservoir storage is accounted for, although an annual drawdown-refill cycle could be added to the depletions of the appropriate tributary. Average evaporation from these reservoirs is also subtracted as an upstream depletion (an accounting of the depletions used appears in Section 5.5).

5.2.2 ADJTC: Salinity Adjustments

This subroutine adjusts monthly natural dissolved solids discharge, and therefore concentrations, for the effects of Upper Basin water depletions.

As explained in the description of the stream salinity model (Chapter 3), the average natural discharge of salt, TN, is taken equal to the average historical value, TH. Because man's effect upon the total dissolved solids discharges during the period of model calibration is nearly constant, the historical discharges from 1940 to 1968 are taken to be a base load condition. To express salinity conditions for depletion levels higher than those of the 1940 to 1968 period, only the effects of additional depletions are considered.

The effects of additional depletions upon stream salinity are taken as a function of the type of consumptive use. The adjustments are expressed in Equation (5.2).

$$ {}_{t}T_{m}^{y} = {}_{t}TN_{m}^{y} - {}_{t}DTDMI_{m} - {}_{t}DTEXP_{m} - {}_{t}DTAGI_{m} \qquad (5.2) $$

where:

$_{t}T_{m}^{y}$ = the adjusted TDS discharge for tributary t, year y, and month m;

$_{t}TN_{m}^{y}$ = the (synthetic) natural TDS discharge;

$_{t}DTDMI_{m}$ = the net removal of or addition to TDS solids from additional municipal and industrial diversions over the (1940-1968) base;

$_{t}DTEXP_{m}$ = the additional exportation of TDS over the base level; and

$_{t}DTAGI_{m}$ = the net effect upon the TDS discharge by additional agricultural diversions.

Depletions corresponding to the last three terms in Equation (5.2) take place within the basin at upstream locations exhibiting lower dissolved solids concentrations than at the modeled location. Removal of salts in each case is taken as the water depletion multiplied by the average TDS concentration of diverted water for each use. Water exported from the basin is assumed to have an average concentration of 88 mgl and water diverted for municipal and industrial uses is assumed to have a concentration of 331 mgl (Weber et al., 1971; pp. 13-14).

No return flow of TDS from municipal and industrial depletions is provided, in accordance with recent policies for maintaining water quality in the Colorado River Basin (Weber et al., 1975; p. 13).

Removal of TDS by agricultural diversions is made at the same rate as for municipal depletions. Additional return flows of dissolved solids from irrigation are estimated as a TDS pick-up per acre of additional irrigated acreage, at the rate of 1.0 ton/acre/yr ($2.7*10^3$ kg/hectare/yr) (USBR, 1971a; p. 35).

5.3 Model Validation

The validation procedure is a method of checking to see if the terms in the mass balance of water and salt at various points in the river basin model correspond to mass flows or changes in mass storage measured or estimated in the actual river basin. In this application, measured monthly streamflows and estimates of side inflows for a given historical period are input to each reservoir. Reservoir evaporation is estimated as a function of storage for each reservoir. Measured discharges are released, and the final storage calculated as the difference between inflows and outflows. The total evaporation is then compared to USBR estimates. The total changes in storage and final storage are compared to measured values over the period. Large discrepancies in evaporation would indicate poor modeling technique. Large discrepancies in storage or storage change would reflect poor modeling of evaporation as well as indicate where other processes, such as bank storage, have been either poorly modeled or neglected.

Two periods were examined during validation. The first period, 1941 to 1962 precedes the completion of Glen Canyon Dam. This period was chosen so that initial filling and bank storage accumulation of Lake Powell would not affect water and salt budgets. Lake Mead, which began filling in 1933, had reached steady state operation by 1941. The second period examined was 1963 to 1968.

A schematic representation of reservoir operation in the validation model is shown in Figure 5.3.

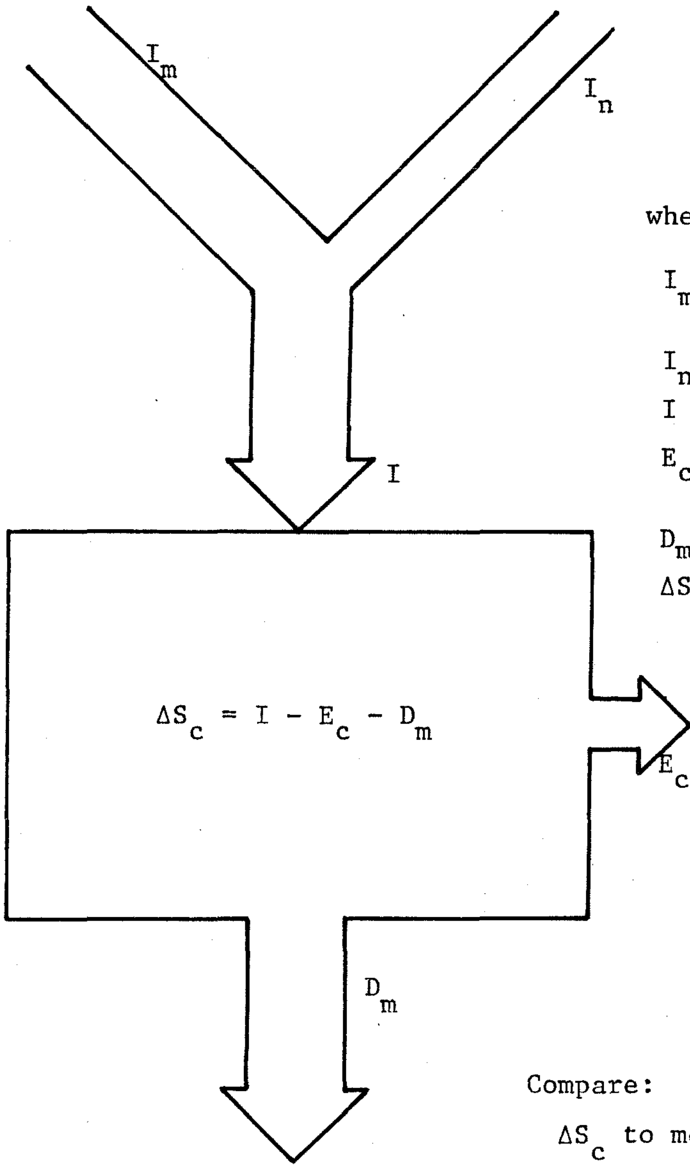
<u>1941-1962</u>

The measured or estimated water and salt budgets, and the modeled budgets for the 1941 to 1962 period are shown in Table 5.1(a,b).

Two areas of agreement in the water balance should be noted: (1) the net change in storage of Lake Mead is matched by the model, and (2) the net evaporation from Lake Mead is also matched. These last two items indicate that the net effect of changes in bank storage or other possible losses are small and within the accuracy of the measured

FIGURE 5.3

Reservoir Operation During Validation Runs



where:

I_m = measured tributary flows;

I_n = unmeasured side inflows;

I = $I_m + I_n$;

E_c = evaporation calculated as a function of storage;

D_m = measured discharge; and

ΔS_c = change in storage calculated.

Compare:

ΔS_c to measured storage changes;

E_c to USBR estimates.

TABLE 5.1(a)

Colorado River Basin Water Budget
for the Period 1941-1962

(22 year totals in MAF)

		Measured	Modeled	
Colorado River	(1)	115	115	
Green River	(1)	94	94	
San Juan River	(1)	38	38	
San Rafael River	(1)	2	2	
Side inflows	(2)	9	9	
TOTAL POWELL INFLOW		258	258	
– ΔS Powell	(5)	0	0	
– Evap. Powell	(5)	0	0	
Powell discharge	(1)	258	258	
Side inflow	(2)	13	13	
TOTAL MEAD INFLOW		271	271	
– ΔS Mead	(1)	– 2	– 1	(4)
– Evap. Mead	(3)	– 19	– 18	(4)
Mead discharge	(1)	250	252	

Notes:

(1) USGS Water Supply Papers; inputs to model.
(2) Above Powell from Iorns et al., (1965) p. 34; Above Mead from USBR information (USBR, 1971a, pp. 32-33), and Feeny (1975). Slightly higher estimates in (USBR, 1969, p. 3, Ch. 5).
(3) USGS Water Supply Papers
(4) Modeled evaporation from evaporation versus storage tables, Change in storage modeled as ΔS = I – E – D.
(5) The period 1941-1962 precedes the filling of Lake Powell.

TABLE 5.1(b)

Colorado River Basin Dissolved Solids
Balance for the Period 1941-1962

(22 year totals in MT)

		Measured	Modeled	
Colorado River	(1)	94	92	(2)
Green River	(1)	56	56	(2)
San Juan River	(1)	21	21	(2)
San Rafael River	(1)	5	5	(2)
Side inflows	(3)	3	3	
TOTAL POWELL INFLOW		179	177	
− ΔS Powell	(4)	0	− 1	
Powell discharge	(1)	190	175	
Side inflow	(3)	44	44	
TOTAL MEAD INFLOW		234	219	
− ΔS Mead	(4)	−(0−1)	− 1	
Mead discharge		233	218	

Notes:

(1) USGS Water Supply Papers.
(2) Modeled as a function of measured streamflows.
(3) From USBR estimates (USBR 1971a; pp. 28-34, and Table 5).
(4) Measured values estimated from historical outflow concentrations and initial/final storages. Modeled values obtained from complete mixing models PWLCHM and MEDCHM.

data. Discrepancies are on the order of at most 5%, within the accuracy of estimates and measurements.

Table 5.1(b) displays a balanced salt budget, balanced to within ± 8% over the period 1941 to 1962. The modeled stream salinities were calculated as a function of the measured streamflow using the stream salinity subroutine. Estimates of side inflows of salt were made from USBR information (USBR, 1971a). Estimates of changes in salt stored in Lake Mead were made using discharge concentrations and initial and final total storage values. The discrepancy between the actual and modeled outflow of salt from Lake Powell is removed from subsequent simulation runs by adjusting the contribution from side inflows upward (see Table 5.5).

1963-1968

The water and dissolved solids budgets for the period 1963-1968 are shown in Table 5.2(a,b). The difference between the measured change in Lake Powell storages and the modeled change in storage is presumably the amount lost to bank storage during the filling of Lake Powell. This difference represents a 23% error in the estimate of accumulated surface storage. The aggregate difference between measured and modeled changes in Lake Mead Surface storage is 7.7%.

The difficulties in forming a mass balance of dissolved solids for the 1963 to 1968 period are compounded by the filling of Lake Powell (Hoffman, 1967). Effects of initial filling upon downstream water quality are difficult to ascertain (USBR, 1971a). The modeled discharge of salts from Lake Mead is not as well reproduced by the

TABLE 5.2(a)

Colorado River Basin Water Budget
for the Period 1963–1968

(6 year totals in MAF)

		Measured	Modeled	
Colorado River	(1)	23.2	23.2	
Green River	(1)	21.8	21.8	
San Juan River	(1)	7.3	7.3	
San Rafael River	(1)	0.4	0.4	
Side inflow	(2)	2.5	2.5	
TOTAL POWELL INFLOW		55.2	55.2	
− ΔS Powell	(1)	−11.1	−13.5	(4)
− Evap. Powell	(3)	− 1.4	− 1.5	(4)
Powell discharge by difference		(42.7)	40.2	
Powell discharge measured	(1)	40.3		
Side inflow	(2)	3.3	3.3	
TOTAL MEAD INFLOW		43.6	43.5	
− ΔS Mead	(1)	+ 9.1	+ 8.4	(4)
− Evap. Mead	(3)	− 4.2	− 4.0	(4)
Mead discharge by difference		(48.5)	47.9	
Mead discharge measured	(1)	48.0		

Notes:

(1) USGS Water Supply Papers; inputs to model.
(2) Above Powell from Iorns *et al.*, (1965), p. 34. Side flows above Mead from Feeny, (1975)
(3) Powell evaporation from tables using recorded storage (no USGS estimates published); Mead evaporation from USGS Water Supply Papers.
(4) Modeled evaporation from evaporation versus storage tables, change in storage taken as $\Delta S = I - E - D$.

TABLE 5.2(b)

Colorado River Basin Dissolved Solids Balance for the Period 1963-1968

(6 year totals in MT)

		Measured	Modeled	
Colorado River	(1)	23	25	(2)
Green River	(1)	15	15	(2)
San Juan River	(1)	6	6	(2)
San Rafael River	(1)	1	1	(2)
Side inflows	(3)	1	1	
TOTAL POWELL INFLOW		46	48	
- ΔS Powell	(4)	-(10-11)	- 12	
Powell discharge by difference		(35-36)	36	
Powell discharge measured	(1)	34		
Side inflows	(3)	+(7-12)	+ 12	
TOTAL MEAD INFLOW		(41-46)	48	
- ΔS Mead	(4)	+(6-10)	4	
Mead discharge by difference		+(47-56)	53	
Mead discharge measured	(1)	47		

Notes:

(1) USGS Water Supply Papers.
(2) Modeled as a function of measured streamflows.
(3) From USBR estimates (USBR, 1971a; pp. 28-34, and Table 5).
(4) Ranges of change in total salt storage calculated total water stored multiplied by max and min discharge concentration observed over the preceeding year.

model. The difference between measured and modeled outflow may be due to a less than average contribution of salts from side inflows or by a substantially smaller contribution from the change in salt stored in Lake Mead.

Model validation over the period 1941 to 1962 confirms the values of average side inflows of water chosen for the model and indicates that an adjustment to side inflows of salt was required. The cumulative effects of bank storage upon the water balance of Lake Mead are seen to be negligible. The mixing model for determining dissolved solids discharges from Lake Mead gives results agreeing with actual discharge within 6%. Validation over the period 1963 to 1968 suggests no reason to alter the model construction or operation. The mass flows of water and dissolved salts below Lake Powell for the period 1963-1968 are significantly effected by the initial filling of Lake Powell. These effects are considered transient in nature and of little consequence in modeling steady-state conditions in the basin.

5.4 Summary of Simulation Variables, Inputs and Outputs

This section summarizes the information requirements for a simulation run and the output obtained.

To facilitate the discussion of results in Chapters 6 and 7, the definitions introduced in Section 1.3.1 are repeated here.

(1) Model parameters - parameters, such as the average January streamflow for tributary 3, which are constants for all simulations and determined from calibration data.

(2) Simulation parameters - parameters set prior to a simulation run which control the simulation process; the number of years to be simulated is a simulation parameter.

(3) System control variables - those variables whose values are set prior to simulation and which prescribe the management configuration used in the simulation. Examples are the level of upstream depletions of water and the maximum allowed reservoir storage.

(4) System variables - any variable in the model whose behavior may be monitored. A complete list is given in Table 5.3.

(5) System response or measures of system performance - the first and second moments of the system variables indicated in Table 5.3. The probability distribution of reservoir discharge, and in particular the probability of failure to meet target discharge, is also a measure of system performance in this study.

5.4.1 Simulation Inputs

Simulation parameters and system control variables comprise the simulation inputs and must be specified for each run. These quantities are listed and briefly defined in Table 5.4.

The values given to the simulation parameters for the simulations performed in this study are discussed in Sections 6.1 and 6.2. The values assigned to the system control variables are presented in Section 5.5.

Table 5.3

System Variables

Variables are listed in downstream order, the moments of variables marked with an asterisk are used as measures of system performance or response. (The symbols indicated appear in the discussions in Chapters 6 and 7).

For each tributary:

1. Natural monthly streamflows
2. Natural monthly dissolved solids flows
3. Natural monthly dissolved solids concentrations
4. Depleted monthly streamflows
5. Depletion adjusted dissolved solids flows
6. Depletion adjusted dissolved solids concentrations

For each reservoir:

5. Total monthly inflow (Powell inflow, I_P)
6. Total monthly dissolved solids inflow

(*) 7. Total reservoir storage (active plus dead storage), S

8. Total dissolved solids storage

(*) 9. Reservoir evaporation, E

(*)10. Reservoir discharge, D

(*)11. Dissolved solids discharge, C

12. Dissolved solids flow of reservoir withdrawals

(*)13. Hydropower generating capacity, P_c

(*)14. Hydropower output, P_o

Table 5.4

Simulation Inputs

(The symbols indicated appear in discussions in Chapters 6 and 7.)

Simulation Parameters:

1. Number of years of transient operation
2. Number of years of simulation operation
3. Initial value to the random number generator (uniquely determines sequence of flows generated).

System Control Variables:

Upper Basin Depletion Level, DPL

1. Monthly exports of water from each tributary basin, (MAF/mo)
2. Monthly municipal and industrial consumption in each tributary basin, (MAF/mo)
3. Monthly irrigation consumptive use in each tributary basin (MAF/mo)
4. Monthly irrigation return flow of dissolved solids in each tributary basin, (MT/mo)
5. Monthly side inflows of water and dissolved solids above Lake Powell (MAF/mo), (MT/mo)
6. Monthly withdrawal from Lake Powell, (MAF/mo).

Lower Basin Depletion Level

1. Monthly side inflows of water and dissolved solids between Lakes Powell and Mead (MAF/mo), (MT/mo)
2. Monthly withdrawal from Lake Mead, (MAF/mo).

(These control variables represent the only quantities within the boundaries of the river system model which are affected by Lower Basin depletions. The remainder of the Lower Basin water demand is imposed as the target discharge for Lake Mead).

Reservoir Operating Parameters

1. Minimum allowable storage of Lake Mead, (MAF)
2. Maximum allowable storage of Lake Mead, (MAF)
3. Minimum allowable storage of Lake Powell, (MAF)
4. Maximum allowable storage of Lake Powell, SP_m (MAF)
5. Target discharge for each reservoir, D_t, (MAF/yr)
6. The initial storage in each reservoir
7. The initial dissolved solids concentration in each reservoir.

5.4.2 Simulation Outputs

The output from a simulation run includes a listing of all input quantities and statistical information for each of the variables listed in Table 5.3. The first and second moments of each variable are printed in tabular form. Their value for each month of simulation can also be printed, but only if specifically requested. Initial and final conditions corresponding to reservoir storage of water and dissolved solids at the beginning and end of the simulation period are printed out.

In addition, the cumulative distributions of annual and 10-year average annual discharge are plotted for each reservoir. Other capabilities are provided for retaining output information on disk storage.

5.5 The Values of Control Variables Used in Subsequent Simulations: DPL, SP_M, D_t

The discussion and presentation of control variable values proceeds in the order indicated in Table 5.4. The values appearing in Tables 5.5 to 5.11 are used in performing the simulations discussed in Chapters 6 and 7. The sources, preparation, and values of water depletion and salinity adjustments data appear in Section 5.5.1. A discussion of the reservoir operating parameters and their values is given in Section 5.5.2.

5.5.1 Water Depletions

An accounting of monthly water consumption by both type and location of use has been compiled for three levels of total Upper Basin water depletions. Simulations performed using each of the three levels of depletion allow system response to be examined for a variety of demand conditions.

The depletion levels used have been selected from projections of future consumptive use. The patterns of water-use therefore represent conditions which may actually be expected to occur in the Colorado River Basin (see Figure 5.4).

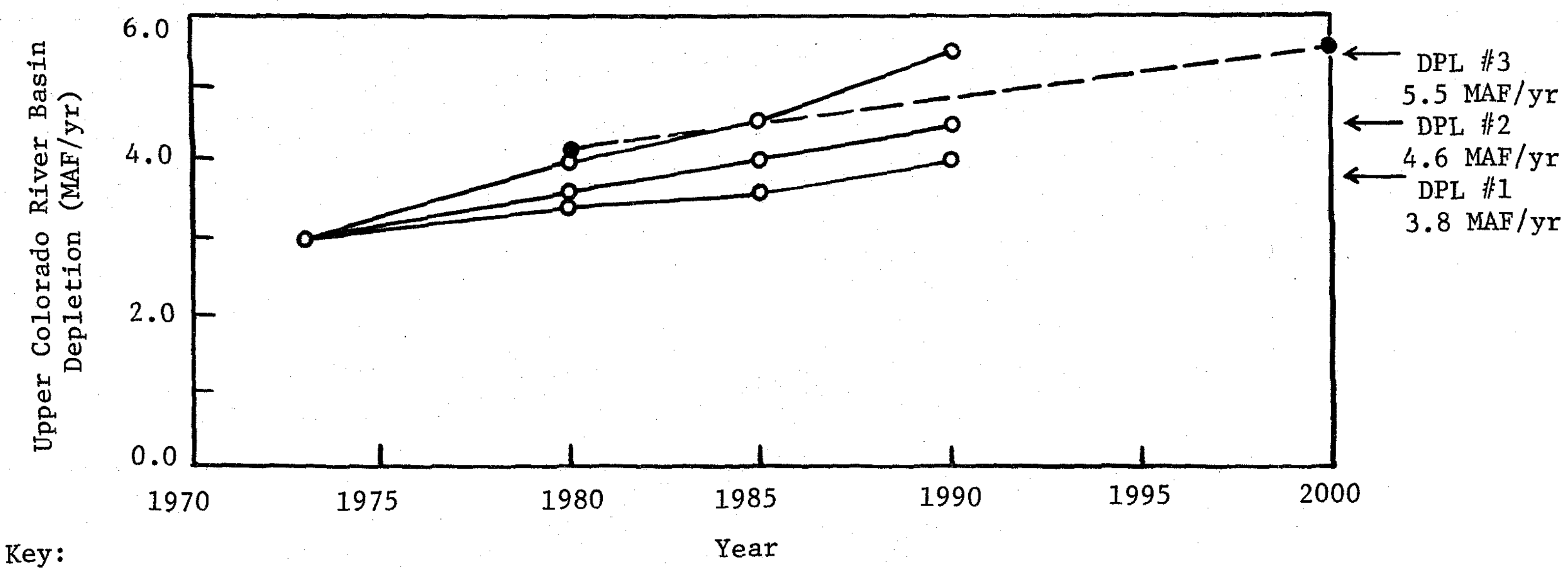
The writer has compiled eight sets of future depletions from which the three presented here have been selected. These three levels, denoted DPL #1, DPL #2, and DPL #3, have been chosen to provide an informative range of depletion conditions. Levels DPL #1 and DPL #2 correspond to existing commitments to planned or authorized water projects. Depletion level DPL #3 includes further expansion of these water projects and additional depletions for the anticipated development of Upper Basin energy resources.

Depletions are divided into the following categories of use: (1) exports of water from the basin; (2) municipal and industrial use; and (3) irrigation consumptive use.

The monthly depletion values required by the model have been obtained from the sources cited in the sections which follow. In cases where only annual depletion estimates are available, monthly values have been calculated in accordance with observed monthly patterns for the particular type of water use.

FIGURE 5.4

Upper Colorado River Basin Depletion Levels



Key:

● Comprehensive Framework Study (1971)

o Weber et al. (1975)

← From Tables 5.6 to 5.7.

The computations performed in assigning values to the depletion control variables are presented in sections 5.5.1.1 to 5.5.1.8

The values obtained for each depletion level are given in Tables 5.5 through 5.8 on the pages which follow. Depletions are summarized in Table 5.9 by both tributary sub-basin and state. Control variable adjustments corresponding to the implementation of salinity control projects are presented in Section 5.5.1.9 and Table 5.10.

5.5.1.1 Water Exports

Water exports on a project by project basis from each tributary sub-basin for the base-line conditions are taken from the Comprehensive Framework Study (1971; Table 2, p. 24); see Tables 5.5 through 5.9. Exports at a higher level of depletion are taken from USBR (1971b) and from Ribbens and Wilson (1973; Tables IX and X).

For instances in which annual quantities must be broken down into monthly values, the monthly pattern of current exports is used. An examination of USGS Water Supply Papers (WSP No. 2124 and 2125) reveals that for the period 1966 to 1970 approximately 65 $\pm$ 5% of the water exported annually was uniformly distributed over the twelve months of the year. The remaining 35% of the annual export was distributed over the April to July growing season.

In distributing annual values of exports over the months of the year, 65% of the total is distributed uniformly. The remaining 35% is distributed over the months of the growing season in the percentages given in Table 2.1.

TABLE 5.5

Control Variables -- Base Line Conditions (2.8 MAF/yr)

(Standard type indicates flow of water in MAF/mo; script type indicates flow of salts in MT/mo)*

Item	Tributary or Location	Units	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR†
Exports	Colorado	MAF/mo	0.023	0.023	0.023	0.030	0.090	0.075	0.045	0.023	0.023	0.023	0.023	0.023	0.424
	Green	MAF/mo	0.007	0.007	0.007	0.009	0.024	0.020	0.013	0.007	0.007	0.007	0.007	0.007	0.112
	San Juan	MAF/mo	0.0	0.0	0.0	0.0	0.001	0.001	0.001	0.0	0.0	0.0	0.0	0.0	0.003
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Municipal Indus.	Colorado	MAF/mo	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.036
	Green	MAF/mo	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.012
	San Juan	MAF/mo	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.036
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Irrigation consumptive use	Colorado	MAF/mo	0.0	0.0	0.0	0.047	0.419	0.326	0.140	0.0	0.0	0.0	0.0	0.0	0.932
	Green	MAF/mo	0.0	0.0	0.0	0.041	0.368	0.286	0.123	0.0	0.0	0.0	0.0	0.0	0.818
	San Juan	MAF/mo	0.0	0.0	0.0	0.019	0.170	0.132	0.057	0.0	0.0	0.0	0.0	0.0	0.378
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Irrigation return flow of dissolved solids	Colorado	MT/mo	*0.0*	*0.0*	*0.0*	*0.031*	*0.278*	*0.216*	*0.093*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.618*
	Green	MT/mo	*0.0*	*0.0*	*0.0*	*0.036*	*0.320*	*0.249*	*0.107*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.712*
	San Juan	MT/mo	*0.0*	*0.0*	*0.0*	*0.015*	*0.131*	*0.102*	*0.044*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.292*
	San Raf.	MT/mo	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Side inflow water	Above Lake Powell	MAF/mo	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.408
Side inflow TDS	Above Lake Powell	MT/mo	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.672*
Withdrawal	Lake Powell	MAF/mo	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.015
Side inflow water	Powell to Mead	MAF/mo	0.072	0.056	0.062	0.058	0.010	0.002	0.069	0.052	0.062	0.038	0.029	0.048	0.558
Side inflow TDS	Powell to Mead	MT/mo	*0.162*	*0.162*	*0.162*	*0.162*	*0.162*	*0.162*	*0.162*	*0.162*	*0.162*	*0.162*	*0.162*	*0.167*	*2.004*
Withdrawal	Lake Mead	MAF/mo	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.130

Sources: Upper Colorado River Water Uses with Projected Depletions at Lee Ferry, USBR (undated, received Aug. 1971).
Ribbens, Richard W. and Wilson, Robert F., "Applications of a River Network Model to Water Quality Investigations for the Colorado River," USBR (Denver, Colorado; 1973), Tables IX and X.
Upper Colorado Region Comprehensive Framework Study (1971); Table 2, page 24.
USBR, Quality of Water: Colorado River Basin, Progress Report No. 5, (January, 1971), page 54.

* 1 MAF/yr = 1.233 km^3/yr; 1 MT/yr = 900 Gg/yr.

† Discrepancies between row totals and figures appearing in this column are due to rounding off of monthly values.

TABLE 5.6

Control Variable Values -- DPL #1 (3.8 MAF/yr)

(Standard type indicates flow of water in MAF/mo; script type indicates flow of salts in MT/mo)*

Item	Tributary or Location	Units	Month												YEAR†
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Exports	Colorado	MAF/mo	0.023	0.023	0.023	0.076	0.157	0.175	0.109	0.023	0.023	0.023	0.023	0.023	0.701
	Green	MAF/mo	0.010	0.010	0.011	0.020	0.071	0.066	0.041	0.023	0.016	0.014	0.011	0.011	0.304
	San Juan	MAF/mo	0.0	0.0	0.001	0.019	0.042	0.041	0.009	0.001	0.0	0.0	0.0	0.0	0.113
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Municipal Indus.	Colorado	MAF/mo	0.004	0.004	0.009	0.013	0.019	0.013	0.007	0.003	0.003	0.003	0.003	0.003	0.084
	Green	MAF/mo	0.009	0.009	0.013	0.027	0.016	0.017	0.012	0.009	0.009	0.024	0.009	0.008	0.162
	San Juan	MAF/mo	0.004	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.004	0.004	0.056
	San Raf.	MAF/mo	0.0	0.0	0.0	0.001	0.002	0.002	0.0	0.0	0.0	0.0	0.0	0.0	0.005
Irrigation consumptive use	Colorado	MAF/mo	0.0	0.0	0.0	0.047	0.421	0.327	0.141	0.0	0.0	0.0	0.0	0.0	0.936
	Green	MAF/mo	0.0	0.0	0.0	0.041	0.368	0.286	0.123	0.0	0.0	0.0	0.0	0.0	0.818
	San Juan	MAF/mo	0.0	0.0	0.0	0.032	0.292	0.227	0.107	0.0	0.0	0.0	0.0	0.0	0.658
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Irrigation return flow of dissolved solids	Colorado	MT/mo	*0.0*	*0.0*	*0.0*	*0.031*	*0.279*	*0.217*	*0.093*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.620*
	Green	MT/mo	*0.0*	*0.0*	*0.0*	*0.036*	*0.320*	*0.249*	*0.107*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.712*
	San Juan	MT/mo	*0.0*	*0.0*	*0.0*	*0.020*	*0.180*	*0.140*	*0.060*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.400*
	San Raf.	MT/mo	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Side inflow water	Above Lake Powell	MAF/mo	0.041	0.041	0.041	0.041	0.41	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.492
Side inflow TDS	Above Lake Powell	MT/mo	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.672*
Withdrawal	Lake Powell	MAF/mo	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.050
Side inflow water	Powell to Mead	MAF/mo	0.072	0.056	0.062	0.058	0.010	0.002	0.069	0.052	0.062	0.038	0.029	0.048	0.558
Side inflow TDS	Powell to Mead	MT/mo	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*2.004*
Withdrawal	Lake Mead	MAF/mo	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.132

Sources: Upper Colorado River Water Uses with Projected Depletions at Lee Ferry, USBR (undated, received Aug. 1971).
Ribbens, Richard W. and Wilson, Robert F., "Applications of a River Network Model to Water Quality Investigations for the Colorado River," USBR (Denver, Colorado; 1973), Tables IX and X.
Upper Colorado Region Comprehensive Framework Study (1971); Table 2, page 24.
USBR, Quality of Water: Colorado River Basin, Progress Report No. 5, (January, 1971), page 54.

* 1 MAF/yr = 1.233 km^3/yr; 1 MT/yr = 900 Gg/yr.

† Discrepancies between row totals and figures appearing in this column are due to rounding off of monthly values.

TABLE 5.7

Control Variable Values -- DPL #2 (4.6 MAF/yr)

(Standard type indicates flow of water in MAF/mo; script type indicates flow of salts in MT/mo)*

Item	Tributary or Location	Units	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR †
			Month												
Exports	Colorado	MAF/mo	0.024	0.024	0.027	0.117	0.190	0.205	0.116	0.030	0.026	0.025	0.025	0.024	0.833
	Green	MAF/mo	0.010	0.010	0.011	0.020	0.084	0.091	0.050	0.023	0.016	0.014	0.011	0.011	0.351
	San Juan	MAF/mo	0.0	0.0	0.001	0.019	0.042	0.041	0.009	0.001	0.0	0.0	0.0	0.0	0.113
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Municipal Indus.	Colorado	MAF/mo	0.003	0.003	0.004	0.017	0.050	0.053	0.015	0.003	0.003	0.003	0.003	0.003	0.160
	Green	MAF/mo	0.020	0.016	0.024	0.052	0.029	0.042	0.015	0.003	0.001	0.037	0.029	0.014	0.282
	San Juan	MAF/mo	0.004	0.004	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.004	0.004	0.056
	San Raf.	MAF/mo	0.0	0.0	0.0	0.001	0.002	0.002	0.0	0.0	0.0	0.0	0.0	0.0	0.005
Irrigation consumptive use	Colorado	MAF/mo	0.0	0.0	0.0	0.055	0.488	0.380	0.163	0.0	0.0	0.0	0.0	0.0	1.086
	Green	MAF/mo	0.0	0.0	0.0	0.045	0.400	0.311	0.134	0.0	0.0	0.0	0.0	0.0	0.890
	San Juan	MAF/mo	0.0	0.0	0.0	0.040	0.357	0.278	0.119	0.0	0.0	0.0	0.0	0.0	0.794
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Irrigation return flow of dissolved solids	Colorado	MT/mo	*0.0*	*0.0*	*0.0*	*0.035*	*0.313*	*0.244*	*0.104*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.696*
	Green	MT/mo	*0.0*	*0.0*	*0.0*	*0.037*	*0.333*	*0.259*	*0.111*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.740*
	San Juan	MT/mo	*0.0*	*0.0*	*0.0*	*0.045*	*0.403*	*0.314*	*0.134*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.896*
	San Raf.	MT/mo	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Side inflow water	Above Lake Powell	MAF/mo	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.492
Side inflow TDS	Above Lake Powell	MT/mo	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.672*
Withdrawal	Lake Powell	MAF/mo	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.152
Side inflow water	Powell to Mead	MAF/mo	0.072	0.056	0.062	0.058	0.010	0.002	0.069	0.052	0.062	0.038	0.029	0.048	0.558
Side inflow TDS	Powell to Mead	MT/mo	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*2.004*
Withdrawal	Lake Mead	MAF/mo	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.262

Sources: Upper Colorado River Water Uses with Projected Depletions at Lee Ferry, USBR (undated, received Aug. 1971).
Ribbens, Richard W. and Wilson, Robert F., "Applications of a River Network Model to Water Quality Investigations for the Colorado River," USBR (Denver, Colorado; 1973), Tables IX and X.
Upper Colorado Region Comprehensive Framework Study (1971); Table 2, page 24.
USBR, Quality of Water: Colorado River Basin, Progress Report No. 5, (January, 1971), page 54.

* 1 MAF/yr = 1.233 km^3/yr; 1 MT/yr = 900 Gg/yr.

† Discrepancies between row totals and figures appearing in this column are due to rounding off of monthly values.

TABLE 5.8

Control Variable Values -- DPL #3 (5.5 MAF/yr)

(Standard type indicates flow of water in MAF/mo; script type indicates flow of salts in MT/mo)*

Item	Tributary or Location	Units	Month												YEAR†
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Exports	Colorado	MAF/mo	0.024	0.024	0.027	0.122	0.234	0.255	0.147	0.030	0.026	0.026	0.025	0.024	0.964
	Green	MAF/mo	0.024	0.024	0.025	0.038	0.140	0.136	0.077	0.037	0.030	0.028	0.025	0.025	0.609
	San Juan	MAF/mo	0.0	0.0	0.001	0.019	0.042	0.041	0.009	0.001	0.0	0.0	0.0	0.0	0.113
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Municipal Indus.	Colorado	MAF/mo	0.003	0.003	0.004	0.017	0.050	0.053	0.017	0.005	0.003	0.003	0.003	0.003	0.164
	Green	MAF/mo	0.037	0.033	0.041	0.069	0.046	0.059	0.032	0.020	0.018	0.054	0.046	0.031	0.486
	San Juan	MAF/mo	0.024	0.024	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.025	0.025	0.306
	San Raf.	MAF/mo	0.0	0.0	0.0	0.001	0.002	0.002	0.0	0.0	0.0	0.0	0.0	0.0	0.005
Irrigation consumptive use	Colorado	MAF/mo	0.0	0.0	0.0	0.055	0.488	0.380	0.163	0.0	0.0	0.0	0.0	0.0	1.086
	Green	MAF/mo	0.0	0.0	0.0	0.050	0.445	0.346	0.149	0.0	0.0	0.0	0.0	0.0	0.990
	San Juan	MAF/mo	0.0	0.0	0.0	0.040	0.357	0.278	0.119	0.0	0.0	0.0	0.0	0.0	0.794
	San Raf.	MAF/mo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Irrigation return flow of dissolved solids	Colorado	MT/mo	*0.0*	*0.0*	*0.0*	*0.035*	*0.313*	*0.244*	*0.104*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.696*
	Green	MT/mo	*0.0*	*0.0*	*0.0*	*0.042*	*0.370*	*0.288*	*0.124*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.824*
	San Juan	MT/mo	*0.0*	*0.0*	*0.0*	*0.045*	*0.403*	*0.314*	*0.134*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.896*
	San Raf.	MT/mo	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Side inflow water	Above Lake Powell	MAF/mo	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.492
Side inflow TDS	Above Lake Powell	MT/mo	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.056*	*0.672*
Withdrawal	Lake Powell	MAF/mo	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.156
Side inflow water	Powell to Mead	MAF/mo	0.071	0.054	0.058	0.054	0.0	0.0	0.057	0.046	0.058	0.036	0.027	0.047	0.508
Side inflow TDS	Powell to Mead	MT/mo	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*0.167*	*2.004*
Withdrawal	Lake Mead	MAF/mo	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.262

Sources: Upper Colorado River Water Uses with Projected Depletions at Lee Ferry, USBR (undated, received Aug. 1971).
Ribbens, Richard W. and Wilson, Robert F., "Applications of a River Network Model to Water Quality Investigations for the Colorado River," USBR (Denver, Colorado; 1973), Tables IX and X.
Upper Colorado Region Comprehensive Framework Study (1971); Table 2, page 24.
USBR, Quality of Water: Colorado River Basin, Progress Report No. 5, (January, 1971), page 54.

* 1 MAF/yr = 1/233 km^3/yr; 1 MT/yr = 900 Gg/yr.

† Discrepancies between row totals and figures appearing in this column are due to rounding off of monthly values.

TABLE 5.9

SUMMARY OF UPPER COLORADO RIVER BASIN DEPLETIONS (MAF/yr)*

Type of Use	Tributary Sub-Basin					Upper Basin Total	State				
	Colo.	Green	San Juan	San Raf.	Powell		Ariz.	Colo.	N. Mexico	Utah	Wyoming
1965-70 Base-Line Conditions †											
Exports	0.424	0.122	0.003	0.0	0.0	0.549	0.0	0.427	0.0	0.122	0.0
Municipal-Industrial	0.036	0.012	0.036	0.0	0.015	0.099	0.015	0.028	0.022	0.017	0.017
Irrigation	0.932	0.818	0.378	0.0	0.0	2.128	0.0	1.224	0.123	0.516	0.265
TOTALS	1.392	0.952	0.417	0.0	0.015	2.776	0.015	1.679	0.145	0.655	0.282
DPL#1 †											
Exports	0.701	0.304	0.113	0.0	0.0	1.118	0.0	0.704	0.110	0.288	0.016
Municipal-Industrial	0.084	0.162	0.056	0.005	0.050	0.357	0.050	0.088	0.042	0.030	0.147
Irrigation	0.936	0.818	0.658	0.0	0.0	2.412	0.0	1.238	0.393	0.516	0.265
TOTALS	1.721	1.284	0.827	0.005	0.050	3.887	0.050	2.030	0.545	0.834	0.428
DPL#2 †											
Exports	0.833	0.351	0.113	0.0	0.0	1.297	0.0	0.876	0.110	0.288	0.023
Municipal-Industrial	0.160	0.282	0.056	0.005	0.152	0.654	0.050	0.164	0.042	0.141	0.258
Irrigation	1.086	0.890	0.794	0.0	0.0	2.770	0.0	1.551	0.393	0.561	0.265
TOTALS	2.079	1.523	0.963	0.005	0.152	4.722	0.050	2.591	0.545	0.990	0.546
DPL#3 †											
Exports	0.964	0.609	0.113	0.0	0.0	1.686	0.0	1.007	0.110	0.538	0.031
Municipal-Industrial	0.164	0.486	0.306	0.005	0.152	1.113	0.050	0.172	0.292	0.341	0.258
Irrigation	1.086	0.990	0.794	0.0	0.0	2.870	0.0	1.551	0.393	0.661	0.265
TOTALS	2.214	2.085	1.213	0.005	0.152	5.669	0.050	2.730	0.795	1.546	0.554

Sources: Upper Colorado River Water Uses with Projected Depletions at Lee Ferry, USBR (undated, received Aug. 1971).
Ribbens, Richard W. and Wilson, Robert F., "Applications of a River Network Model to Water Quality Investigations for the Colorado River," USBR (Denver, Colorado; 1973), Tables IX and X.
Upper Colorado Region Comprehensive Framework Study (1971); Table 2, page 24.
USBR, Quality of Water: Colorado River Basin, Progress Report No. 5, (January, 1971), page 54.

* 1 MAF/yr = 1.233 km^3/yr; 1 MT/yr = 900 Gg/yr.

† Upper Basin total depletions are not equal to the values given at the top of Tables 5.5 to 5.8 due to round-off and the inclusion of depletions affecting side inflows below Lake Powell.

5.5.1.2 Municipal and Industrial Depletions

Base-line values for annual municipal and industrial depletions are obtained from the Comprehensive Framework Study (1971; Table 2, page 24) and from the USBR (1971b).

Annual values are distributed uniformly over the months of the year.

5.5.1.3 Irrigation Consumptive Use

Depletions for irrigated agriculture are modeled in terms of the volume consumed through crop evapotranspiration. In practice, an amount of water is diverted to the area being irrigated and the portion of the water not consumed either enters the ground water system by deep percolation or returns to the stream as surface or subsurface flow (Hyatt et al., 1970; Ch. IV). Eventually all of the water not consumed returns to river channel to become either surface or subsurface streamflow. Lag-times for return flows may be on the order of hours for surface return flows or years for ground water flows, and depend upon the distance of the irrigated lands from the river channel.

By modeling only irrigation depletions, an assumption is made that return flows occur within the basic time period of one month. Since most of the irrigated acreage in the Upper Colorado Basin is adjacent to the stream channel from which depeltions are made this assumption is justified, at least to first order.

For all levels of depletion, annual agricultural consumption is distributed over the months of the growing season, April through July, in the percentages specified in Table 2.1 (see Chapter 2).

Base-line irrigation depletions are taken from the Comprehensive Framework Study (1971; Table 5, p. 57). Higher levels of irrigation depletions are taken from Ribbens and Wilson (1973; Table X).

5.5.1.4 Total Dissolved Solids Loading from Irrigation Return Flows

As described in Section 5.2.2, increases in total dissolved solids loading due to irrigation return flows are modeled as a function of the acreage irrigated. Further, only return flows from irrigation above the base-line conditions must be considered, as stated in Section 3.3.2 and again in Section 5.2.2. Increases in irrigated acreage for each depletion level are obtained from Ribbens and Wilson (1973; Table X).

5.5.1.5 Side Inflows above Lake Powell

Ungauged side inflows of water and salt are modeled as constant monthly inputs to the river system. These inputs are treated as control variables so that adjustments for depletions and salinity control projects affecting these flows may be imposed.

The sources of information for base-line conditions have been given in Tables 5.1 and 5.2. As indicated in Section 5.3, modeled side inflows of salt have been adjusted upward to correct for the observed imbalance in Table 5.1(b).

Side inflows of water and salt above Lake Powell are displayed in Tables 5.5 to 5.8 for each level of depletion. Depletion levels DPL #1 to DPL #3 exhibit a side inflow of water greater than the base-line value due to water salvage in the Lake Powell area (Ribbens and Wilson, 1973; Table X).

5.5.1.6 Monthly Withdrawals from Lake Powell

At the present time water is withdrawn from Lake Powell for steam-electric power generation and other municipal and industrial uses near the reservoir. Eventually 0.15 MAF (0.18 km^3) will be withdrawn annually, primarily for power production by the Navajo and Kaiparowitz generating stations.

5.5.1.7 Side Inflows Between Lakes Powell and Mead

Base-line values of side inflows of water and total dissolved solids are obtained from the sources given in Tables 5.1 and 5.2. The Dixie Project in southwestern Utah is the only project whose depletions will significantly affect side inflows of water to this reach of the river. This project will divert water from the Virgin River, a tributary which flows directly into Lake Mead. Monthly depletions are modeled using information provided by Ribbens and Wilson (1973; Table X).

Monthly side inflows of total dissolved solids have been given non-zero values even for months in which side inflows of water decrease to nearly zero. The non-zero contribution of salts is maintained because the sources of TDS are predominantly low volume steady discharges from highly saline springs (USBR, 1971a; page 32).

5.5.1.8 Monthly Withdrawals From Lake Mead

Net withdrawals by the state of Nevada from Lake Mead for municipal and industrial use in the Las Vegas and Boulder City areas presently total approximately 0.02 MAF/yr (0.03 km^3/yr). Higher depletion levels are modeled using data from Ribbens and Wilson (1973; Table X).

5.5.1.9 Adjustments to Control Variable Values for Modeling the Effects of Salinity Control Projects

The reductions in salt loadings from each tributary or side inflow due to the implementation of anticipated salinity control projects are also modeled. These projects have been devised to control flows of salt from irrigated lands as well as from natural diffuse and point sources of dissolved solids (U.S.C., 1974; Colorado River Salinity Control Act, PL 93-320, Titles I and II).

The effects of the salinity control projects are modeled by altering the values of irrigation pick-up of salt and side inflows of salt as shown in Table 5.10. The quantities of salt removed by the projects are taken from EPA estimates (EPA, 1971; pages 9 to 10).

5.5.2 Reservoir Operating Parameters

The control variables, which together with the operating rule described in Section 5.2.3 determine the releases from each reservoir, are called reservoir operating parameters. These parameters are listed in Table 5.4, and consist of maximum and minimum allowed storages and target discharges for both Lakes Powell and Mead.

TABLE 5.10

Adjustments to Control Variable Values for Modeling the Impact of Salinity Control

Item	Tributary or Location	Units	Month												YEAR †
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Irrigation return flow of dissolved solids	Colorado	MT/mo	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036	-0.036	-0.432
	Green	MT/mo	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.204
Side inflow TDS	Powell to Mead	MT/mo	-0.042	-0.042	-0.042	-0.042	-0.042	-0.042	-0.042	-0.042	-0.042	-0.042	-0.042	-0.042	-0.504

Source: Location and annual salinity reductions taken from U.S. EPA, "The Mineral Water Quality Problem of the Colorado River Basin", (1971); pp. 9-10.
More recent estimates of salinity reductions taken from Weber, Ernest M., <u>et al.</u>, "Models Applied to Salinity Projection", paper presented at the Seminar on Colorado River Basin Modeling Studies, Utah State University, Logan, Utah, July 17, 1975; page 15.

* 1 MAF/yr = 1.233 km^3/yr; 1 MT/yr = 900 Gg/yr.
† Discrepancies between row totals and figures appearing in this column are due to rounding off of monthly values.

In addition, the initial storage of water and total dissolved solids (or the total dissolved solids concentration) must be specified at the beginning of each simulation run. These initial conditions are input as control variables although transient operation of the model is performed to insure that their values in no way affect the output of the model.

The value or range of values assigned to each of these control variables is discussed in the following sections and displayed in Table 5.11.

5.5.2.1 Lake Powell Operating Parameters

The minimum possible storage in Lake Powell is constrained to the volume of dead or inactive storage, as given in Table 4.1 and again in Table 5.11. The maximum storage allowed in Lake Powell has been varied between simulation runs as explained in the context of management investigations in Chapter 7. The upper value is limited by the design maximum storage, as indicated in the table.

The target discharge for Lake Powell is set equal to 8.23 MAF/yr (10.15 km^3/yr). This value is equal to the target discharge established by the 1970 Operating Criteria for Lake Powell (see Section 1.2.3). The Operating Criteria actually state that 8.25 MAF pass the 1922 Compact Point at Lee Ferry, Arizona each year. Since an average of 0.02 MAF enter the main river channel between Glen Canyon Dam and Lee Ferry, Arizona, the required discharge from Lake Powell is only 8.23 MAF/yr.

TABLE 5.11

Reservoir Operating Parameters

CONTROL VARIABLE	VALUE OR RANGE		COMMENTS
Lake Powell:			
Minimum storage	2.00 MAF	(2.47 km^3)	Dead or inactive storage
Maximum storage, SP_M	3.0-27.0 MAF	(3.7-33.3 km^3)	Up to design maximum
Target Discharge, D_t	8.23 MAF/yr	(10.15 km^3)	Operating criteria (see text)
Initial Storage	full		(arbitrary)
Initial TDS conc.	644 mg/ℓ		(arbitrary)
Lake Mead:			
Minimum storage	2.38 MAF	(2.93 km^3)	Dead or inactive storage
Maximum storage, SP_M	29.76 MAF	(36.69 km^3)	Design Maximum
Target Discharge, D_t	7.0-8.25 MAF/yr	(8.63-10.7 km^3/yr)	Brackets downstream demand
Initial Storage	full		(arbitrary)
Initial TDS conc.	690 mg/ℓ		(arbitrary)

The initial storage in Lake Powell is set equal to the maximum storage. The initial storage is arbitrary in the sense that adequate transient operation is performed to allow system response to become independent of initial conditions (see Section 6.1). For the same reason, the initial total dissolved solids concentration of Lake Powell water is arbitrary, and has been set to the average 1968 value.

5.5.2.2 Lake Mead Operating Parameters

The maximum and minimum storages of Lake Mead are set equal to the design values given in Table 4.1. This choice of values is discussed further in Section 7.2.2.

The target discharge from Lake Mead is set equal to the annual demand to be satisfied below Lake Mead. The Operating Criteria specify that under normal conditions, following the completion of the Central Arizona Project, releases and withdrawals from Lake Mead will be sufficient to satisfy a consumptive use of 7.5 MAF/yr in the Lower Basin and the Mexican treaty obligation of 1.5 MAF/yr.

While the Lower Basin states are allowed to consume more than their legal allotment when surplus water exists, they will eventually be constrained to the consumptive use of only 7.5 MAF/yr (9.2 km^3/yr). In the future, therefore, the Lower Basin depletions below Lake Mead and the commitment to Mexico of 1.5 MAF/yr will require a total release from Lake Mead of 7.0 MAF/yr (8.6 km^3/yr) (Ribbens and Wilson, 1973; Tables IX and X).

For the simulations presented in Chapters 6 and 7 a target discharge of 8.25 MAF/yr (10.17 km^3/yr) was imposed upon Lake Mead. This value was chosen so that the capabilities of Lakes Powell and Mead in meeting equal target discharges might be compared. Simulations were also performed using a Lake Mead target discharge of 7.0 MAF/yr, the long range demand below Lake Mead.

The values of initial Lake Mead storage and total dissolved solids concentration are set as they were for Lake Powell, and are given in Table 5.11.

CHAPTER 6

MODEL TESTING AND STABILITY OF SYSTEM RESPONSE

Several sets of simulations were made to determine information necessary for subsequent studies and to examine the nature of the system. For the purpose of obtaining stationary distributions for system variables it was necessary to estimate the transient time required for system response to become independent of initial conditions. Transients in system response result if initial conditions are atypical of operating conditions. The number of years for which the system is observed, the simulation time, was also determined. To obtain meaningful results it is necessary for the simulation time to be long enough so that the stable or steady-state response of the system is reached; in other words, further observation provides no new information regarding system performance.

Additional trial simulations were made to determine the effects of modeling changes in bank storage.

6.1 Transient Time Determination

The time required to fill a reservoir under average inflow and discharge conditions is one measure of the transient time of a single reservoir system. For example, at the highest level of stream depletions given in Table 5.10, the average inflow to Lake Powell is $\overline{I}$ = 8.4 MAF/yr (10.4 km^3/yr). At a target discharge D_t = 8.25 MAF/yr (10.2 km^3/yr) the time required to fill the 27 MAF reservoir can be estimated as

$$(6.1) \qquad \frac{S}{\overline{I} - D_t} = \frac{27}{8.4 - 8.25} = 180 \text{ years}$$

Because reservoir discharge, evaporation, discharge TDS concentration, and hydropower generating capacity all depend upon reservoir storage, only reservoir storage was examined in determining a transient time for model operations.

Using identical streamflow sequences and imposing the highest level of stream depletions, two simulations of 200 years of observations were made. In the first simulation the initial storages of both Lake Powell and Lake Mead were set to their maximum values. In the second simulation both reservoirs were given zero initial storage. The transient time of the system was taken to be the number of years of simulation required for the reservoir storages of the two runs to coincide.

It was found that the time sequences of Lake Powell storage coincided after approximately 65 years. Roughly 125 years were required for the sequences of Lake Mead storage to coincide.

A transient time of 150 years was used in all subsequent simulations.

The long transient times observed are important in the context of Colorado River Basin management. The result shows that substantial periods of time are required for reservoir storage to recover from severe drawdown, barring curtailment of either upstream or downstream depletions.

6.2 Determination of Simulation Time and Stability of System Response

The simulation time is the number of years for which the system is observed. It is desired that there be a sufficient number of observations to provide stable estimates of system response.

A common practice for obtaining stable measurements of system response from simulation studies is to make several simulations and treat them as replications of a single experiment. Analyzing the results from several runs may indicate convergence and provide estimates of average response and variance of response (Emshoff and Sisson, 1970; Mize and Cox, 1968). The length of each simulation and the number of simulations required for a given degree of convergence determine the efficiency and feasibility of this approach. No standard technique for determining either the length or number of simulations presently exists, and their determination has been labeled an art (Mize and Cox, 1968).

Factors affecting the total length of simulation required to obtain convergence of system response are (1) the variability of the stochastic inputs to the model (Melentijevich, 1965); (2) the degree of dependency or autocorrelation between observations within a simulation run (Emshoff and Sisson, 1970); and (3) the degree of convergence desired.

In the context of hydrologic simulation, the variability in runoff sequences is generally high. Simulation length increases with the size of the reservoirs, or number of possible reservoir states, as shown by Vicens and Schaake, (1972). Reservoir size in this sense is taken relative to average inflow, simulation time increasing as average inflow decreases. For simulations of the type used in this study the stochastic inputs are autocorrelated and the state of the system (reservoir storage) is dependent upon the state of the system in previous time periods, both factors contributing to long simulation times. Finally, convergence of the extremes of distributions requires longer simulations than for convergence of the first and second moments. Each of these factors <u>increases</u> the total simulation times required for stabilization of the response of hydrologic systems.

Other factors <u>limit</u> the practical length or number of simulation runs. Computer costs may be prohibitive in some cases. A more important issue with respect to design decisions has to do with the quality of information obtained from long simulations. Yevjevich (1972a; p. 144) cautions that generation of long sequences of hydrologic data does not serve to increase the amount of information contained in the original data sample. Aside from presentations of statistical techniques for establishing confidence intervals of parameter estimates, the writer has found no discussion in the literature on hydrologic simulation relating the information content of the original data to the quality of simulation results.

Simulation estimates of average reservoir discharge and storage are used to examine the convergence of system response in Sections 6.2.1 and 6.2.2 respectively.

Another measure of system response was taken to be the probability of failure to meet target discharge. Stability of the distribution of reservoir discharge is explored in Section 6.2.3.

6.2.1 Examination of Mean Reservoir Discharge

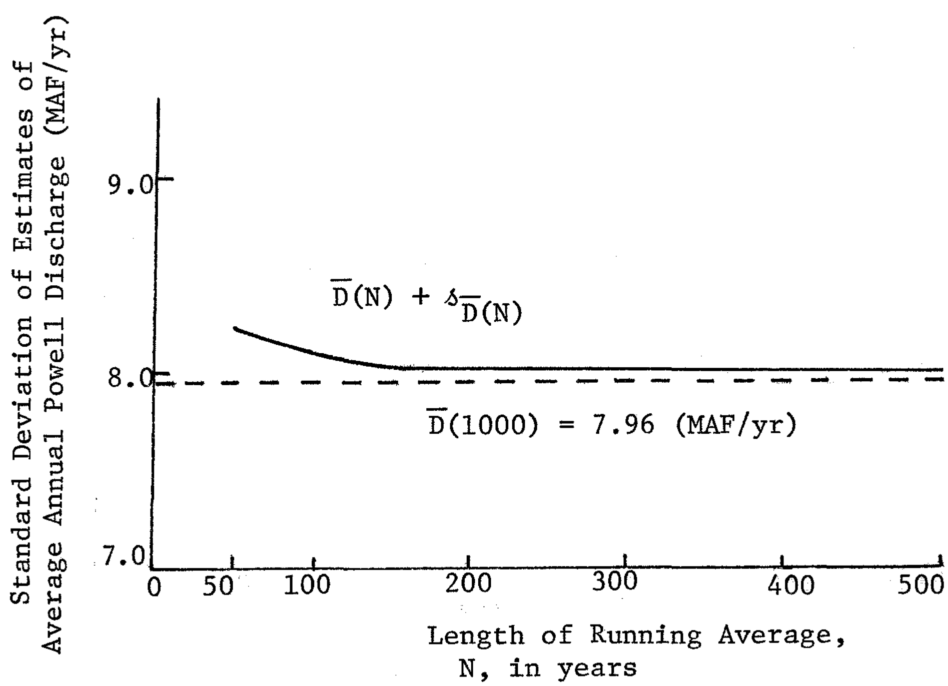
Simulations of increasing length (numbers of years) were made to examine the convergence of estimates of mean reservoir discharge. Simulations of equal length, but using different streamflow sequences, were made to examine the variability of mean response with changes in the stochastic inputs. Single simulations of 200 years of observation are shown to provide good estimates of mean reservoir discharge.

One simulation of 1000 years was performed to provide information on the convergence of estimates of average Lake Powell discharge. The highest level of stream depletions was imposed, lowering the average Lake Powell inflow to 8.4 MAF/yr (10.1 km^3/yr) and providing a worst case for the determination of simulation time. Running averages of annual discharge $\overline{D}(N)$ were formed using average times of N = 50, 100, 200, and 500 years. The standard deviations, $s_{\overline{D}(N)}$, of the N-year averages are used to examine convergence of the mean.

The decrease of $s_{\overline{D}(N)}$ with increasing N is shown in Figure 6.1. For an averaging period of 200 years the standard deviation, $s_{\overline{D}(200)}$, of the estimate of mean discharge is approximately 1% of the mean

FIGURE 6.1

The Variance of Estimates of Average Annual Powell Discharge
Versus Simulation Time



value. The rate at which the standard deviation decreases, or the rate of convergence is seen to be low for N greater than 200.

Also, the 90% confidence interval for annual discharge is $\pm$ 1% for a simulation of 200 years. Measurements of annual Powell discharge are reported accurate to within $\pm$ 5% (USGS, Water Supply Paper, 1973).

These results show that a simulation of 200 years yields a value for average annual discharge whose reliability lies within that of the model calibration data. Further refinement of the estimate of average discharge through increasingly longer simulations is slight for the reasons discussed above.

To investigate the sensitivity of mean Powell discharge to different streamflow sequences, ten streamflow sequences of 200 years were generated. Simulations at the lowest depletion level, DPL #1, and at maximum allowed Powell storage values of SP_M = 15 MAF and SP_M = 27 MAF were performed using each of the ten streamflow traces.

The variance in reservoir discharge decreases and the variance of storage increases as the volume of the reservoir is increased. For this reason the case with SP_M = 15 MAF was used to examine the variability in mean discharge between simulations. The target discharge of Lake Powell was set to 8.23 MAF/yr (10.1 km^3/yr) in accordance with the value specified in Section 5.5.

The output from the ten simulations indicates that differences in estimates of average Lake Powell discharge could not be judged statistically significant (Figure 6.2). The simulations were treated as replications of a single experiment and their results combined.

FIGURE 6.2

Average Annual Lake Powell Discharge from Simulations Using Different Inflow Sequences (Maximum Allowed Powell Storage, SP_M = 15 MAF) (Target Discharge, D_t = 8.23 MAF/yr)

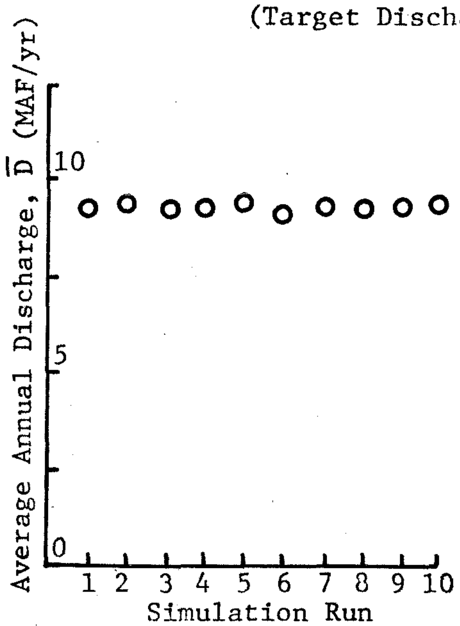
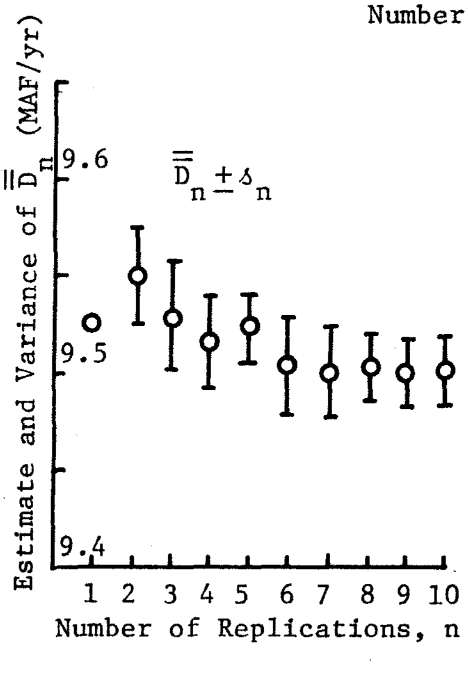


FIGURE 6.3

The Decrease in the Variability of Average Discharge Estimates with Increase in the Number of Replications



$$s_n^2 = \sum_{i=1}^{n} \frac{(\overline{\overline{D}}_n - \overline{D}_i)^2}{n(n-1)},$$

where n = the number of replications included in the estimate of $\overline{\overline{D}}_n$;

$\overline{\overline{D}}_n$ = the average discharge over n replications; and

$\overline{D}_i$ = the average discharge from the i^{th} replication.

(Emshoff and Sisson, 1970; p. 200).

As the number of replications, n, is increased, the variability of δ_n, of the estimate of average discharge $\bar{\bar{D}}_{(N)}$, is seen to decrease slowly (Figure 6.3). The mean discharge, for the system control variables prescribed, appears to stabilize after seven replications have been included.

The same result would not necessarily be obtained from a single simulation of 1400 years. The storage conditions at the end of the first 200 years of simulation could affect reservoir behavior during the following 150 years, as shown in the preceding section. The results from treating seven independent 200 year simulations as replications would be expected from a single simulation of 2450 years. In this application, the advantage of using independent simulations is to insure that independent estimates of average discharge are obtained. However, since the values of the seven estimates are not significantly different, replication is of no value in the determination of average discharge.

A single simulation of 200 years is found to provide a good estimate of average reservoir discharge.

6.2.2 Examination of Mean Reservoir Storage

The sensitivity of estimates of average storage to different inflow sequences was also examined to see if stable response is obtained from one simulation of 200 years.

As stated in Section 6.2.1, storage variability increases with maximum reservoir storage. For this analysis the maximum allowed Lake Powell storage, SP_M, was set to SP_M = 27 MAF. Lake Powell storage exhibits higher variability than Lake Mead storage due to the unregulated nature of Powell inflows. The average Lake Powell storages from ten simulations using different streamflow sequences were examined.

The estimate of average storage from a single simulation of 200 years has a confidence interval of $\pm$ 1% of the average value. Averages from the remaining nine simulations are found to vary from run to run (Figure 6.4), and some of the differences may be judged statistically significant. The largest difference observed is 1.6 MAF or 7% of the average storage.

As before, the convergence of the estimate may be observed by treating the simulations as replications. Figure 6.5 shows that the value of the average, $\bar{\bar{S}}_n$, appears to converge after eight or nine replications. The variability of the estimate, s_n, is observed to decrease very little as the number of replications increases.

Estimates of average storage, like the estimates of average discharge, vary from run to run, but the differences are small and replication contributes little to the accuracy of the result.

6.2.3 Examination of the Lower Extremes of the Reservoir Discharge Distributions

An important reservoir management concern is the probability that the reservoir fails to meet target discharges, called simply reservoir failure. To determine this probability accurately it is necessary that the extremes of the probability distribution of discharge become stable or cease to change with increasing numbers of observations.

The legal imposition of reservoir discharge requirements and the development of water rights in the Colorado River Basin place great

FIGURE 6.4

Average Lake Powell Storage from Simulations
Using Different Inflow Sequences
(Maximum Allowed Powell Storage, SP_M = 15 MAF)
(Target Discharge, D_t = 8.23 MAF/yr)

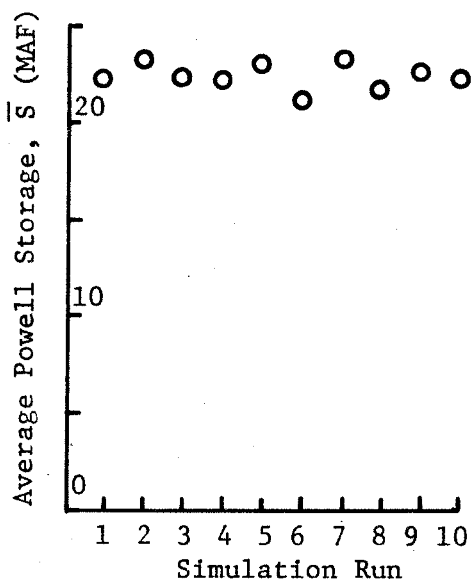
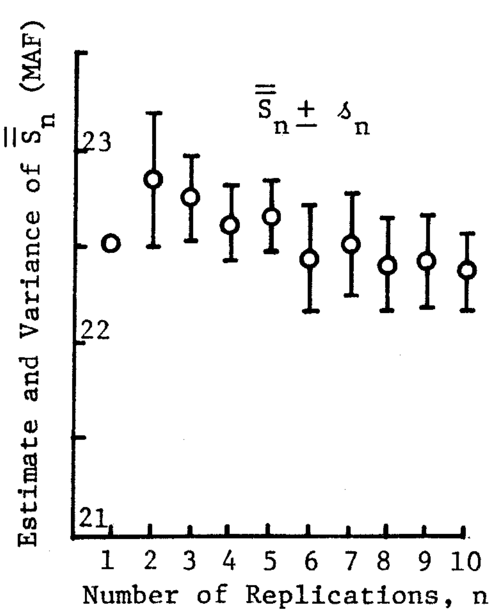


FIGURE 6.5

The Decrease in Variability of Average Storage
Estimates with Increase in the Number of
Replications



$$s_n^2 = \sum_{i=1}^{n} \frac{(\bar{\bar{S}}_n - \bar{S}_i)^2}{n(n-1)} ,$$

where n = the number of replications included in the estimate of $\bar{\bar{S}}_n$;

$\bar{\bar{S}}_n$ = the average storage over n replications; and

$\bar{S}_i$ = the average storage from the i^{th} replication.

(Emshoff and Sisson, 1970; p. 200).

importance on the reliability with which target demands can be met. As reported in Chapter 1, discharge requirements for Lake Powell have been expressed as annual and ten year average target discharges.

The simulation program produces tables and plots of the cumulative distributions of both the annual and ten year average discharges of Lakes Powell and Mead. From these plots the probability of failure to meet any given discharge can be read.

The ten simulations introduced in Section 6.2.1 were used to explore the stability of the discharge distribution. For visual clarity, only the distributions produced by four of the inflow sequences are displayed in Figures 6.6 to 6.9. The four distributions displayed include the cases of highest and lowest probabilities of reservoir failure, and two other cases chosen at random. Cumulative probabilities are displayed as the percentage of years for which discharge is less than or equal to a specified value.

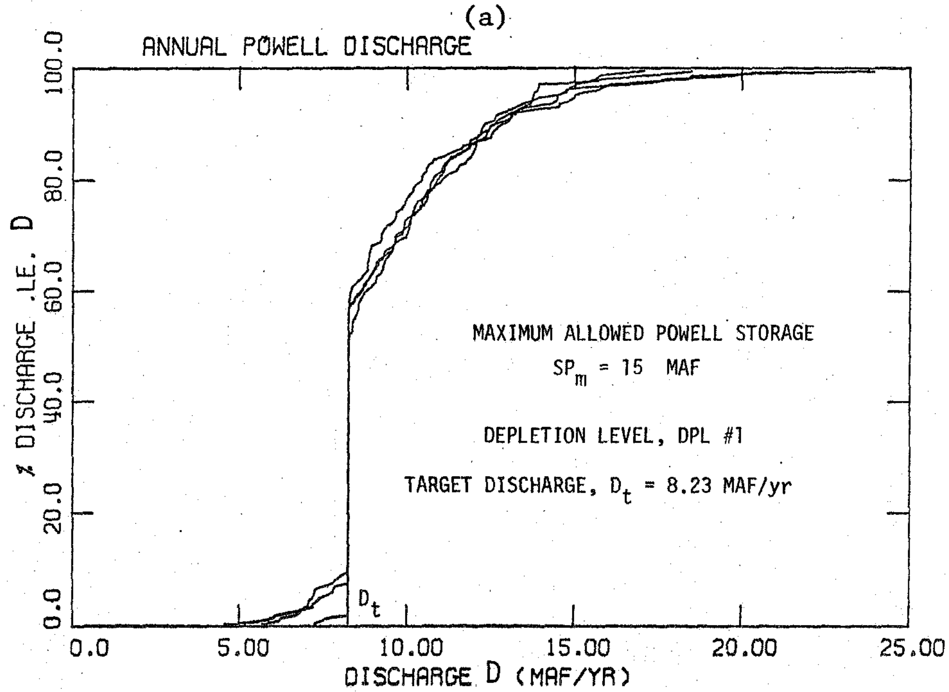
The distributions of annual discharge in Figures 6.6(a,b) and Figures 6.7(a,b) show that target discharge, D_t, is maintained for a large percentage of years. Discharges above the target indicate that additional releases were required to obey maximum storage constraints. Discharges below the target reflect incidents of reservoir failure, at which times storage is reduced to the minimum or dead storage value.

The differences between the distributions of annual discharge cannot be judged significant on the basis of a Kolmogorov-Smirnov cumulative distribution test (see Section 2.3.5). However Figure 6.6(a) displays a wide range of probabilities of Lake Powell failure. Failure to meet the target discharge of 8.23 MAF varies 0.0+ to 10% for the case

FIGURE 6.6(a,b)

Cumulative Distributions of Annual Powell and Mead Discharge for Four Inflow Sequences (SP_M=15)

(a)



(b)

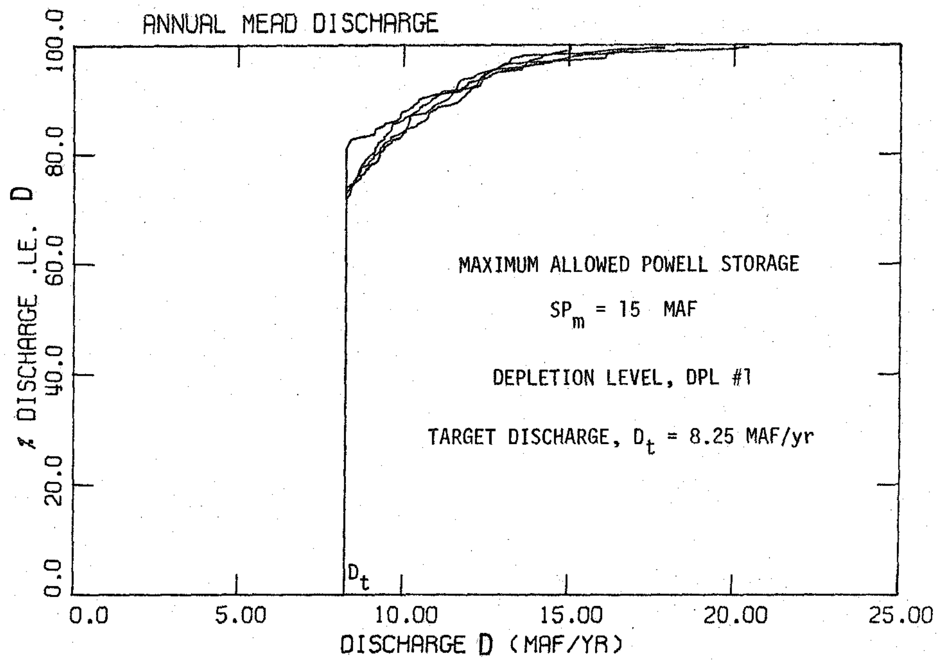
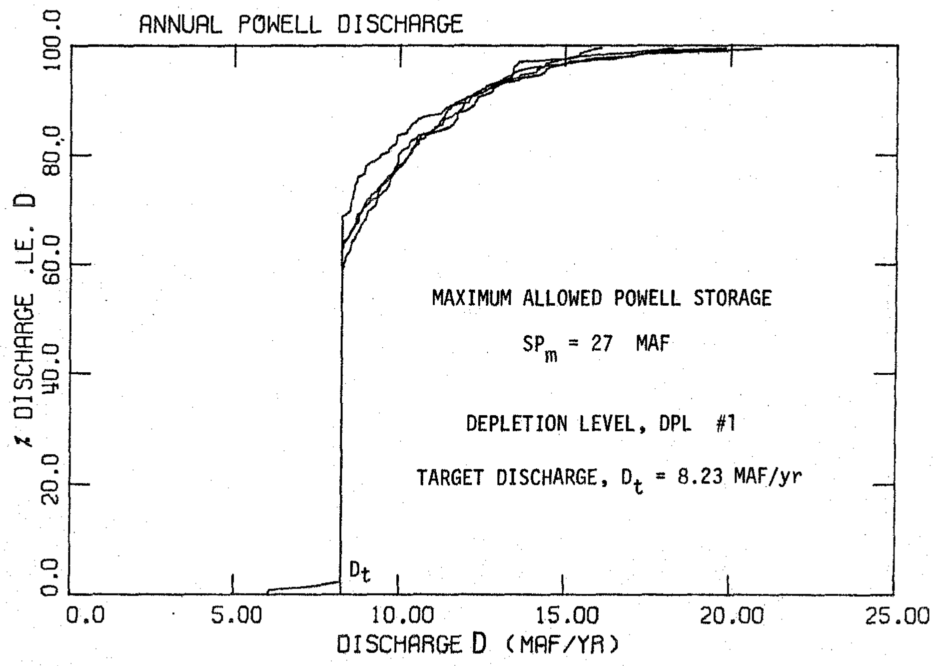
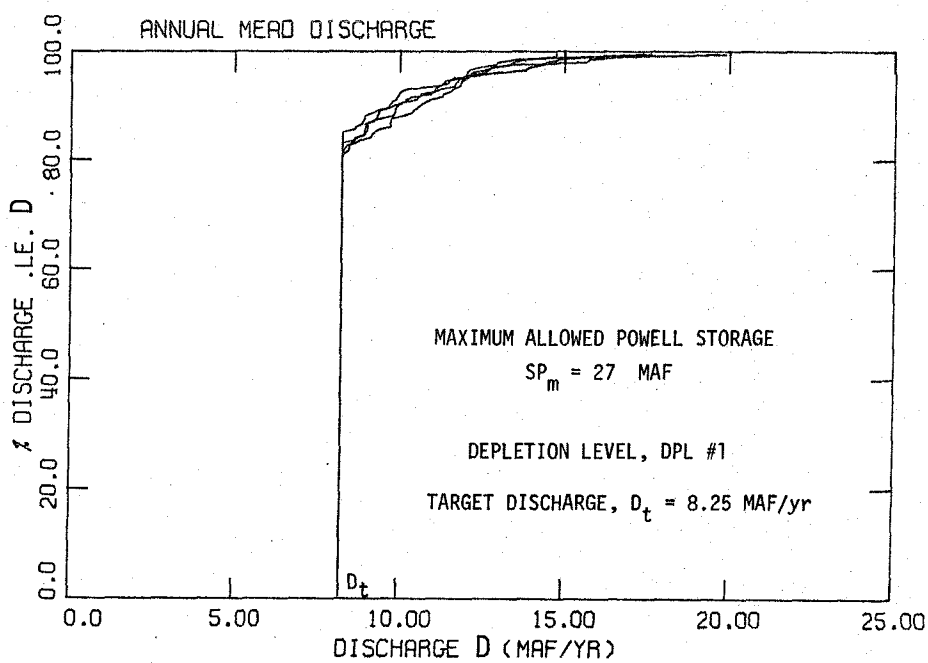


FIGURE 6.7(a,b)

Cumulative Distribution of Annual Powell and Mead Discharge for Four Inflow Sequences ($SP_M = 27$)





SP_M = 15 MAF (the notation of 0.0+ is used to indicate that no incidents of failure were observed in a given, 200 year simulation). The probability of failure to meet an annual Powell discharge of 7.5 MAF/yr ranges from $0.0\pm$ to 7.5% for SP_M = 15 (Figure 6.6(a) and from 0.0+ to 2% for SP_M = 27 (Figure 6.7(a)).

These differences, while not significant on the basis of the Kolmogorov-Smirnov test, would have a great effect upon decisions of design or operation of reservoirs. A simulation using one inflow sequence indicates that a maximum Powell storage of one-half the design value is sufficient to meet downstream demands with high reliability. Another simulation, whose inflow sequence is derived from the same data base as the first, indicates that such a reservoir operating policy will cause Powell to fail on the average of one year in every 10.

The distributions of annual Lake Mead discharge are seen to vary little from sequence to sequence (Figures 6.6(b) and 6.7(b)). Discrepancies occur in the region of excess discharge. Again, the differences are not statistically significant.

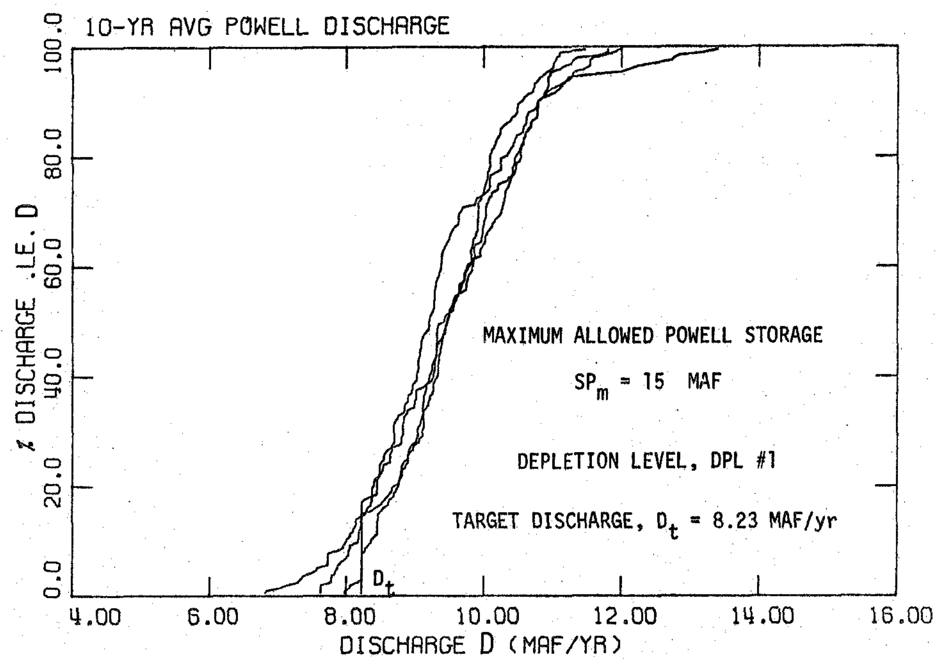
Cumulative distributions of the 10-year average discharge for both reservoirs exhibit large differences. Figures 6.8(a,b) show the distributions of the 10-year average discharge from both Powell and Mead for the case with SP_M = 15. The case with SP_M = 27 is shown in Figures 6.9(a,b). The graphs represent the percentage of simulated years for which the average discharge over the previous ten years is less or equal to some value, D.

For the case with SP_M = 15, large differences in probability of Powell failure are observed (Figure 6.8(a)). Failure to maintain

FIGURE 6.8(a,b)

Cumulative Distributions of 10-yr Average Annual Powell and Mead Discharge for Four Inflow Sequences (SP_M=15)

(a)



(b)

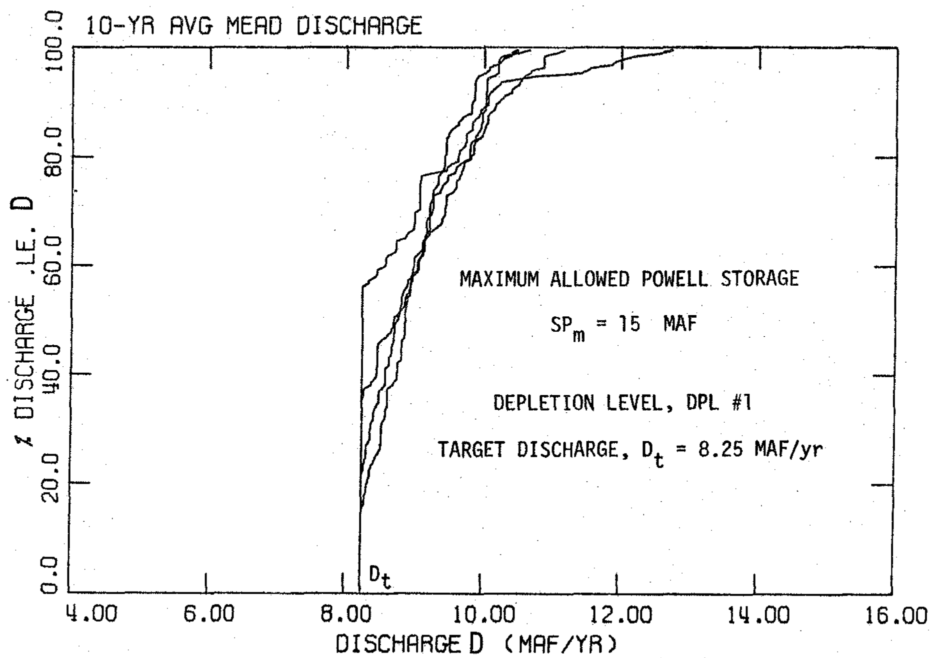
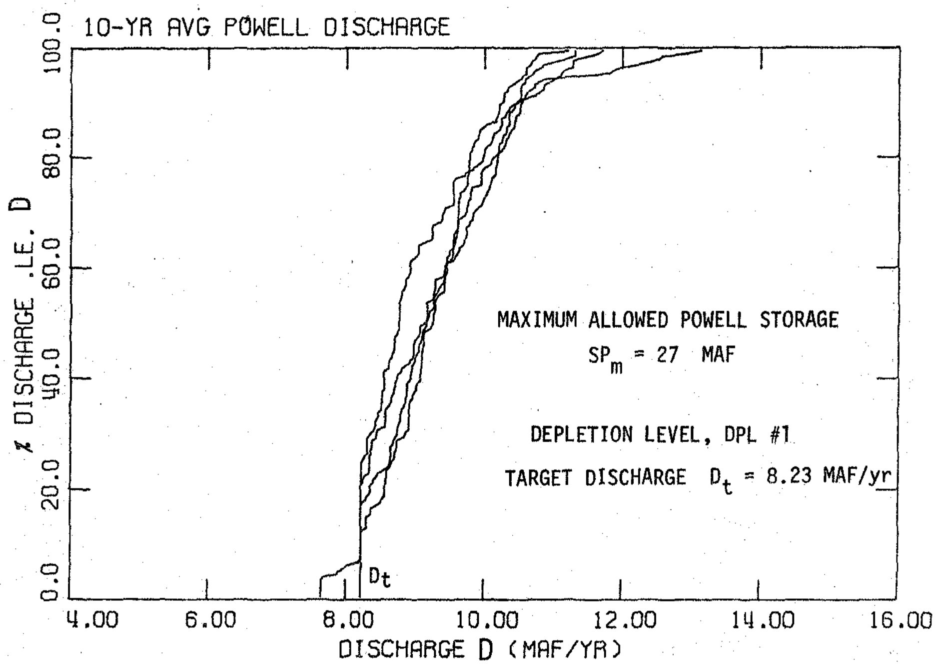


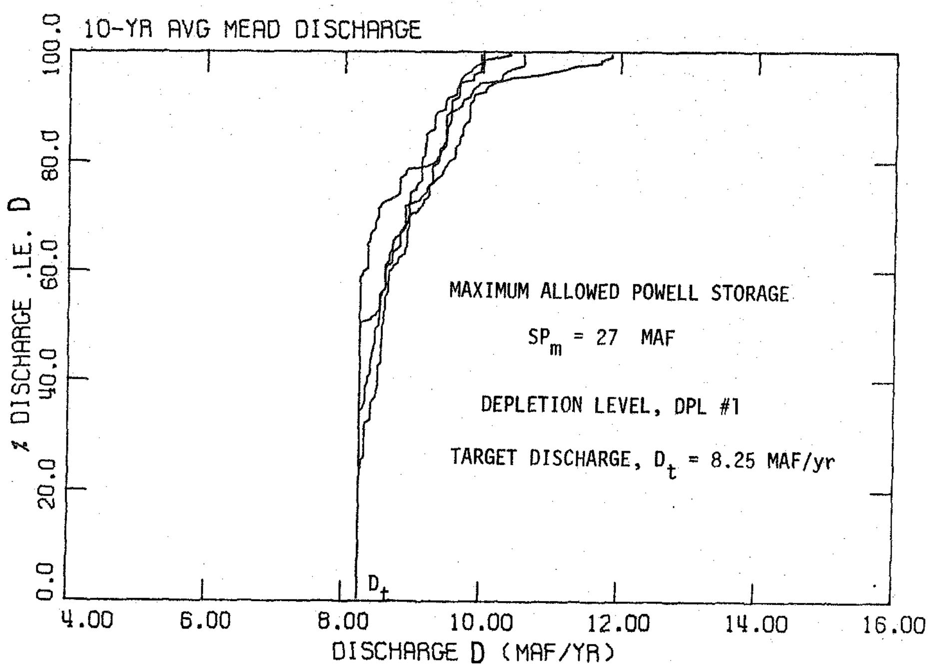
FIGURE 6.9(a,b)

Cumulative Distributions of 10-yr Average Annual Powell and Mead Discharge for Four Inflow Sequences (SP_M=27)

(a)



(b)



a 10-year average discharge equal to the target discharge ranges from 0.0+% in one simulation to 14.5% in another. Failure to meet the Compact required 10-year average discharge of 7.5 MAF/yr ranges from 0.0+ to 4.7%.

Discharges from Lake Mead for this case are seen to remain greater than or equal to the 8.25 MAF/yr target in all four simulations (Figure 6.8(b)). The probability of excess deliveries or spills from Mead varies considerably. The case with $SP_M = 27$ exhibits the same variability in response (Figure 6.9(a,b)).

The extremes of the discharge probability distributions are expected to converge toward stable values as the number of years of simulations is increased, subject to the inherent limitation of the finite data base. The output from ten, independent simulations was used to examine the characteristics of this convergence.

Data from each successive simulation is used to form the accumulated probability that annual reservoir discharge was less than a given amount, D. The same statistics were generated for the 10-year average discharges of D = 8.23 and 7.5 MAF/yr. The accumulated probability that discharge was less than or equal to D is plotted as the number of simulations included rises from one to ten.

From the figure it is difficult to determine whether the probability of failing to maintain a 10-year average discharge of 8.23 MAF (denoted by circles in the figure) continues to rise or has converged to a value near 0.07 (7% of years observed). The probability of failing to maintain a 10-year average discharge of 7.5 MAF/yr is low, but continues to vary between 0.0+ and 0.01 as more observations are included.

Figure 6.11 displays similar information on 10-year average Powell discharge when the maximum allowed Powell storage is increased to SP_M = 27 MAF. For this case the probability of failing to meet the specified discharge is lower, due to the greater storage provided. An increase in the probability of failure is observed following inclusion of the eighth simulation. In order to determine whether the extreme conditions encountered during that particular simulation were representative of conditions which could be expected in one out of every ten simulations, an additional ten simulations were performed using new streamflow sequences. None of the additional simulations produced the large number of failures observed in simulation number eight, above.

Figures 6.10 and 6.11 show that extreme points in the probability distribution of reservoir discharge fail to converge to clearly discernible values when 2000 observations (years) are included in their determination. The data presented in the figures are from simulations using the lowest value of upstream depletions. The probability of reservoir failure increases and the variability in the tails of these distributions increases as depletions increase.

6.2.4 Comments on the Presence of Variations in the Probability of Reservoir Failure

The simulation results presented in Section 6.2.3 display the difficulty encountered in attempting to determine the probability of reservoir failure. Because the values obtained depend upon the streamflow sequence used, the true probability of reservoir failure remains

FIGURE 6.10

Accumulated Probability of Lake Powell Failure as the Number of Simulations Increases (Maximum Allowed Powell Storage, SP_M = 15 MAF)

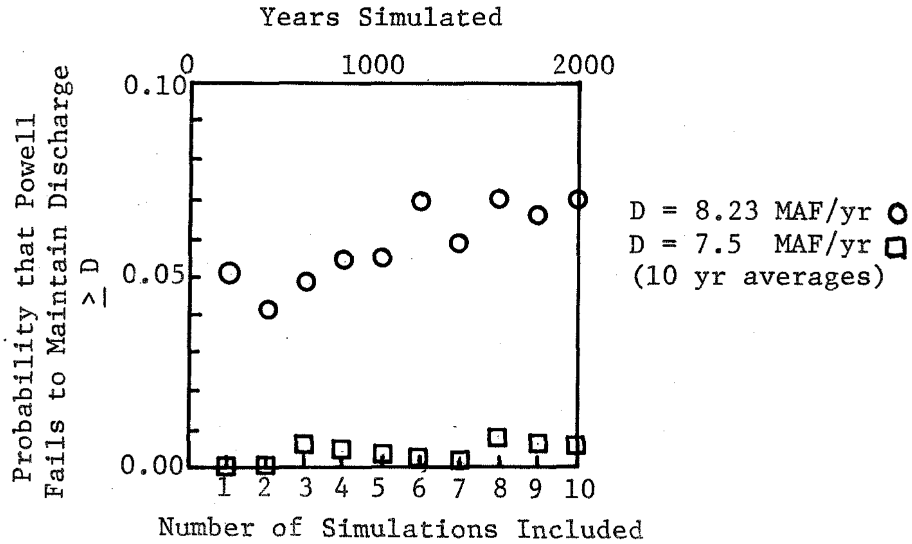
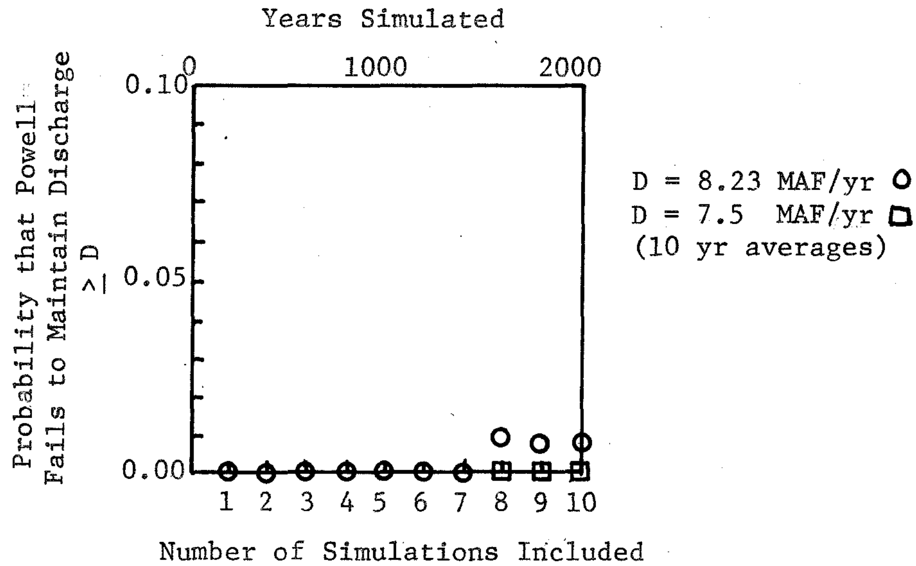


FIGURE 6.11

Accumulated Probability of Lake Powell Failure as the Number of Simulations Increases (Maximum Allowed Powell Storage, SP_M = 27 MAF)



uncertain. This uncertainty is important in that its presence increases the risks inherent in making management decisions.

The following questions may be posed: (1) how much of the observed variation in response is the result of properties of the hydrologic processes modeled, and how much is the result of a failure to model all relevant streamflow characteristics; (2) can the uncertainty in response be lessened through refinement of the model; and (3) given the uncertainty in response, how should the output of the model be interpreted and used in making management decisions?

The first and second questions concern the validity of the model and are discussed in this section. The third question involves model application and is addressed in Chapter 7.

The limited data base used for calibration introduces an inherent uncertainty into the values of all quantities examined with the model. This uncertainty can be decreased by recalibrating the existing model as more data become available. However, there are streamflow characteristics that are not necessarily reproduced by the synthetic streamflow generator used in the model. One suggestion for improving the streamflow generator is presented here.

An examination of the ten simulations performed with the model indicated that the variation in frequency of reservoir failure was related to the differences in patterns of years of high and low runoff. This observation suggests that information about naturally occurring patterns of high and low runoff might indicate modifications to the model that would provide more accurate determination of system response. For example, analyses of run-length (duration) and run-sum (severity) probabilities might provide useful information regarding streamflow patterns (Yevjevich, 1972a, b). Model modification could include the generation of streamflows using the fractional noise model, developed specifically with the idea of preserving streamflow pattern characteristics (Mandelbrot and Wallis, 1968). However, fractional noise models are still in a developmental stage (Jackson, 1975; p. 57). Analyses of runs probabilities and application of any streamflow model suffer from the limited quantity of data available.

The data base of 40 years used to calibrate the streamflow model can not provide information for modeling runoff patterns which might be expected to occur over the 300 year lifetimes of the reservoirs in the Colorado River system. In fact, the entire 80 years of runoff data from the Lees Ferry gauge has recently been shown to exhibit only a small portion of the variance which has been observed in long-term, tree-ring correlated runoff data (Stockton, 1975; Jacoby, 1975). Stockton reported that tree-ring reconstructions of annual runoff for the last 300 years reveal that the mean, variance, and serial correlation of Colorado River flows are slowly varying, non-cyclic functions of time.

In the absence of additional information on hydrologic processes in the Colorado River Basin, the uncertainty associated with the frequency of reservoir failure must be accepted as a property of the system. Extremely long simulations of five to ten thousand years might produce stable extremes of the discharge probability distributions. However, the probabilities so obtained would have no practical value. As mentioned in the introductory remarks to Section 6.2, extended simulation cannot serve to increase the information content of recorded data used for model calibration (Yevjevich, 1972a).

On the basis of the above arguments, the presentation of results given in Chapter 7 is based upon simulations employing a streamflow sequence of 350 years; 150 years of transient operation is performed, and statistical information is obtained from observations of the remaining 200 years of simulation. The utility of using a single streamflow sequence is discussed in the context of model application appearing in Chapter 7.

6.3 The Effects of Including Bank Storage

The importance of modeling bank storage changes in Lakes Powell and Mead was assessed. In one simulation bank storage changes were modeled according to Equations 4.1 and 4.2. Another simulation, identical in all other respects, was made in which changes in bank storage were always equal to zero. In the calculation of discharge dissolved solids concentrations, the reservoir mixing volume was taken to include the volume held in bank storage (after Hendrick, 1973). No in-bank sources or sinks of dissolved solids were modeled.

Differences in discharge, storage, evaporation, and concentration statistics for the two runs were not found to be statistically significant. Subsequent simulations are made with no accounting of bank storage changes.

6.4 Summary

Operation of the Colorado River system model from extreme initial reservoir storage conditions has indicated that system response is subject to transient behavior for periods as long as 150 years.

Reservoir storage and annual discharge data from a simulation of 1000 years are used to determine how many years of simulation are necessary to provide good estimates of average discharge and storage. Simulations of 200 years of observations are shown to provide stable average values. Ten simulations using different streamflow sequences of 200 years in length reveal small differences in average reservoir discharge and storage.

The lower extremes of the cumulative probability function (CDF) of reservoir discharge are used to determine the probability that a reservoir fails to deliver a specified discharge. The values toward the lower extremes of the discharge CDF differ from simulation to simulation for the ten streamflow sequences used. The observed differences are significant in the context of reservoir design.

A simulation length providing stable values of extreme discharge probabilities was sought by progressively combining the data from all ten simulations, thereby increasing the number of observations from 200 to 2000. Definitive results were not obtained. The differences in extreme discharge probabilities have been observed to correspond to differences in patterns of years having high and low runoff. A suggestion is made that additional hydrologic information might be used to indicate runoff patterns that would be unlikely to occur in the Colorado River Basin.

Additional tests of the model reveal that excluding bank storage changes from the model has no significant effect upon steady state system response.

CHAPTER 7

BASIN MANAGEMENT EXAMINATION: RESERVOIR OPERATION AND REQUIRED STORAGE

7.1 Introduction

This chapter presents the results of a management study performed using the simulation model. Also displayed is the value of the simulation method for examining the relationships between the many variables required to describe a complex water resource system.

7.1.1 The Management Policies Examined

The *existing management policy* referred to in this chapter is to utilize the full storage capacities of Lakes Powell and Mead in an attempt to satisfy current institutional constraints imposed on the system. This policy is examined and compared to the alternate policy defined below.

The *alternate policy* consists of providing a reliable supply of water sufficient to meet the water demands in the basin. As stated in Sections 1.2.4 and 1.3, the simulation model was used to determine the reservoir storage required to meet various levels of demand in the Upper and Lower Colorado River Basins.

Since the reservoirs being studied currently exist, these storage determinations are equivalent to determining whether all of the storage supplied by these facilities need be used. The required storage determinations were performed by simulating river basin operation for selected values of maximum reservoir storage. Simulation outputs were then examined to reveal whether or not the water demands were successfully maintained.

It will be shown that a wide range of Lake Powell and Lake Mead storage capacities are capable of satisfying the requirements of the alternate policy. In Section 7.4.2, a particular combination of reservoir storage capacities is selected as one example of alternative basin management. The simulation outputs corresponding to this particular management policy are compared to those of the existing policy in order to indicate the potential benefits of a change in management practices.

The streamflow depletion levels and target reservoir discharges imposed upon the system correspond to projected patterns of water use and are in accordance with established water rights to Colorado River water (see Section 5.5.1).

The target discharges corresponding to downstream water demands or institutional constraints are imposed as annual requirements. The ability of each reservoir to maintain target discharge was measured by reading from cumulative probability distributions of reservoir discharge the probability that discharge is less than the target. Because one institutional discharge requirement specified by the 1922 Compact is expressed in terms of the 10-year average discharge, the cumulative distributions of the 10-year average discharge were also examined (Section 5.4).

The other system outputs used to evaluate management configurations are the average storage, evaporation, power generating capacity and downstream TDS concentration for each reservoir and for the modeled system as a whole.

7.1.2 The Synthetic Streamflows Used and the Interpretation of Simulation Model Output

Tests of the simulation model revealed that the lower extremes of the probability distributions of reservoir discharge did not converge rapidly to stable values as the number of observations increased (Section 6.2.3). The uncertainty present in the distributions formed from a limited number of observations is important in the context of determining the probability of failing to meet specified reservoir discharges (reservoir failure). The question of how the model might still be used in making management decisions was posed.

First, the model has indicated the degree of uncertainty in the probability of reservoir failure. This result is important with regard to the use of the Bureau of Reclamation model and other models being used to study the Colorado River Basin. As mentioned in Section 2.3.1, the USBR model is a dynamic simulation model, each simulation run providing only one sample of system operation under given depletion and operating conditions. Many simulations are required to produce an estimate of average response or a distribution for response in a particular future year. The USBR model is calibrated with the data from the same period of record used in this study. The results obtained here suggest that large uncertainties in predicted system response should be expected and recognized.

In the study presented here simulations were made employing a single sequence of stochastic inputs. The discharge probability distributions produced were used to indicate relative changes in reservoir performance associated with changes in reservoir storage capacity and target discharge. The utility of this strategy has been demonstrated for instances where simulations using different sequences display variation in response (Conway, 1963).

Second, the results presented in Sections 6.2.1 and 6.2.2 show that statistically good measures of average system response (storage, evaporation, and so forth) are obtained from a single simulation of 200 years.

On the basis of these arguments and the material presented in Chapter 6, simulations employed a single streamflow sequence of 350 years; 150 years of transient operation were performed, and statistical information was obtained from the remaining 200 years of simulation. The streamflow sequence used was chosen at random from the set of ten sequences introduced in Chapter 6.

Section 7.2 contains a summary of the control variable values used in the study and a discussion of certain assumptions which affect the interpretation of model outputs. The output from the simulations performed is described in Section 7.3. Section 7.4 presents the management conclusions that can be drawn from the simulation results. A summary of the chapter appears as Section 7.5.

7.2 Summary of Control Variable Values and Pertinent Assumptions

The system control variables defined in Section 5.4 are (1) the level of streamflow depletions; (2) the minimum and maximum storages allowed in each reservoir; and (3) the target discharge from each reservoir. Only certain of these variables were altered in making the simulations presented. The control variables used are the streamflow depletion level (DPL), the maximum storage of Lake Powell (SP_M), and the target discharge from Lake Mead (D_t).

Values of these control variables were chosen to provide an informative range of system response. This strategy, known as selective simulation, is commonly used as a screening process when system response is dependent upon a continuum of values of several control variables (Buras, 1972; Linsley and Franzini, 1972). An alternative procedure would involve optimization with respect to one or more of the control variables. The latter procedure was not used in this study for two reasons. First, when optimization is based on the simulation outputs, gradient search methods must be used, requiring numerous simulation runs (Beard, 1967). Additional runs may be required to determine the nature of the optima obtained. Second, optimization generally proceeds in an economic context, requiring value estimates for water storage, water uses, power, recreation, salinity and flood damages, and so forth (for examples see Schweig and Cole, 1968; Monarchi et al., 1973; and Mejia et al., 1974). This type of analysis is considered beyond the scope of the present study.

The choice of control variables given and assumptions relevant to the interpretation of model output are discussed below. The control variable values used in this study are summarized in Table 7.1 (see Tables 5.5 to 5.11).

7.2.1 Streamflow Depletion Levels

The three depletion levels used in the study are those defined in Section 5.5. The water uses and the volumes consumed represent conditions which may be expected to occur in the basin at some time (Figure 5.5). The three levels of Upper Basin depletions are nearly equally spaced, as shown in Table 7.1, and create a range of average inflows to Lake Powell. The highest level, DPL #3, is the highest rate of consumption which the Upper Basin is expected to be able to attain, given a slightly higher average annual streamflow than that used in this study (Weber, 1975).

The depletion values given in Table 7.1 correspond to streamflow depletions upstream from Lake Powell. As explained in Section 5.5 each depletion level also specifies the magnitudes of reservoir withdrawals and ungauged side inflows.

Several assumptions regarding the adjustment of streamflows for depletions were stated in Section 5.2.1. To review, a worse case test of reservoir reliability is created by maintaining a constant depletion even in years of low flow.

There may be occasions when the streamflow in a given month is less than the depletion specified for that month. In these instances the entire streamflow is depleted. Other reservoirs in the Upper Basin, having a combined storage capacity of 6.7 MAF (8.3 km^3), are expected to supply any unsatisfied portion of the demand.

TABLE 7.1

Control Variable Values

Target discharges imposed on Lake Powell and Lake Mead, D_t

Powell	Mead
D_t = 8.23 MAF/yr (10.1 km^3/yr)	D_t = 8.25 MAF/yr (10.2 km^3/yr)
	D_t = 7.00 MAF/yr (8.6 km^3/yr)

Upper Basin depletion levels imposed, DPL*			**Average Depleted Inflow to Lake Powell, $\overline{I}_P$**	
DPL #1	3.8 MAF/yr	(4.7 km^3/yr)	9.9 MAF/yr	(12.2 km^3/yr)
DPL #2	4.6 MAF/yr	(5.7 km^3/yr)	9.2 MAF/yr	(11.3 km^3/yr)
DPL #3	5.5 MAF/yr	(6.8 km^3/yr)	8.4 MAF/yr	(10.4 km^3/yr)

Maximum allowed reservoir storages imposed on Lake Powell and Lake Mead SP_M, SM_M†

Powell	Mead
SP_M = 3 MAF (3.7 km^3)	SM_M = 29.76 MAF (36.7 km^3)
15 MAF (18 km^3)	
27 MAF (33 km^3)	

*Value represents depletions upstream of Lake Powell. Each depletion level also specifies reservoir withdrawals and magnitudes of side inflows (see Tables 5.5 to 5.8).

†Storage values represent total storage. Lake Powell dead, or inactive storage equals 2.00 MAF (2.47 km^3) and Lake Mead dead storage equals 2.38 MAF (2.93 km^3).

To model curtailment of upstream consumptive use in years when streamflows and reservoir storage are low (1) would require some economic means of deciding which uses to curtail and at what times of the year, and (2) would not constitute as rigorous a test of reservoir reliability.

7.2.2 Reservoir Operation and Operating Parameters

The changes in the probability of reservoir failure and other measures of system response were determined as a function of changes in maximum Lake Powell storage, SP_M. It is shown in Section 7.3 that the three values of SP_M given in Table 7.1 are adequate to establish the relationships between maximum allowed Lake Powell storage and system response.

The maximum allowed storage of Lake Mead is another control variable. This variable was not altered in this study since the Lake Mead area is more highly developed than the Lake Powell area in terms of recreational and other local acitivites. The installed hydroelectric power generating capacity of Hoover Dam is nearly 1½ times that of Glen Canyon Dam (Table 4.1). In performing these simulation studies it was considered desirable to sacrifice as little generating capacity as necessary when restricting maximum storages.

The control variable defined as target reservoir discharge is fixed for Lake Powell, in accordance with the existing Operating Criteria and the Lower Basin and Mexican water rights (Section 1.2.3). Target discharge for Lake Mead takes the values 7.00 MAF/yr (8.63 km^3/yr) and 8.25 MAF/yr (10.2 km^3/yr), which represent a range of possible demands downstream from Lake Mead (see Section 5.5.2.2).

Discharges from Lakes Powell and Mead are determined during simulation using the linear release rules described in Section 5.2.3. This release rule attempts to meet the specified target discharge whenever possible.

A technical concern related to reservoir operation involves the capacity of Glen Canyon Dam outlet structures. If maximum Lake Powell storage is to be constrained below the spillway level, it is necessary to be able to discharge all inflows through either the power penstocks or bypass structures. For the lowest imposed Upper Basin depletion level, the average June inflow to Powell, 2.37 MAF/mo, exceeds the capacity of these structures which is 2.35 MAF/mo (see Table 4.1).

This matter was addressed during the court battle to restrict the maximum storage of Lake Powell for the preservation of the Natural Bridge National Monument (Anderson and Perkins, 1973, p. 36). One solution proposed was to construct a lower spillway. A second suggestion was to increase discharge in months prior to high flows to provide storage below the restricted level for accommodating inflows in later months. The estimated cost of spillway modification was set at $50,000,000 (Anderson and Perkins, 1973).

In performing the simulations in this study it is tacitly assumed that any required discharge may be made, through modified spillway structures if necessary. The storage drawdown strategy requires forecasts of future flows and so could not be treated by the present form of the model.

The values of annual hydropower output produced by the model assume that the entire discharge passes the generating turbines. The values of hydroelectric power generating capacity and energy output are calculated assuming a load factor of 1.0.

7.3 Presentation of Simulation Output

This section describes the output of the simulations performed. To reiterate, in this study system response or performance is measured by (1) the probability with which Lakes Powell and Mead fail to maintain specified discharges; and (2) the average response defined by average reservoir storages, average annual evaporation, average power generating capacity, and annual average TDS concentrations.

The system response recorded from each of eighteen simulations is to be described. These simulations correspond to the eighteen combinations of the control variable values given in Table 7.1; three values of maximum allowed Powell storage, three levels of streamflow depletions, and two Lake Mead target discharges are imposed.

Some difficulty is encountered in attempting to describe the changes in several measures of system response with respect to changes in each control variable. The material is organized in the following manner: (1) Section 7.3.1 reports two general observations which were useful in determining the number of simulations to perform; (2) Section 7.3.2 describes how the probability distributions of reservoir discharge are affected by changes in each control variable; (3) Section 7.3.3 describes the changes in average storage, evaporation, and power generating capacity with respect to changes in each control variable; and

(4) Section 7.3.4 describes the changes in average TDS concentration resulting from changes in each control variable. In the latter three sections the control variables are varied in the order presented in Table 7.1. System response is examined as a function of maximum allowed Powell storage and then depletion level for one value of Lake Mead target discharge. The other value of target discharge is imposed and the examination repeated.

7.3.1 General Observations on Average System Response as a Function of Maximum Lake Powell Storage

To trace changes in average storage, evaporation, power capacity, and TDS concentrations as a function of maximum Powell storage, SP_M, it was necessary to determine how many different storage maxima should be imposed. Figures 7.8, 7.9, and 7.10 display these average quantities as a function of maximum Powell storage for each depletion level. For the lowest depletion level, DPL #1, averages are indicated for five different maximum Powell storages. The average outputs of Lake Powell (Figure 7.9), Lake Mead (Figure 7.9), and the Lake Powell plus Lake Mead totals (Figure 7.10) are seen to vary nearly linearly with SP_M (these figures appear in Section 7.3.3). Two exceptions are the power capacity and power output of Lake Powell. These quantities decrease rapidly as average storage drops below the storage at rated power head, 14.1 MAF (Table 4.1).

Because the break point of the power capacity curve is at approximately 15 MAF and because the other relationships are very nearly linear, only three values of maximum allowed Powell storage were used in subsequent simulations. The equally spaced values SP_M = 3, 15, and 27 MAF were used.

Weber has reported that the large amount of storage provided by Lakes Powell and Mead and the subsequent mixing of inflowing waters serve to remove monthly fluctuations in salinity apparent upstream of Lake Powell (Weber et al., 1975).

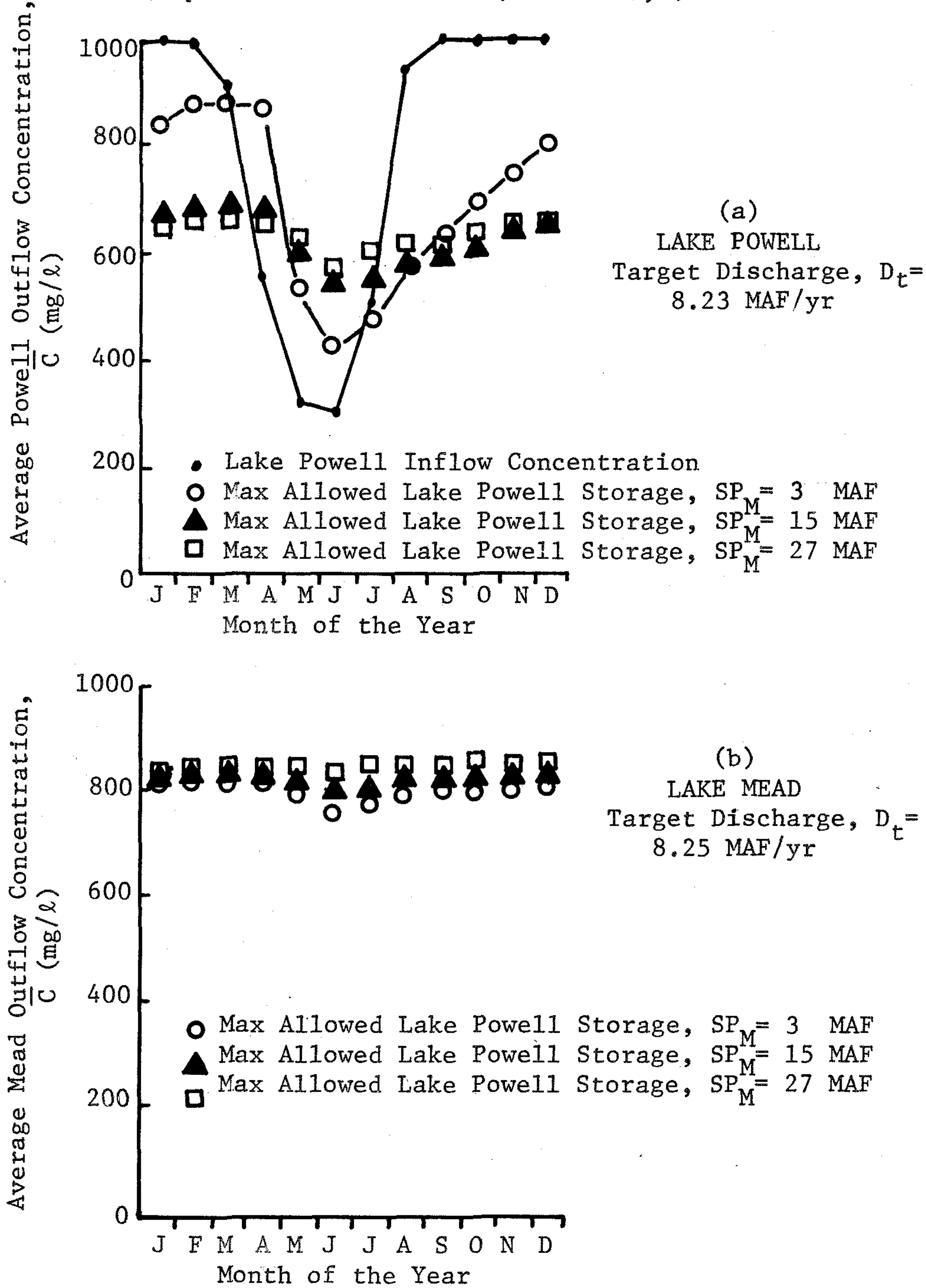
It is suspected that lower Powell storages could have a substantial effect upon downstream TDS concentrations. For this reason the effect of decreased Powell storage upon the mixing capability of the reservoir was examined. Figure 7.1 displays the average monthly TDS concentrations downstream from Lakes Powell and Mead for three values of maximum allowed Powell storage. Results are for the case with target Mead discharge equal to 8.25 MAF/yr and depletion level DPL #1.

It is observed that the mixing capability of Lake Powell is only slightly affected by constraining storage to 15 MAF. The only effect observed below Lake Mead is the decrease in concentration due to the decrease in total evaporation as SP_M is reduced. These simulation results are based upon the Lake Powell salinity model which assumes that the mass of total dissolved solids is conserved.

Including the effects of precipitation of salts during the summer months would cause slightly lower concentrations to be observed during those months. The effect of the precipitation of salts would only be significant for the values of SP_M above 15 MAF, as suggested by Figure 4.4. Again, the variation in monthly average TDS concentrations calculated below Lake Mead would remain small regardless of the value of SP_M.

FIGURE 7.1 (a,b)

The Effect of Restricting Maximum Allowed Lake Powell Storage Upon Downstream Dissolved Solids Concentrations (Depletion Level: DPL #1; 3.8 MAF/yr)



7.3.2 Reliability of Water Supply

The reliability of the water supply afforded by Lakes Powell and Mead was measured by the probabilities with which each reservoir failed to deliver specified discharges. Figures 7.2 (a, b) through 7.4 (a, b) display the cumulative distribution functions (C.D.F.) of annual discharge from Lakes Powell and Mead. Figures 7.5 (a, b) through 7.7 (a, b) display the cumulative distribution functions of 10-year average annual discharge for both reservoirs. Each figure shows, for one value of upstream depletions, the C.D.F. generated for each value of maximum Powell storage.

Only the results for Lake Powell target discharge $D_t = 8.23$ MAF/yr and Lake Mead target discharge $D_t = 8.25$ MAF/yr are shown. These results are discussed in Section 7.3.2.1. The results when Lake Mead target discharge is changed to $D_t = 7.0$ MAF/yr are discussed in Section 7.3.2.2.

Observations are made with regard to the probability of failing to maintain the specified target discharge and the 1922 Compact requirements of (1) 7.5 MAF/yr and (2) a 10-year average of 7.5 MAF/yr (see Section 1.2.3). Recalling the arguments presented in Section 7.1.2, the distributions shown are compared in a relative manner and the extremes of the distributions should not be considered to indicate an absolute measure of system performance.

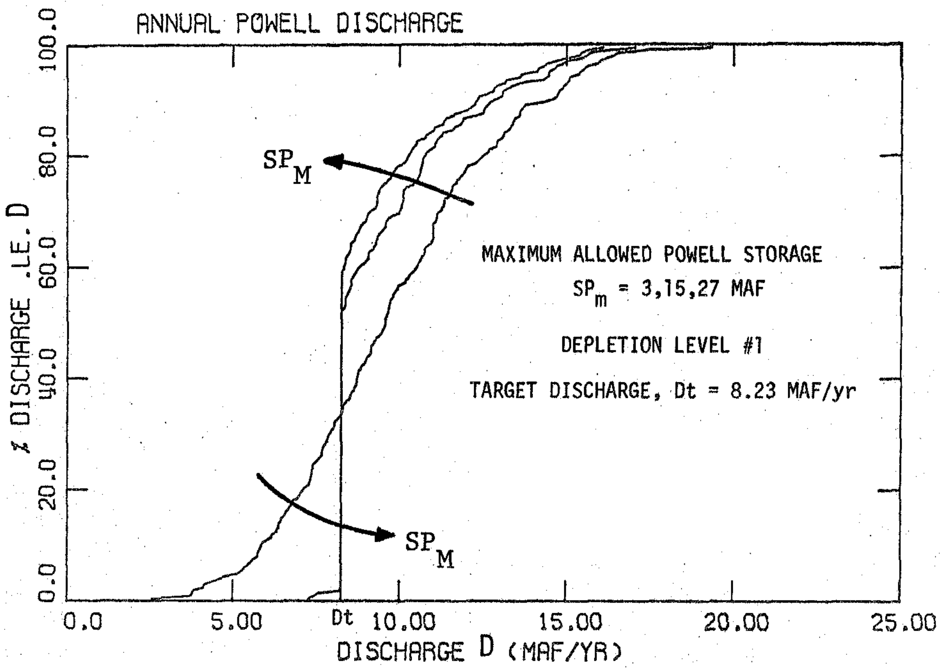
7.3.2.1 Lake Mead Target Discharge $D_t = 8.25$ MAF/yr

Figures 7.2 (a, b) to 7.4 (a, b) show the C.D.F.'s of annual Lake Powell and Lake Mead discharge for depletion levels 1, 2, and 3,

FIGURE 7.2(a,b)

Cumulative Distributions of Annual Powell and Mead Discharge as a Function of SP_M for DPL #1

(a)



(b)

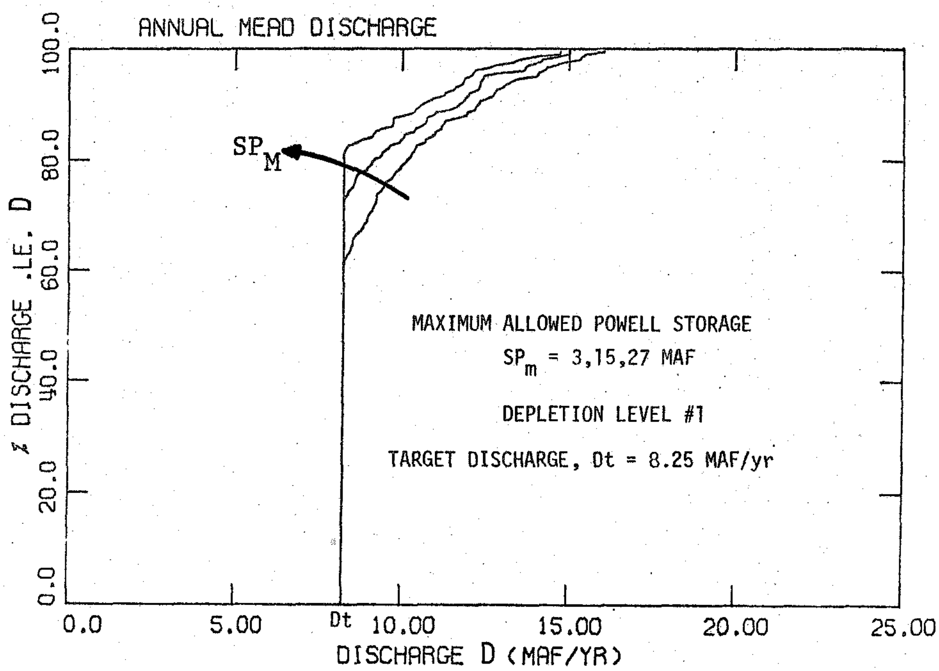
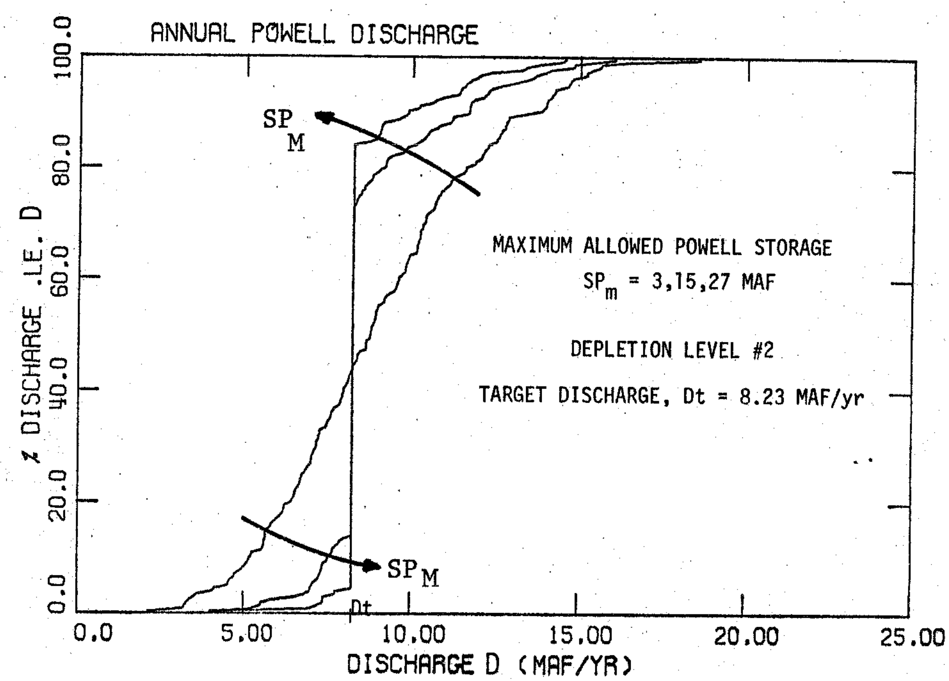


FIGURE 7.3(a,b)

Cumulative Distributions of Annual Powell and Mead Discharge as a Function of SP_M for DPL#2

(a)



(b)

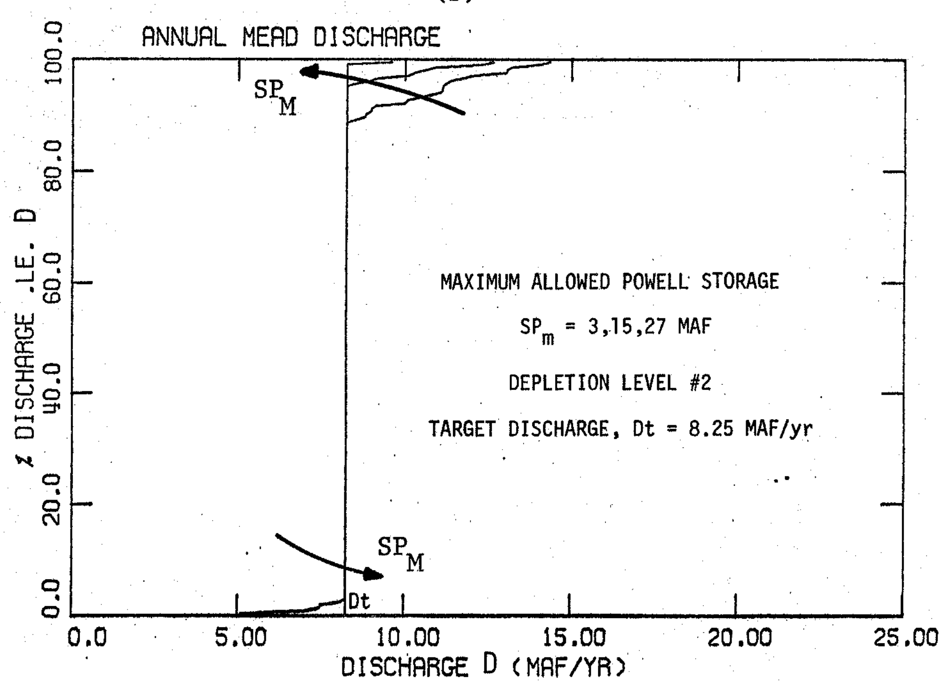
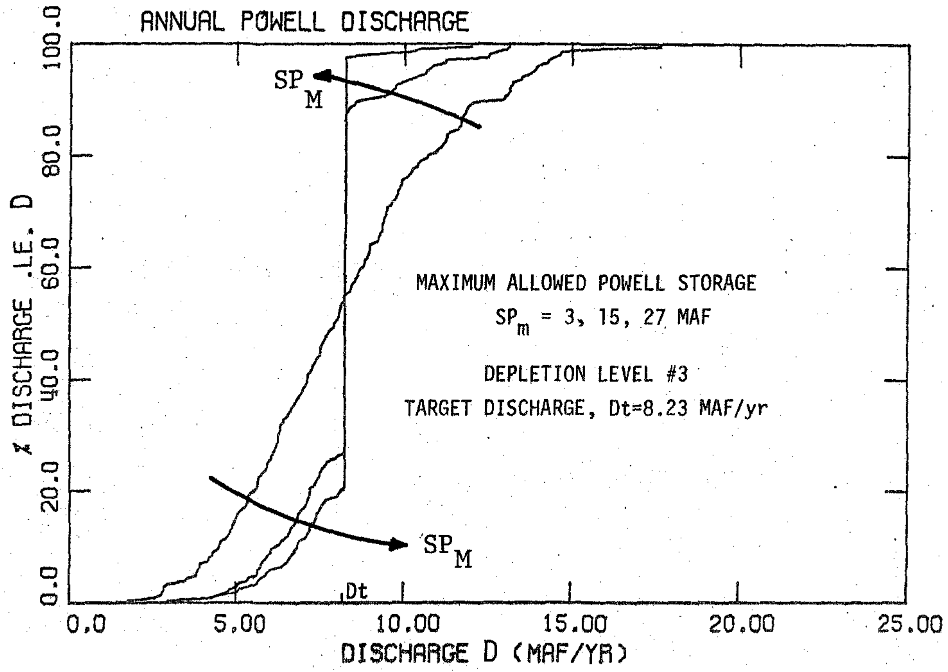


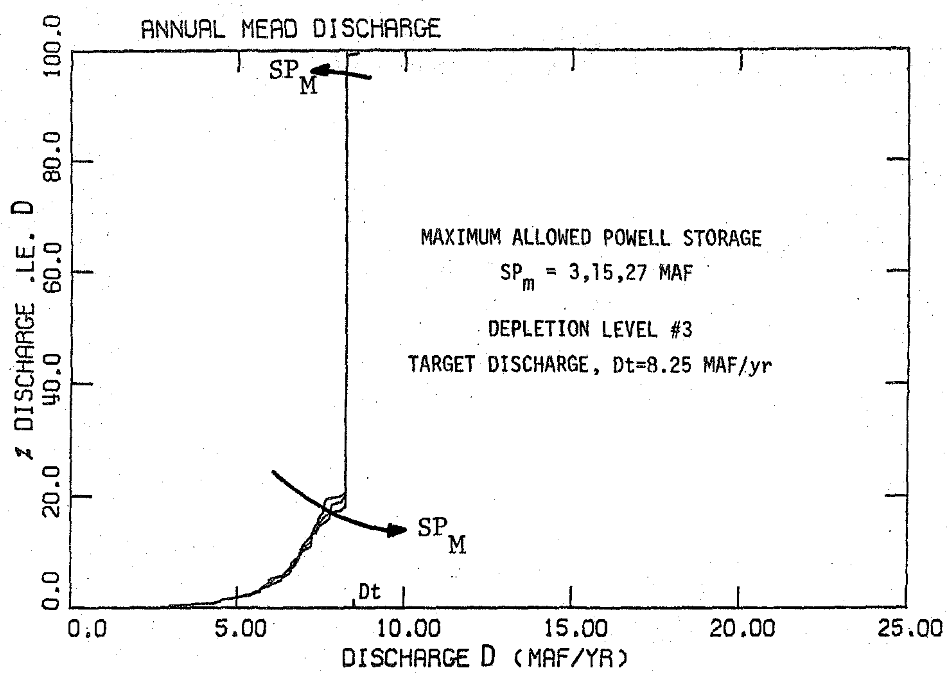
FIGURE 7.4(a,b)

Cumulative Distributions of Annual Powell and Mead Discharge as a Function of SP_M for DPL #3

(a)



(b)



respectively. The arrows in each figure show how the distributions change as maximum allowed Powell storage, SP_M, is increased. In each figure the vertical lines at discharge equal to the target discharge, D_t, indicate the percentage of years for which the target discharge was met exactly. Discharges greater than D_t indicate that additional discharges were required to meet maximum storage constraints. Discharges less than D_t indicate failure for the reservoir to supply D_t, and correspond to years in which the reservoir has emptied.

In general the percentage of discharges less than D_t for both reservoirs decreases as the maximum allowed Lake Powell storage, SP_M, is increased. The percentage of years in which excess discharges occurred also decreases as SP_M increases.

As the depletion level, DPL, increases, the probability (percentages of years) of reservoir failure increases (compare Figures 7.2 (a, b), 7.3 (a, b), and 7.4 (a, b) for a constant value of SP_M). The lower reservoir inflow associated with increased upstream depletions also results in a lower proability of excess discharge.

Figures 7.2 (a), 7.3 (a), and 7.4 (a) show that Lake Powell is only able to maintain the target discharge, D_t = 8.23 MAF/yr, at the lowest depletion level and with full storage capacity, SP_M = 27 MAF. The proability with which Lake Powell fails to deliver 7.5 MAF/yr can also be read in each figure. This discharge is always met at the lowest depletion level for SP_M = 15 and SP_M = 27 MAF. At the higher depletion levels the reservoir fails to provide 7.5 MAF/yr in some years.

Figures 7.2(b) and 7.3(b) show that for depletion levels 1 and 2, 3.8 and 4.7 MAF/yr, respectively, Lake Mead is capable of maintaining a target discharge of 8.25 MAF/yr when Lake Powell storage capacity is as low as SP_M = 15 MAF. At the highest depletion level, 5.5 MAF/yr, the reduced inflow to Lake Mead results in reservoir failure even when SP_M = 27 MAF (Figure 7.4(b)). As the depletion level is increased the probability of excess discharges also decreases. Almost no excess Lake Mead discharges occur at the highest depletion level, signifying that the reservoir rarely fills completely.

Figures 7.5(a, b), 7.6(a, b), and 7.7(a, b) are similar to those above except that they show the C.D.F.'s of 10-year average discharges from both reservoirs. The behavior of these curves with respect to changes in SP_M or depletion level is similar to that observed in the previous figures.

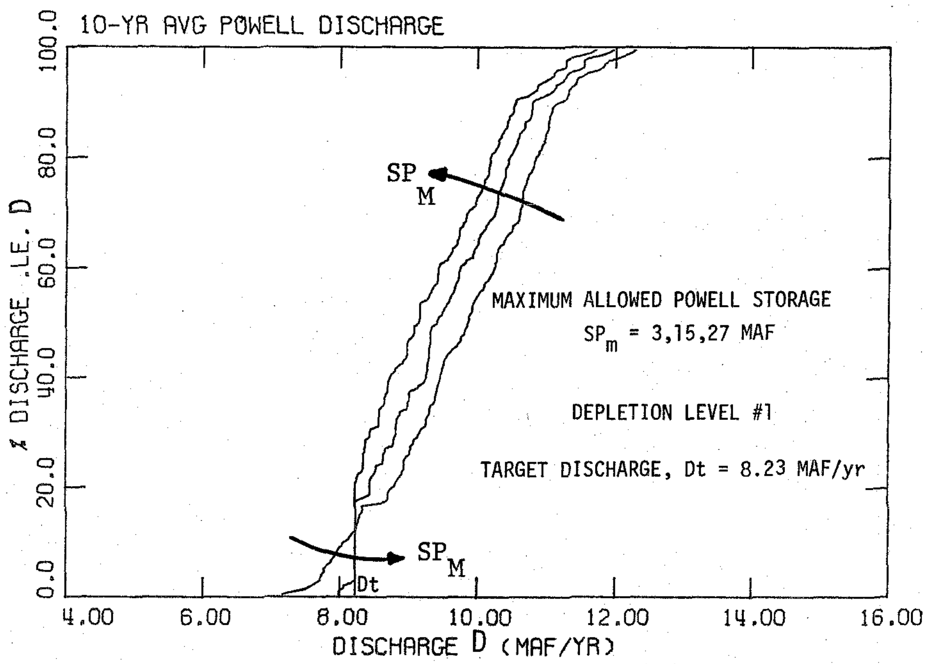
For the lowest depletion level Lake Powell is able to maintain a 10-year average discharge of 7.5 MAF/yr, the 1922 Compact requirement with a storage capacity as low as SP_M = 15 MAF. For the second level of depletions the reservoir meets the requirement when SP_M = 27 MAF, but fails roughly 7 percent of the time when SP_M = 15 MAF. For the highest level of depletions, 5.5 MAF/yr, the Compact requirement is not maintained by Lake Powell for some number of years at each of the storage capacities imposed.

By comparison, Lake Mead is able to maintain a 10-year average discharge of 7.5 MAF/yr at both the first and second depletion levels, even if Lake Powell storage is constrained to only 3 MAF (approximately zero <u>active</u> storage). At the highest depletion level this 10-year average

FIGURE 7.5(a,b)

Cumulative Distributions of 10-yr Average Annual Powell and Mead Discharge as a Function of SP_M for DPL #1

(a)



(b)

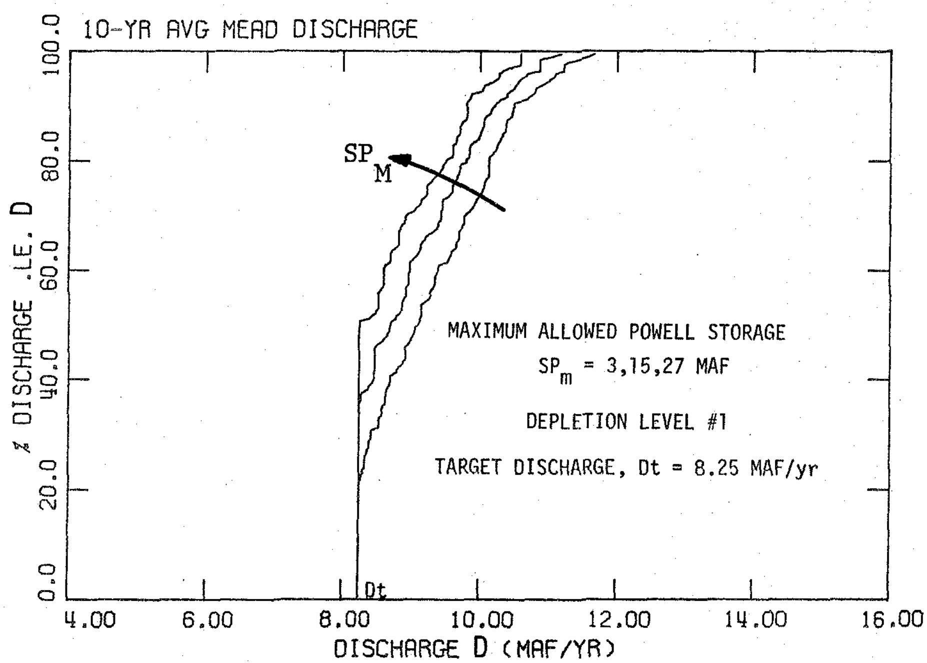
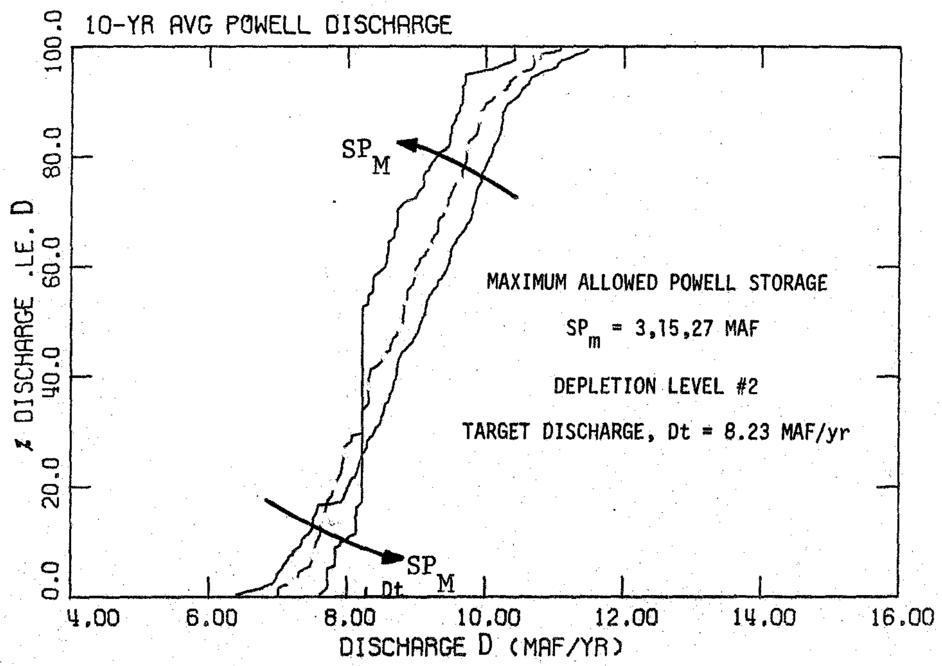


FIGURE 7.6(a,b)

Cumulative Distributions of 10-yr Average Annual Powell and Mead Discharge as a Function of SP_M for DPL #2

(a)



(b)

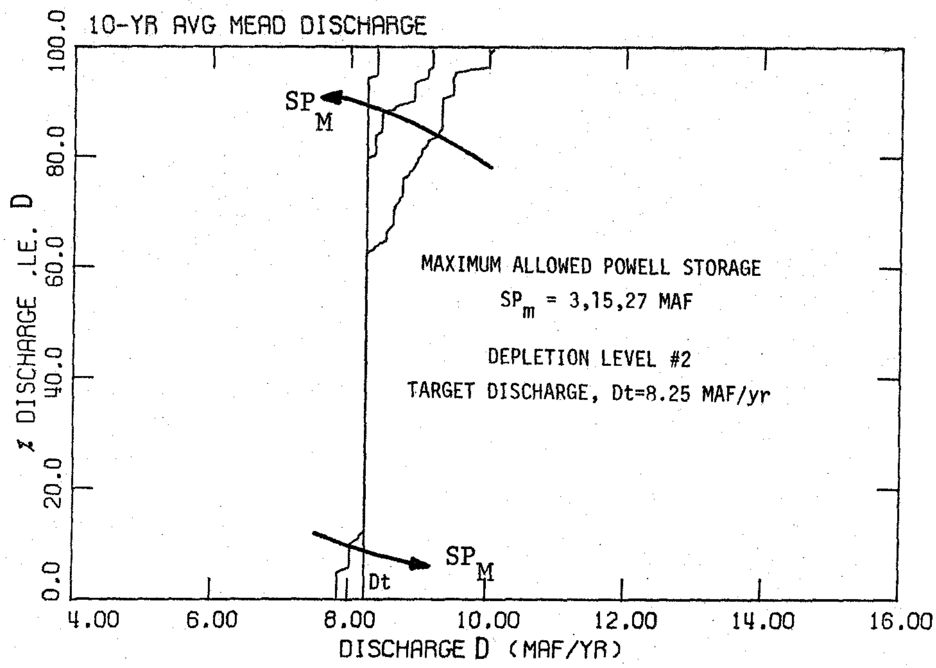
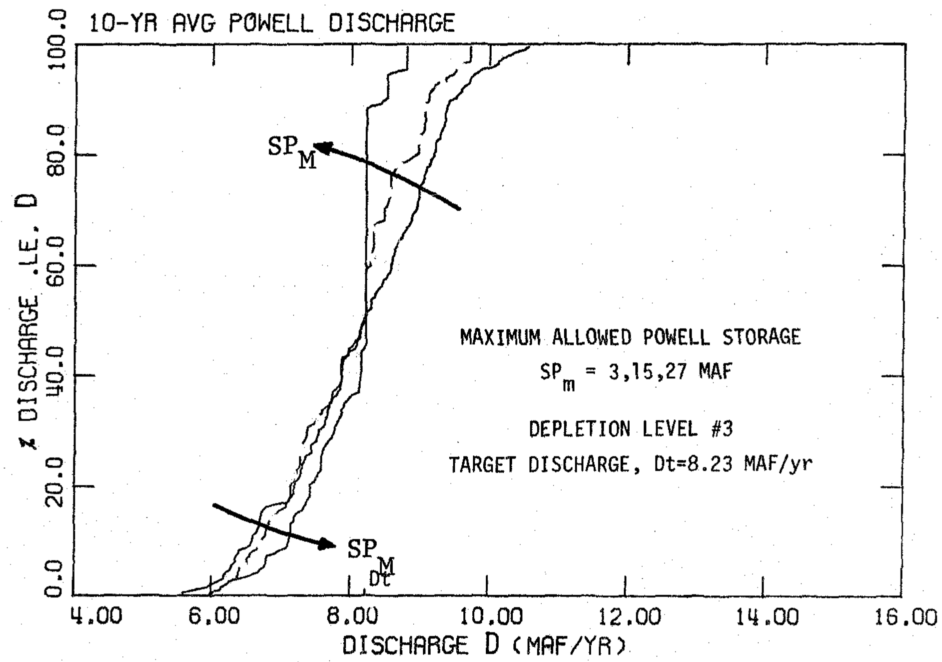


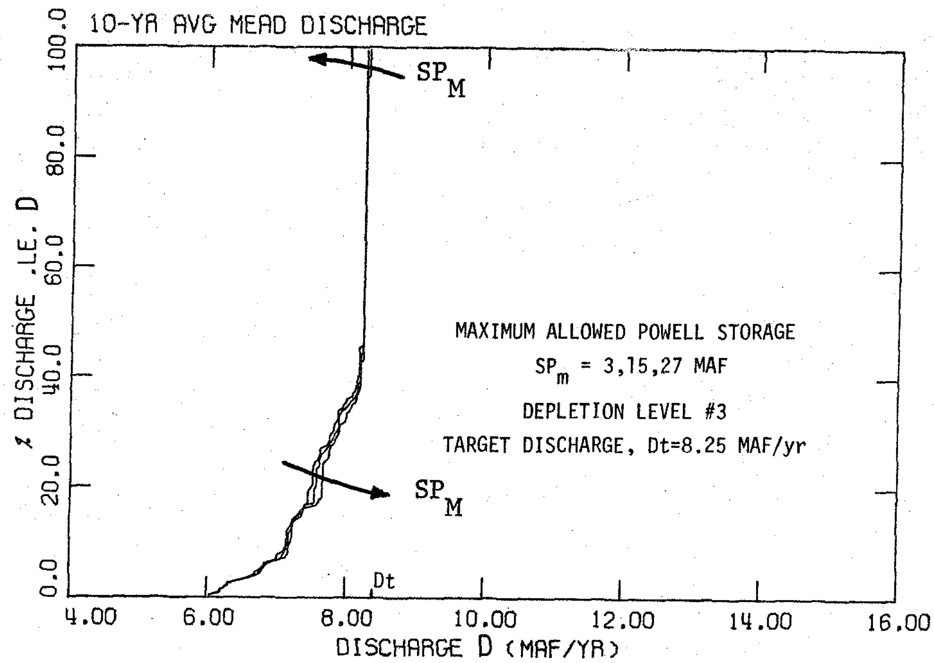
FIGURE 7.7(a,b)

Cumulative Distributions of 10-yr Average Annual Powell and Mead Discharge as a Function of SP_M for DPL #3

(a)



(b)



discharge cannot always be maintained by Lake Mead regardless of the amount of storage provided by Lake Powell. From the relative positions of the three C.D.F.'s in Figure 7.7(b) it appears that the amount of storage provided by Lake Powell has no effect on the 10-year average discharge from Lake Mead.

7.3.2.2 Lake Mead Target Discharge D_t = 7.0 MAF/yr

Changing the target discharge of Lake Mead to 7.0 MAF/yr has no affect on the discharge from Lake Powell. As mentioned in Section 5.5.2.2, 7.0 MAF/yr is the long range future water demand downstream from Lake Mead.

Simulations showed that this target discharge could be maintained by Lake Mead for every depletion level imposed and for all three Lake Powell storage capacities. Further, the 10-year average discharge from Lake Mead was also greater than or equal to 7.0 MAF/yr in all cases.

7.3.3 Average Storage, Annual Evaporation, and Power Capacity

This section describes the changes in measures of average system response for changes in control variables. These measures of response are used in Section 7.4 to indicate the merits of one management policy over another.

The presentation of material is organized as in the previous section. Numerical values are given in Appendix C for the quantities displayed graphically in this section.

7.3.3.1 Lake Mead Target Discharge D_t = 8.25 MAF/yr

Figures 7.8 and 7.9 display the average storage, annual evaporation, annual discharge, power generating capacity, power output, and discharge TDS concentrations for Lakes Powell and Mead. These averages are displayed as functions of maximum allowed Lake Powell storage for each depletion level. Figure 7.10 displays the Lake Powell plus Lake Mead average total storage, total annual evaporation, total power generating capacity, and power output. All of the outputs presented in these graphs is for the case with Lake Mead target discharge D_t = 8.25 MAF/yr.

Figure 7.8 shows that the average storage and average annual evaporation of Lake Powell increase as the maximum allowed Powell storage, SP_M, is increased. Average annual discharge is seen to decrease by the amount of increased evaporation. For a given value of SP_M, each of the above quantities decreases as higher depletion levels are imposed, as denoted by the different symbols in the figure. Power generating capacity increases as SP_M is increased. As the level of depletions is increased the power generating capacity is observed to decrease due to the lower reservoir storages attainable. It is significant to notice that even for SP_M = 27 MAF the generating capacity has dropped to 67 percent of rated capacity for the highest depletion level. For all depletion levels, the generating capacity when SP_M = 15 MAF is between 15 and 20 percent less than when SP_M = 27 MAF.

FIGURE 7.8

AVERAGE MODEL OUTPUT VERSUS MAXIMUM ALLOWED POWELL STORAGE

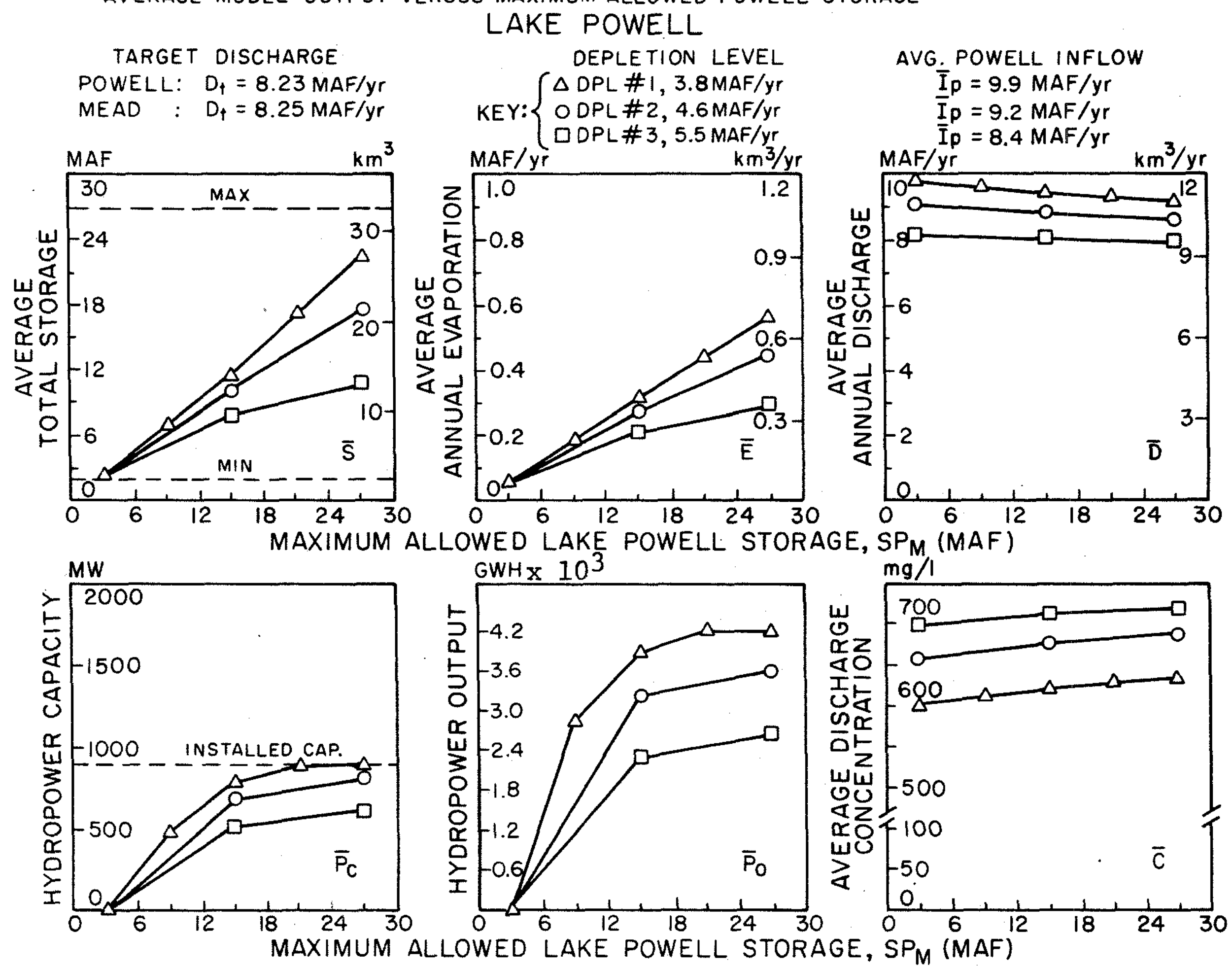
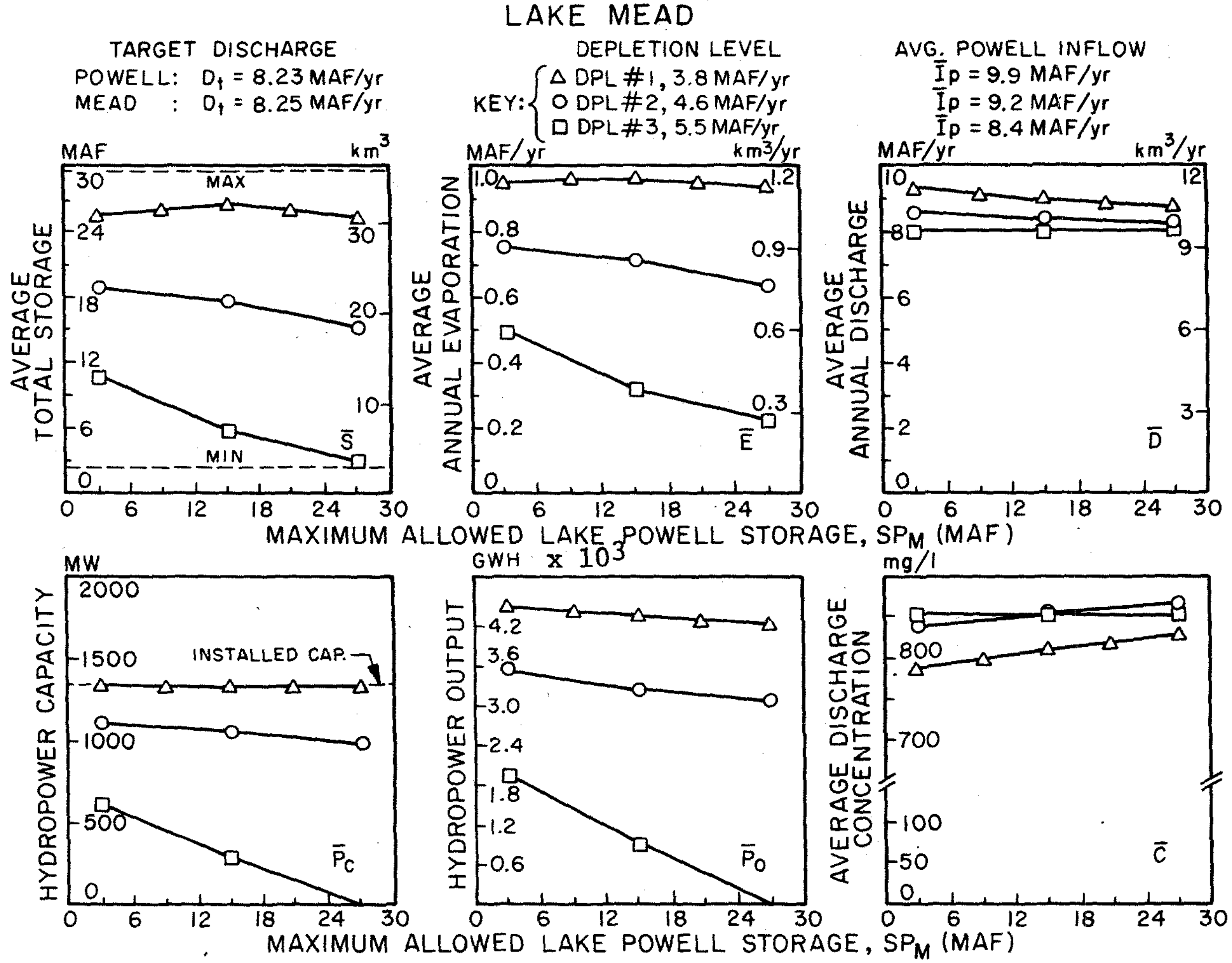


FIGURE 7.9

AVERAGE MODEL OUTPUT VERSUS MAXIMUM ALLOWED POWELL STORAGE, LAKE MEAD TARGET DISCHARGE, D_t = 8.25 MAF/yr



The average outputs from Lake Mead, displayed in Figure 7.9, generally decrease as the maximum allowed storage in Lake Powell is increased. For the lowest level of depletions Lake Mead outputs are affected very little by the storage capacity provided by Lake Powell. At the higher depletion levels the decreased inflow to Lake Mead causes significant reductions in all of the output quantities except discharge TDS concentration (see Section 7.3.3). At the highest depletion level the average inflow is only 0.43 MAF/yr greater than the water demand, equal to target discharge plus reservoir withdrawals (Table C-3 in Appendix C). This low inflow causes average Lake Mead storage to drop to only 3.2 MAF, with a resulting loss of all power generating capacity.

The total average outputs of the model displayed in Figure 7.10 summarize the effects of changes in depletion level and maximum allowed Powell storage on the system as a whole. For depletion levels 1 and 2, average storage, annual evaporation, power capacity, and power output increase as SP_M is increased. For the highest depletion level total storage and evaporation remain nearly constant. Total power capacity, much less than the total installed capacity, is highest for SP_M = 15 MAF.

7.3.3.2 Lake Mead Target Discharge D_t = 7.0 MAF/yr

Average Lake Powell outputs are not affected by changing the target discharge of Lake Mead to 7.0 MAF/yr. Figure 7.11 shows the average outputs from Lake Mead for this target discharge and Figure 7.12 shows the total outputs from Lake Powell plus Lake Mead.

FIGURE 7.10

AVERAGE MODEL OUTPUT VERSUS MAXIMUM ALLOWED POWELL STORAGE, LAKE MEAD TARGET DISCHARGE, D_t = 8.25 MAF/yr

TOTAL: LAKE POWELL PLUS LAKE MEAD

TARGET DISCHARGE
POWELL: D_t = 8.23 MAF/yr
MEAD : D_t = 8.25 MAF/yr

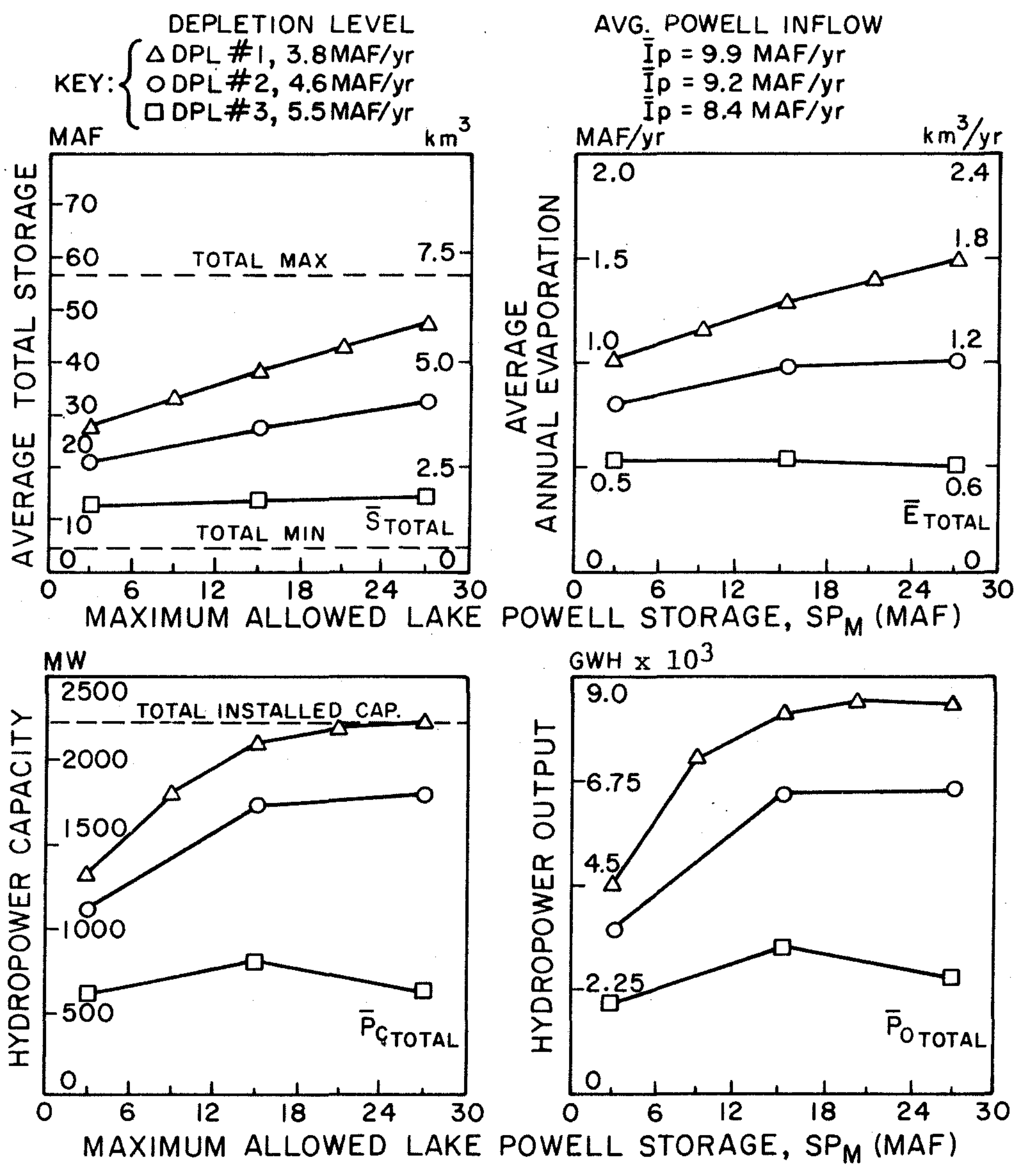


FIGURE 7.11

AVERAGE MODEL OUTPUT VERSUS MAXIMUM ALLOWED POWELL STORAGE,
LAKE MEAD TARGET DISCHARGE, D_t = 7.00 MAF/yr

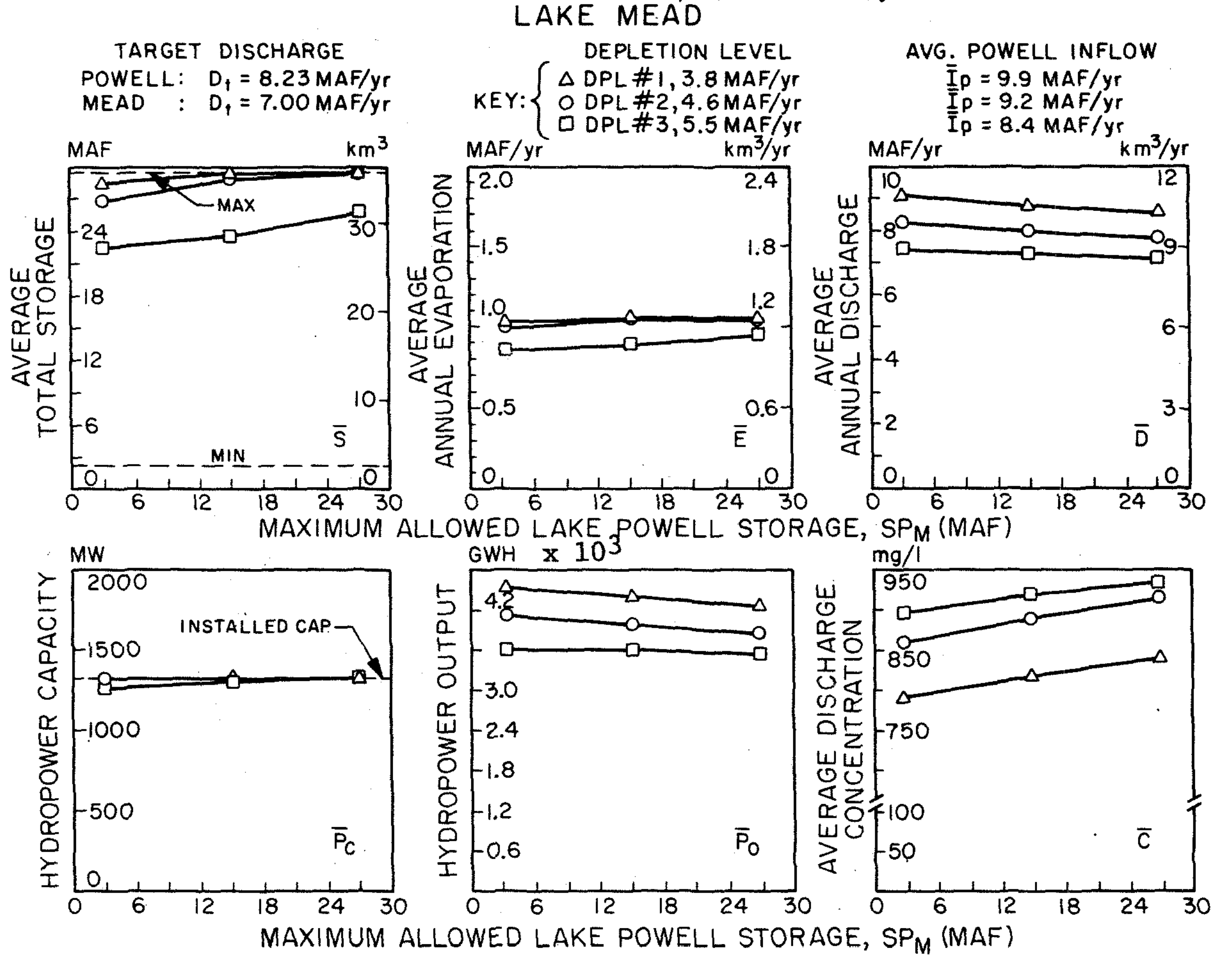
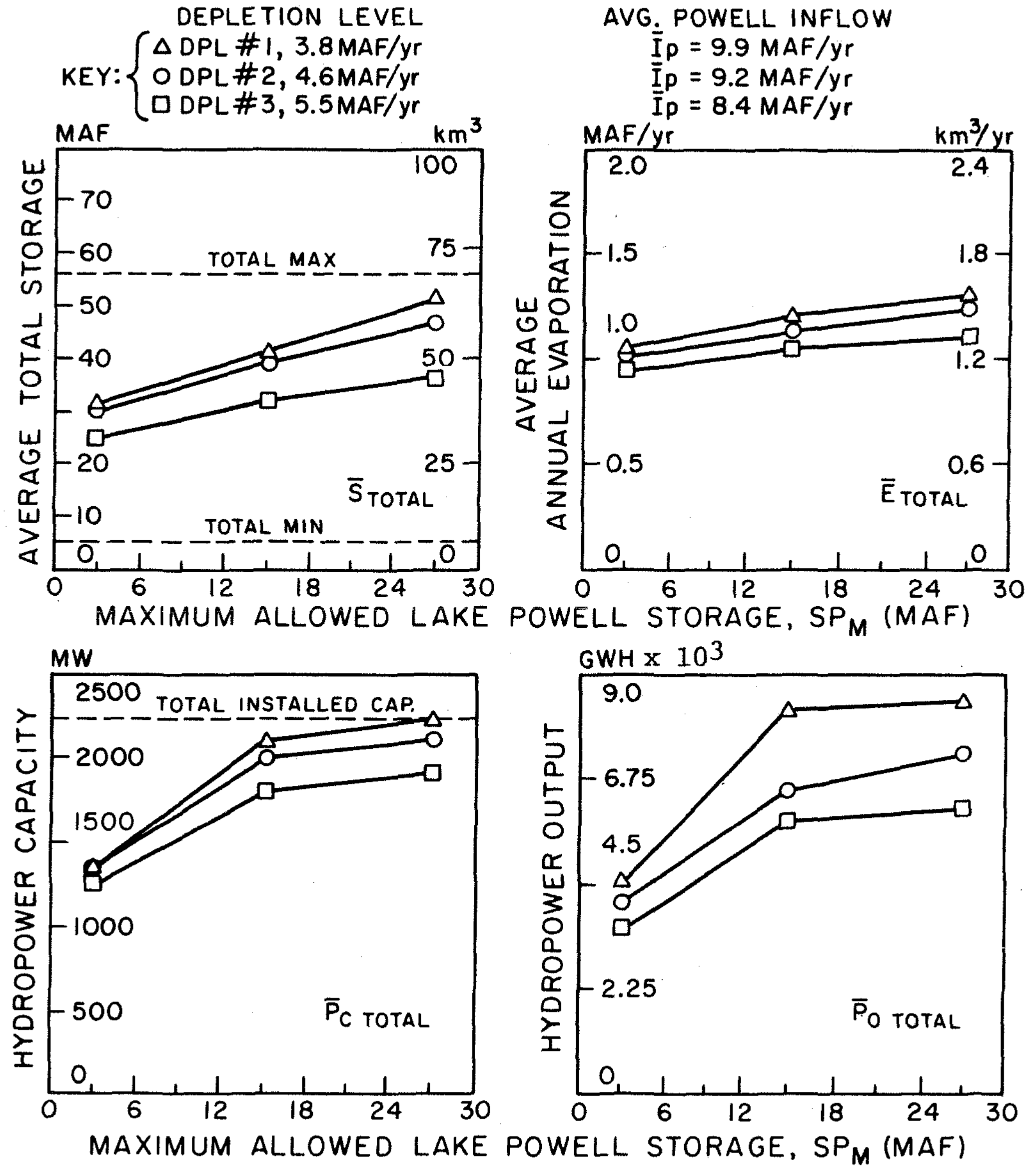


FIGURE 7.12

AVERAGE MODEL OUTPUT VERSUS MAXIMUM ALLOWED POWELL STORAGE, LAKE MEAD TARGET DISCHARGE, D_t = 7.00 MAF/yr

TOTAL: LAKE POWELL PLUS LAKE MEAD

TARGET DISCHARGE
POWELL: D_t = 8.23 MAF/yr
MEAD : D_t = 7.00 MAF/yr



At a target discharge of D_t = 7.0 MAF average Lake Mead storage is seen to increase slightly as the storage capacity of Lake Powell is increased. This result is due to the regulation of Lake Mead inflow provided by Lake Powell. Because average Lake Mead storage changes little as SP_M is increased, average annual evaporation and power capacity also change very little. Average annual discharge decreases due to the increase in Lake Powell evaporation as SP_M is increased. The effect upon these quantities by increasing the level of depletions is seen to be small.

The average total output of Lake Powell plus Lake Mead is seen to be less affected by depletion levels than in the case when target Mead discharge was 8.25 MAF/yr. In particular, it should be noted that the total power capacity when SP_M = 15 MAF is 95 percent of the value when SP_M = 27 MAF for each depletion level.

7.3.4 Average Discharge TDS Concentrations

Figure 7.8 displays the average TDS concentrations in Lake Powell discharge based upon the conserved mass model presented in Chapter 4. Figures 7.9 and 7.11 show the resulting concentrations below Lake Mead for target Mead discharges of 8.25 and 7.0 MAF/yr, respectively.

In each figure, concentrations are observed to increase as the storage capacity of Lake Powell is increased. This increase in concentration results from the increase in evaporation as average storage increases. The one exception to this general trend is observed in Figure 7.9. In the case with the highest depletion level, the concentration below Lake Mead remains constant as SP_M is increased. This result may be understood by observing that total Lake Powell plus Lake Mead average evaporation is also constant as SP_M is increased (Figure 7.10).

Comparing Figures 7.9 and 7.11 shows that the average concentration below Lake Mead increases as the target discharge from Lake Mead is decreased.

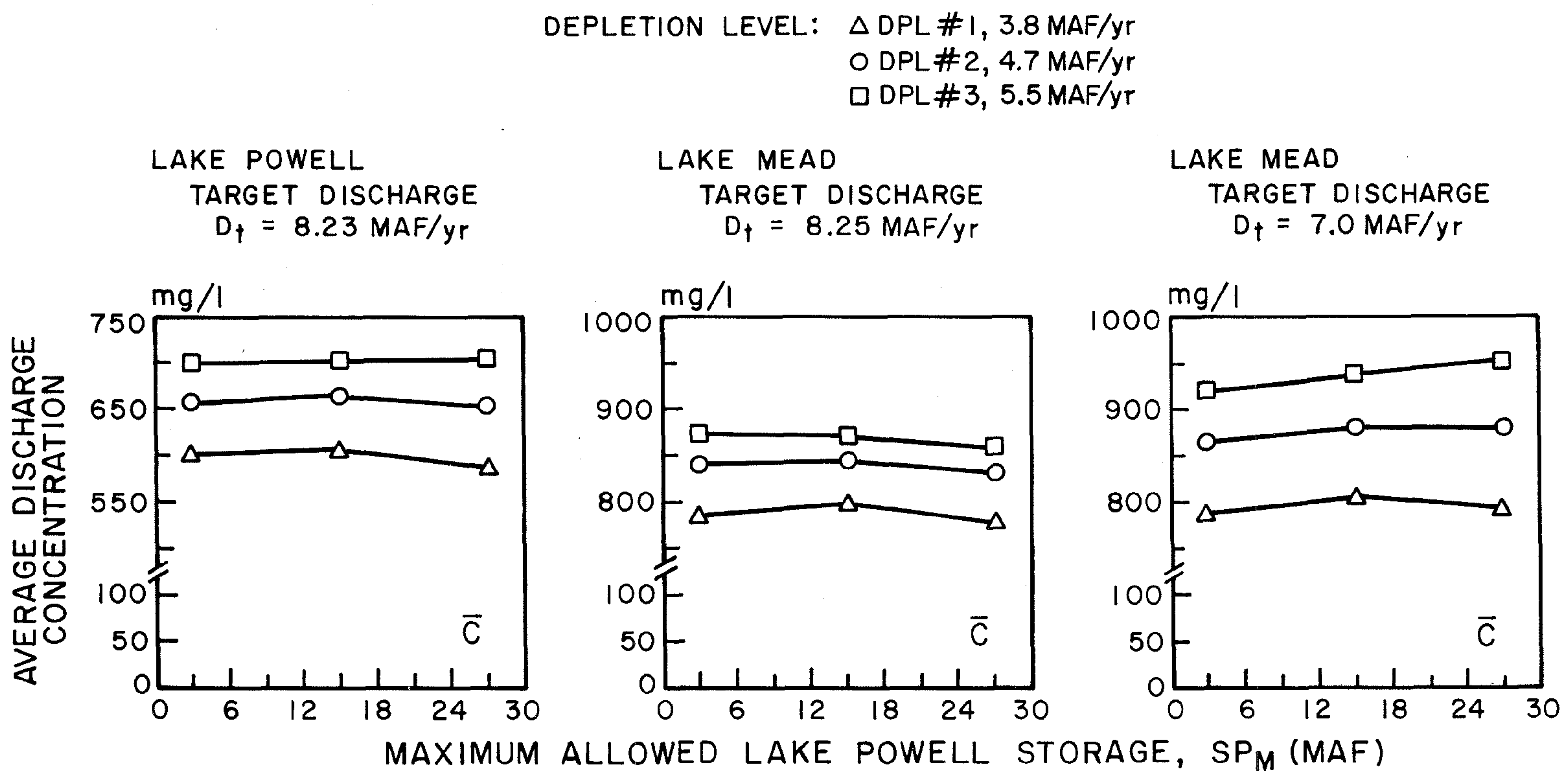
A model of average discharge TDS concentration in which precipitation of salts as a function of average storage was also presented in Chapter 4. That model was used to calculate the average concentrations that would result below Lakes Powell and Mead for each of the simulation cases. These values are displayed in Figure 7.13.

The figure shows that for some depletion levels the average concentration below Lake Powell decreases as the storage capacity of the lake is increased. This result is strongest at the lowest depletion level, the case in which the change in average storage is greatest in going from SP_M = 15 to SP_M = 27 MAF.

The average TDS concentration below Lake Mead is also observed to decrease as the storage capacity of Lake Powell is increased from SP_M = 15 to SP_M = 27 MAF. For the lowest level of depletions, the change in concentration is approximately 14 mg/ℓ. When the target discharge from Lake Mead is set to 7.0 MAF/yr the average concentration is observed to rise as SP_M is increased for the higher two depletion levels. This increase results from the relatively low average storage maintained in Lake Powell and the high amount of evaporation from Lake Mead (Figures 7.8 and 7.11).

FIGURE 7.13

Average Discharge TDS Concentrations Calculated Using the Lake Powell Precipitation Model



The simulation results presented above are used in the following section to draw conclusions regarding the management of the Colorado River Basin.

7.4 Management Implications of Simulation Results

The simulation results described in the previous section must be interpreted in the context of the management concerns of the Colorado River Basin. These have been identified in Chapter 1 to be: (1) the reliable supply of water to locations of water demand; (2) the conservation of water and generation of electric power; and (3) salinity control. Each of these concerns is addressed in the sections that follow.

The management policies compared are: (1) the existing or standard policy of utilizing the installed storage capacities of Lakes Powell and Mead to meet the institutional discharge constraints imposed by the Long-Range Operating Criteria; and (2) the utilization of less than the installed capacity of Lake Powell to maintain a reliable supply of water at the locations of water demand.

The institutional constraints may be summarized as (1) maintaining a release of 8.23 MAF/yr from Lake Powell; (2) maintaining a 10-year average release of 7.5 MAF/yr from Lake Powell; and (3) maintaining a sufficient discharge from Lake Mead to satisfy all legal water rights downstream from Hoover Dam.

The locations of water demand are upstream of Lake Powell and downstream from Lake Mead, plus some demand for water at each reservoir site. No appreciable demand for water exists between the two reservoirs at the present time.

7.4.1 Reliability of Water Supply

7.4.1.1 Conclusions Derived from This Study

The simulation outputs described in Section 7.3.2 show that for some levels of Upper Basin streamflow depletions Lake Powell is unable to maintain one or both of the Operating Criteria constraints. These outputs are summarized in Table 7.2. It is seen that Lake Powell can only satisfy the annual and 10-year average discharge constraints in all years for the lowest depletion level, 3.8 MAF/yr, provided that the full capacity of the reservoir is utilized.

The actual water demand to be supplied is located downstream from Lake Mead (the demands for water at each reservoir site are maintained in all years of all eighteen simulations; see Appendix C, Tables C-1 through C-6). Table 7.2 shows the reliability with which Lake Mead supplies two levels of downstream demand, 8.25 MAF/yr and 7.0 MAF/yr. A discharge of 7.0 MAF/yr is considered necessary to meet the long-range water demand below Lake Mead. At the lower two levels of Upper Basin depletions, Lake Mead is able to maintain either downstream demand even if Powell storage is limited to only 15 MAF. At the highest level of Upper Basin depletions, 5.5 MAF/yr, Lake Mead is capable of supplying 7.0 MAF/yr even if no storage is provided by Lake Powell.

The results presented here show that at the anticipated levels of future Upper Basin depletions the present management policy is incapable of meeting the existing management goals. The proposed alternate policy neglects the existing management goals (operating constraints), and attempts only to insure a reliable supply of water at

TABLE 7.2

Summary of System Outputs - Percentage of Years During Which Discharge Requirements are Not Maintained*

	LAKE POWELL		LAKE MEAD	
Depletion Level, DPL; and Maximum Allowed Powell Storage, SP_M	% Years Powell Fails to Supply: Annual Demand D_t = 8.23 MAF/yr	% Years Powell Fails to Supply: 10-yr Avg. Dem. D_t = 7.5 MAF/yr	% Years Mead Fails to Supply: D_t = 8.25 MAF/yr	% Years Mead Fails to Supply: D_t = 7.0 MAF/yr
DPL #1 (3.8 MAF/yr)				
SP_M = 3 MAF	3.4	2.1	0.0	0.0
SP_M = 15 MAF	2.5	0.0	0.0	0.0
SP_M = 27 MAF	0.0	0.0	0.0	0.0
DPL #2 (4.6 MAF/yr)				
SP_M = 3 MAF	44.0	12.5	3.0	0.0
SP_M = 15 MAF	14.0	6.8	0.0	0.0
SP_M = 27 MAF	4.5	0.0	0.0	0.0
DPL #3 (5.5 MAF/yr)				
SP_M = 3 MAF	56.0	28.0	20.0	0.0
SP_M = 15 MAF	27.0	32.0	20.0	0.0
SP_M = 27 MAF	20.0	21.0	18.0	0.0

*From simulations using one 200 year inflow sequence; numbers presented are intended to show relative behavior of reservoir reliability only.

the locations of water demand. These latter management goals can be achieved even if the total storage capacity of the system is reduced. Before a reduction in Lake Powell storage capacity can be considered economically as well as politically practical, other system outputs corresponding to other Colorado River management concerns must be examined.

7.4.1.2 Results of Other Studies

The conclusions presented above regarding the supply of water in the Colorado River Basin may be compared to those reported by studies of future development of the Colorado River. It was shown in Chapter 6 that the initial storage conditions in Lakes Powell and Mead affect future reservoir operation for a number of years, suggesting that repeated dynamic simulation would provide a better picture of future conditions than the static simulations performed here. However, the long-run statistical information obtained from static simulation has been shown in Section 7.4.1.1 to provide useful information regarding the overall management of the basin at particular levels of water demand.

At the present time, state and federal agencies calculate the quantity of water available for Upper Basin development by subtracting from an estimate of the average natural streamflow the annual quantity to be provided to the Lower Basin. Using the average natural flow estimate appearing in this study, and denoting the water available for Upper Basin use by Q^*:

$$(7.1) \qquad Q^* = \overline{N} - D_t$$
$$= 13.61 - 8.23$$
$$= 5.38 \text{ MAF/yr } (6.63 \text{ km}^3\text{/yr}) .$$

Typical values of Q^* found in other studies of Colorado River development range from 4.7 to 5.8 MAF/yr corresponding to estimates of $\overline{N}$ equal to from 13.0 to 14.0 MAF/yr (see Chapter 3). In a recent study performed by the Colorado River Board of California for the Colorado River Salinity Control Forum, the uncertainty in estimates of average flow and future development were recognized and ranges of each quantity were used in estimating future average salinity conditions (Weber _et al._, 1975).

The point to be made regarding these calculations concerns the assumption that water depletions may grow to equal the average flow in the river. Aside from the matter of uncertainty in the value of the average flow, high levels of water use limit the ability of the system to withstand _variations_ in streamflow.

As mentioned in Chapter 1, those who drafted the 1922 Compact recognized the variability in streamflow when they expressed the Lower Basin demand in terms of a 10-year average rather than an annual flow requirement. Also, the construction of Glen Canyon Dam was inspired by the need to store sufficient water in the Upper Basin so that the Lower Basin demand might be met during periods of low runoff. However, the design storage requirement of 27 MAF was based upon an examination of the historical flow sequence.

The popularity of synthetic hydrology, as stated in Chapter 2, lies in its ability to generate many possible flow sequences based on statistical information extracted from the historical data. The simulation model, calibrated with data from the low runoff period 1930 to 1968, shows that storage of 27 MAF is insufficient to reliably supply the annual demand when Upper Basin depletions equal 4.7 MAF/yr.

Previous projections of water available for the development of the Upper Basin have paid insufficient attention to the variations in streamflow and the future ability of Lake Powell to satisfy the institutional constraints imposed upon it. The results of this study show that higher rate of water use in the Upper Basin may be tolerated if the management goals in the entire Colorado Basin are revised.

7.4.2 Conservation of Water and the Production of Power

At this point in the study of basin management it is desirable to limit the number of simulations examined. In particular, the cases for which SP_M = 3 MAF are not examined further because it is considered desirable to maintain some hydroelectric power generating capability at Lake Powell. The discussion that follows is limited to a comparison of outputs from (1) simulations using a maximum Powell storage capacity of SP_M = 27 MAF, in accordance with the existing policy; and (2) simulations using a maximum Powell storage of SP_M = 15 MAF, one possible configuration which satisfies the goals of the alternate policy. Hereafter, operating Lake Powell with a maximum storage of 15 MAF and satisfying the water demands of the basin is defined to be the <u>alternate management policy</u>. The <u>existing policy</u>, as before, consists of utilizing the full capacities of both reservoirs in attempting to satisfy the institutional operating constraints.

These policies are compared on the basis of the effect of reduced Powell storage upon average annual evaporation and average power generating capacity. The effect of reduced Powell storage upon salinity is examined in the next section of this chapter.

Reduction of the total evaporation from Lakes Powell and Mead is a benefit to the system since the water can be put to other uses. Reductions in power generating capacity must be compensated by more expensive methods of power production and represent a cost to the system.

Table 7.3 is a summary of the simulation outputs, showing average total evaporation and average total power generating capacity for all eighteen simulations. The columns give the values of the indicated quantities for each value of Mead target discharge and Powell storage capacity used. The horizontal blocks designate the three depletion levels imposed.

At the lowest level of streamflow depletions the alternate policy saves 0.21 to 0.25 MAF/yr that is evaporated under the standard policy. The amount of evaporation conserved depends upon the target discharge of Lake Mead. By comparison, snowpack augmentation in the Upper Colorado Basin could possibly provide an average of 2.3 MAF/yr of additional runoff (Weisbecker, 1974). Also, a savings of 0.25 MAF/yr would satisfy 83% of Nevada's legal allotment to Colorado River water.

At this level of depletions the alternate policy costs the system 117 MW of power generating capacity, or 5% of the total installed capacity (Table 7.3 and Figures 7.10 and 7.12). If fossil fuel or nuclear

TABLE 7.3

Summary of Simulation Outputs - Average System Response

			Lake Mead Target Discharge D_t					
			D_t = 7.00 MAF/yr			D_t = 8.25 MAF/yr		
Maximum Allowed Powell Storage, SP_M(MAF)			SP_M=3	SP_M=15	SP_M=27	SP_M=3	SP_M=15	SP_M=27
Depletion Level DPL #1 3.8 MAF/yr	Average Total Evaporation	$\overline{E}_T$ (MAF/yr)	1.09	1.38	1.63	1.02	1.29	1.50
	Average Mead Discharge	$\overline{D}$ (MAF/yr)	9.17	8.89	8.63	9.23	8.96	8.75
	Average Total Power Capacity	$\overline{P}_{cT}$ (MW)	1328	2111	2228	1326	2111	2228
	Average TDS conc. below Mead (1)	$\overline{C}$ (mg/ℓ)	792.	818.	841.	785.	810.	829.
	Average TDS conc. below Mead (2)	$\overline{C}$ (mg/ℓ)	792.	804.	789.	787.	798.	778.
Depletion Level DPL #2 4.6 MAF/yr	Avg. Total Evap.	$\overline{E}_T$ (MAF/yr)	1.05	1.32	1.50	0.81	0.98	1.07
	Avg. Mead Disch.	$\overline{D}$ (MAF/yr)	8.30	8.02	7.83	8.52	8.35	8.26
	Avg. Tot. Power Cap.	$\overline{P}_{cT}$ (MW)	1328	2018	2131	1100	1728	1792
	Avg. TDS conc. (1)	$\overline{C}$ (mg/ℓ)	862.	892.	913.	838.	856.	866.
	Avg. TDS conc. (2)	$\overline{C}$ (mg/ℓ)	864.	882.	880	842.	848.	836.
Depletion Level DPL #3 5.5 MAF/yr	Avg. Total Evap.	$\overline{E}_T$ (MAF/yr)	0.91	1.11	1.25	0.54	0.53	0.51
	Avg. Mead Disch.	$\overline{D}$ (MAF/yr)	7.51	7.32	7.18	7.93	7.95	7.96
	Avg. Tot. Power Cap.	$\overline{P}_{cT}$ (MW)	1265	1818	1928	612	794	603
	Avg. TDS conc. (1)	$\overline{C}$ (mg/ℓ)	895.	920.	936.	854.	854.	852.
	Avg. TDS conc. (2)	$\overline{C}$ (mg/ℓ)	923.	942.	953.	876.	870.	863.

Notes: (1) Average concentration by simulation using the conserved mass model.
(2) Average concentration calculated including precipitation in Lake Powell.

power plants were used to replace 117 MW of power capacity, the water required by cooling towers would amount to 0.003 MAF/yr, or less than 1.5% of the evaporation conserved (these figures assume a thermal to electricity conversion efficiency of 40%).

The remainder of the evaporation conserved by the alternate policy could be used in either the Upper or Lower Basin for energy production or for the extraction and processing of the energy resources that exist in the Upper Basin. Estimates of water consumption requirements for various energy resource processing operations are given in Table 7.4. Each of the Upper Basin states holds significant reserves of both oil shale and coal (Metz, 1974; Walsh, 1974). Although it is difficult to predict how much of either of these resources will be developed in the future, Weber presents a range of 1990 consumptive use estimates for Upper Basin energy development (Weber et al., 1974). The high estimates for the year 1990 include 0.685 MAF/yr for processing and producing power from coal, and 0.225 MAF/yr for the processing of oil shale. At the present time, questions of water availability and ownership inhibit attempts to predict how much of these energy resources can be utilized in the future. The availability of an additional 0.21 to 0.25 MAF/yr obtained from reductions in evaporation, while still subject to questions of ownership, would allow development of these resources to proceed.

How the conservation and useful consumption of evaporation affects salinity is included in Section 7.4.3.

At the second and third levels of streamflow depletions the implementation of the alternate management policy results in a smaller reduction in evaporation than observed above (Table 7.3).

The cases corresponding to Lake Mead target discharges of D_t = 8.25 MAF/yr are not discussed because of the extreme storage, power, and discharge conditions which occur at depletion levels two and three (Figures 7.3, 7.4, and 7.10).

The reduction in evaporation is significant for the cases where the target discharge from Mead is 7.0 MAF/yr; 0.18 MAF/yr and 0.14 MAF/yr are conserved at depletion levels DPL #2 and DPL #3 respectively. These quantities are equal to approximately one-half the Nevada allotment. If devoted entirely to thermal electric power production this amount of water could provide 5600 to 7200 MW of additional capacity.

At these higher depletion levels a loss of hydroelectric power capacity of between 97 and 300 MW is experienced even under the existing management policy (Table 7.3). Under the alternate policy the power capacity of the system is decreased an additional three to six percent, or to between 210 and 410 MW below the installed capacity of the system. To provide thermal electric replacement of 410 MW would require 0.010 MAF/yr of cooling water, or less than 8% of the amount of evaporation conserved by the alternate policy.

The remainder of the conserved evaporation could be assigned to other beneficial uses. Table 7.4 indicates that if the remaining 0.13 MAF/yr were applied to coal gasification 1300 million cubic feet per day could be produced. Over 800,000 barrels of oil could be produced per day if this volume of water was applied to processing oil shale.

Table 7.4

Consumptive Water Use Requirements for Energy Resource Processing Operations

Energy	Coal Requirement (MT/yr)	Water Consumed (MAF/yr)	Water Consumed (km^3/yr)
Coal gasification 250×10^6 cu.ft./day	6.5	0.02 - 0.03	0.025 - 0.037
Coal Hydrogenation 100,000 barrels/day	15.0	0.02 - 0.03	0.025 - 0.037
Oil Shale 100,000 barrels/day		0.012 - 0.020	0.015 - 0.025

Source: Clyde, Calvin G., "Energy Production and Water Supply" in <u>Energy, the Environment and Water Resources</u>, proceedings, University Council on Water Resources, Utah State University, Logan, Utah, July 28, 1974, page 328.

7.4.3 Average Total Dissolved Solids Concentrations

The impact that different management policies have upon TDS concentrations is difficult to assess at the present time. Two models have been presented for predicting the TDS concentrations downstream of Lake Powell. The resulting average concentrations below Lake Mead are included in Table 7.3 (see notes below table). One TDS model assumes that the mass of total dissolved solids is conserved while flowing through Lakes Powell and Mead. The other model assumes a relationship describing the loss of TDS through precipitation of salts in Lake Powell.

The values given in Table 7.3 show that the conserved-mass model predicts an improvement in water quality from implementation of the alternate management policy. However, the precipitation model predicts a deterioration in water quality results from the implementation of this policy.

If the conserved-mass model is assumed to be descriptive of the actual system, the water quality improvements afforded by adopting the alternate management policy can be assessed. The alternate policy results in reduced evaporation which lowers TDS concentrations through dilution. For the lowest depletion level and a Mead target discharge of 7.0 MAF/yr, the reduction in TDS concentration below Lake Mead is 23 mg/ℓ. This change represents a decrease in average concentration of only 3%. However, if the existing management policy were maintained, a removal of 0.27 MT/yr (million tons per year) would be required to produce the same reduction in concentration. By comparison, the largest desalting plant in the world, to be located near the U.S.-Mexico border, will remove 0.56 MT/yr (calculated from information found in Stamm, 1975). Other salinity control projects in the Colorado River Basin are to remove a combined estimate of 0.4 MT/yr. At other depletion levels and target discharges, the decreases in concentration associated with the alternate policy range from 10 to 21 mg/ℓ or equivalent reductions of from 0.11 to 0.23 MT/yr.

If, on the other hand, the precipitation-model is assumed to be more representative of actual conditions, then the degradations of water quality associated with adopting the alternate policy are as great as the improvements predicted by the conserved-mass model (see Table 7.3).

Using data that is presently available it is not possible to determine which model provides a better approximation of reality. It has been demonstrated in Chapter 4 that precipitation of salts in Lake Powell is a significant process affecting downstream salinity. The difficulty lies in trying to determine the rate of precipitation as a function of storage. If, for instance, the mass precipitated were constant over a large range of reservoir storage, then Lake Powell discharge salinities could be determined using the conserved-mass model. The mass precipitated would be implicitly accounted for during model calibration as an adjustment to the ungauged side inflow of total dissolved solids.

Other aspects of water quality indicate advantages of adopting the alternate management policy over the existing policy.

First, the sodium absorption ratio (SAR) is an important water quality index with regard to plant growth. Water uptake in plants is best when the value of the SAR is low. The SAR is given by:

$$\text{SAR} = \frac{[\text{Na}^+]}{\left(\frac{[\text{C}_a^{++}] + [\text{M}_g^{++}]}{2}\right)^{\frac{1}{2}}} \tag{7.2}$$

where concentrations are in milliequivalents per liter. Sodium does not precipitate in Lake Powell, and is concentrated by the evaporation from the reservoir. To maintain as low an SAR as possible, evaporation should be kept minimal by reducing lake storage. If the calcium concentration remains high because precipitation of calcium carbonate is reduced, the SAR is actually improved (lowered). This effect may or may not be significant. Better lake chemistry models for Lakes Powell and Mead are required to produce a definitive statement.

Second, it has been reported that at high storage levels anaerobic conditions exist in the hypolimnion of Lake Powell. Power turbines with design lifetimes of 20 years are said to last as little a time as 6 months (Reynolds, 1975). Induced reservoir mixing, hypolimnion aeration, or reduced reservoir storage are methods for dealing with this problem.

7.4.4 The Effect of Reduced Lake Powell Storage upon Recreation

The potential loss in recreational benefits associated with a decreased level of Powell storage deserves to be mentioned. Anderson *et al.*, (1973) examined the possible impacts of restricting Powell storage to elevation 3606 in connection with the effort of several interest groups to preserve the Rainbow Bridge National Monument. Their study indicated that there would not necessarily be a decrease in the total number of lakeside recreational sites if the maximum storage were decreased to that elevation (elevation 3606 corresponds to a total Lake Powell storage of 14.7 MAF or 18.1 km^3). Anderson also reports that wilderness recreation in the Lake Powell area would probably be adversely affected by allowing Lake Powell to fill to its design storage capacity. With regard to lake level fluctuations and their impact upon recreation, seasonal drawdown would occur regardless of lake capacity. The simulation results presented in Tables C-1 to C-3 (Appendix C) show that the variance in Powell storage decreases as SP_M is decreased, due primarily to the increased discharges necessary to maintain lower lake levels.

It can be concluded that the net effect of decreased storage upon recreational benefits is uncertain but evidently small in magnitude.

7.4.5 Additional Simulations Performed Using the Model

Two sets of additional simulations were performed. In the first set, simulations with reduced Lake Powell capacities were performed in which withdrawals from Lake Powell were increased. The withdrawals were increased by an amount equal to the evaporation conserved by operating Lake Powell at the lower storage capacity. No return flow of dissolved solids is assumed to occur. These simulations were performed to see the effect of Upper Basin consumption of the conserved water upon downstream salinities and the probability of reservoir failure.

Downstream TDS concentrations equal those from the previous simulations with reduced Powell storage capacity. Because the conserved evaporation was no longer being discharged from Lake Powell, the probability that Lake Powell failed to meet target discharges increased slightly. The probability that Lake Mead failed to meet target discharges, however, was unchanged. This result supports the implementation of the alternate management policy.

The second set of additional simulations modeled the implementation of authorized or anticipated salinity control projects. Reductions of total dissolved solids flows in the modeled portion of the Colorado River Basin were made as described in Section 5.5.1.9 and Table 5.9. Simulations with the maximum allowed storage of Lake Powell at SP_M = 15 MAF and SP_M = 27 MAF were made. In both cases the TDS concentration below Lake Mead was reduced by 90 mg/ℓ. These simulations were performed to indicate the value of the model in exploring other areas of basin management besides those examined in this study.

7.5 Summary and Conclusions of Basin Management Examinations

The value of the method of analysis presented in this paper has been demonstrated through the use of the simulation model in comparing certain alternative management policies for the Colorado River Basin. Measurements of system performance used in making these comparisons are the average system outputs and the cumulative distribution of reservoir discharge. Methods of analysis employed in previous studies of the Colorado River Basin have not provided this information.

The management configurations examined were chosen so that the reservoir storage required for meeting basin water demands could be determined. The procedure consisted of iteratively increasing the maximum allowed storage of Lake Powell and checking to see whether or not a reliable water supply was maintained. The procedure was repeated for three levels of basin water demands. The streamflow depletions imposed above Lake Powell were 3.8, 4.6, and 5.5 MAF/yr (4.4, 5.7, and 6.8 km^3/yr).

Assumptions made regarding reservoir operation and the imposition of Upper Basin water depletions have been explicitly described. The assumptions invoked serve to provide a worse case for the assessment of policy alternatives.

The <u>existing management policy</u> requires that the discharge from Lake Powell be at least 8.23 MAF/yr (10.1 km^3/yr) or average not less than 7.5 MAF/yr (9.2 km^3/yr) for any 10 -year period. The simulations performed show that Lake Powell storage is capable of meeting both of these requirements only at the lower of the three depletion levels imposed, and only if the entire 27 MAF capacity of the lake is utilized. At the second level of depletions only the 10-year average requirement can be met.

Ignoring the institutional discharge constraints and concentrating on meeting downstream water demands shows that a reliable water supply can be maintained without utilizing the full capacity of Lake Powell. Further, a supply of water sufficient to meet the long-range downstream water demands can be maintained even at the highest level of Upper Basin depletions.

The policy of reducing the maximum allowed storage in Lake Powell to 15 MAF and attempting to satisfy water demands rather than institutional discharge constraints is called the <u>alternate management policy</u>. The costs associated with adhering to this policy are discussed. These costs, or alternatively, the benefits obtained by relaxing the existing institutional constraints have been expressed in terms of the physical quantities gained or lost.

Implementation of the alternate policy results in the conservation of significant quantities of water that would be lost through evaporation if the existing policy were maintained. Between 0.10 and 0.25 MAF/yr can be conserved. Reductions in hydroelectric power generating capacity associated with implementing the alternate policy are of at most 120 MW. It has been shown that a small portion of the evaporation conserved is sufficient to meet the cooling tower requirements for replacing this power capacity through fossil fuel or nuclear power generation. One possible use for the remainder of the conserved evaporation is for the development of energy resources in the Upper Colorado River Basin.

The effect that the alternate policy would have upon total dissolved solids concentrations is difficult to determine. Incomplete knowledge of the chemical processes occurring in Lake Powell make even a qualitative impact assessment impossible. Depending upon the assumptions regarding the precipitation of salts in Lake Powell the alternate policy may raise or lower discharge TDS concentrations by as much as 20 mg/ℓ. Other water quality concerns regarding the composition of ions in Lake Powell discharge and the corrosiveness of water discharged from Glen Canyon Dam suggest arguments in favor of reducing the storage capacity of Lake Powell. Reduced storage may produce lower downstream sodium absorption ratios and prevent the corrosion of power turbines. Again, additional chemical information must be acquired and included in the model before definitive results can be forthcoming.

The adoption of the alternate management policy would generate a dispute among the water interests in the seven basin states regarding water rights. The benefits and costs associated with the change in policy would have to be distributed in some way among the basin states. This study makes no attempt to define how these impacts might be equitably distributed. The analyses presented have intended to provide information about the Colorado River system, establishing a more adequate basis for studying Colorado River management alternatives than has previously existed.

CHAPTER 8

SUMMARY, CONCLUSIONS, AND SUGGESTIONS FOR FURTHER RESEARCH

Management of large river basins generally involves recognition of a variety of concerns such as water-supply reliability, water quality, and water use. The number of variables involved and their interrelationships inhibit the application of analytical techniques to such management problems unless a greatly simplified description of the system is possible. However, in practice it is rarely possible to simplify the system and retain the essential features of the problem, and so it becomes necessary to develop numerical methods for assessing management policies.

In this study a simulation method has been developed to examine alternative policies for managing a river basin. The region of application is a major portion of the Colorado River Basin, an arid water basin possessing a relatively low and highly variable streamflow. Since the potential uses for Colorado River water far exceed average runoff, the allocation of available water among competing uses represents a complex problem in basin management.

The total dissolved solids concentration of Colorado River water, which is naturally high compared to other streams, has risen dramatically in recent years as a result of return flows from irrigation and increases in consumptive uses throughout the basin. The agencies responsible for managing the river have been increasingly concerned with the problem of deteriorating water quality and its impact upon industry and agriculture.

In addition, efforts to provide a reliable supply of good quality water to locations of water demand are constrained by a body of political and legal requirements known as the Law of the River. These requirements, to a large degree, dictate the operation of the flow-regulating structures on the river and the locations and magnitudes of water consumption. The product of hard-fought compromises and traditions of western law, these institutional constraints are slow to change; although the research of management alternatives which ignore or relax these constraints has been encouraged, little work in this area has been performed.

The simulation model developed in this study provides a means for generating statistical information which is useful in evaluating and comparing a wide range of management strategies. This information is obtained by modeling the stochastic inputs to the river system, as well as the interactions of the variables defining the system, and simulating system behavior until the desired information is obtained.

The technique has been employed to examine existing and some alternative reservoir operating policies, and to identify those policies which might best satisfy the needs of the Colorado River Basin.

8.1 The Simulation Model

Applying the method of simulation to the study of Colorado

River management requires modeling the stochastic streamflow and stream salinity inputs to the system and modeling the effects of water depletion and reservoir operation upon water availability and quality. The river system model encompasses the major tributaries upstream of Lake Powell and extends to a point just downstream of Lake Mead.

Generation of synthetic tributary streamflow sequences is performed using a model of the form developed by Thomas and Fiering (1962). The monthly streamflows generated embody the serial and cross-correlation characteristics of the recorded flows and are shown to be statistically indistinguishable from the historical sequence.

Stream salinities were modeled by formulating a relationship between total dissolved solids (TDS) concentrations and streamflow. This relationship was used to generate sequences of monthly TDS concentrations from the previously generated streamflow sequences.

Depletions of water from the system are modeled according to location and type of water use so that the effect of depletions upon salinity could be included in the model. Depletions have been categorized as irrigation consumption, municipal and industrial consumption, and exports to other basins. The locations of water demand are in the tributary sub-basins above Lake Powell and in the region downstream from Lake Mead. Some additional water demand occurs at each reservoir site, although no significant use of water is made in the canyon region between the two reservoirs.

The mass routing of water through Lakes Powell and Mead included the effects of evaporation as a function of reservoir storage and the month of the year. Hydroelectric power generation is modeled as a function of the elevation of reservoir storage.

A complete mixing model was found to provide an adequate representation of the concentration of total dissolved solids in reservoir discharge. An examination was made of available information regarding the precipitation and dissolution of dissolved solids in Lakes Powell and Mead. There is evidence that a net loss of TDS is occurring in Lake Powell due to the precipitation of calcium carbonate. If the mass of salts precipitated is not a function of reservoir storage, then reductions in storage, and subsequent reductions in evaporation, will cause the discharge TDS concentration to decrease. If the mass precipitated decreases with reductions in storage, the effect of reduced evaporation will be offset. Data presently available are inadequate for developing a definitive model of precipitation versus storage. In this study two models have been developed and used. One model conserves the total mass of TDS passing through Lake Powell. The second model assumes that the mass precipitated is proportional to the surface area and detention time of the reservoir.

Reservoir operation, or the scheduling of releases is performed by meeting target discharges whenever possible. The reservoirs are operated independently.

The complete simulation model consists of submodels of each of the above processes and a main program which directs a variety of input and output activities.

Outputs from the computer model consist of monthly and annual averages and standard deviations of reservoir discharge, evaporation, storage, power capacity, and downstream salinity. The cumulative probability distributions of annual reservoir discharge are also recorded. These distributions are used to determine the probability with which either reservoir fails to supply a specified target discharge.

8.2 Use of the Model in Examining the Characteristics of the System

Preliminary simulations were made to determine the period of transient operation necessary to remove the effects of initial conditions upon the statistics generated by the model. A transient time of 150 years was determined and used in subsequent simulations. Additional simulations were performed to find the number of years of simulation required to produce stable statistical information. The average values of reservoir storage and discharge were found to converge to within acceptable limits for simulations of 200 years. The extremes of the distribution functions of reservoir discharge, however, were not observed to converge to stable values even as the number of years sampled approached 2000. Serious questions are posed as to the adequacy of 40 years of model calibration data to provide sufficient information regarding the frequency of extreme river flows which produce extremes in reservoir discharge.

In the context of making management decisions, extended simulations would eventually produce stable but misleading information regarding frequencies of reservoir failure. This result has significant implications with regard to interpretation of the results obtained by other studies of the Colorado River system and for the results presented here. In subsequent simulations a sample of 200 years was used to compare system performance on the basis of average reservoir outputs. The distributions of reservoir discharge obtained and the frequencies of reservoir failure observed were used to indicate the relative abilities for different management configurations to provide reliable water supplies. The variability in the historical runoff data prohibits an accurate determination of these probabilities, and until such time as the extremes of the runoff distributions are better known all statistical analyses of management policies must be treated with a degree of circumspection.

8.3 Application of the Simulation Model to Management Studies

The management policies investigated consist of meeting legislated discharge requirements at a specified location below Lake Powell (the present policy), and of satisfying water needs at the location of water demand below Lake Mead (an alternate policy). The legal requirements on releases from Lake Powell are to attempt to maintain an annual discharge of 8.23 MAF/yr (10.10 km^3/yr) or an average discharge of not less than 7.5 MAF/yr (9.25 km^3/yr) over any ten year period.

The institutional constraints on the operation of Lake Powell are disregarded in implementing the alternate policy. However, established water rights throughout the basin were inherently observed when assigning values to the levels and locations of water depletions and water demands.

The simulation model was used to determine the reservoir storage required to maintain the discharges required by each policy. Since the reservoirs presently exist, the storage determination and comparison of the two policies is equivalent to asking whether the alternate policy may be employed without utilizing the entire storage presently provided. Further, are significant reductions in evaporation and changes in salinity likely to result, and how significant is any loss in hydroelectric power generation?

The required storage determination was performed by varying the maximum storage allowed in Lake Powell while allowing the entire volume of Lake Mead to be used. Three values of maximum Lake Powell storage were imposed; total storages of 3 MAF (3.7 km^3), 15 MAF (18.5 km^3), and 27 MAF (33.3 km^3) were used. These simulations were repeated for each of three levels of upstream water depletions and two values of Lake Mead target discharge. The values of depletions imposed above Lake Powell are 3.8 MAF/yr (4.7 km^3/yr), 4.6 MAF/yr (5.7 km^3/yr), and 5.5 MAF/yr (6.8 km^3/yr). The two Lake Mead target discharges are 8.25 MAF/yr (10.2 km^3/yr) and 7.0 MAF/yr (8.6 km^3/yr). In all, eighteen control variable configurations were studied.

Examination of the cumulative distribution of Lake Powell discharge indicated whether a particular configuration was capable of satisfying the discharge requirements of the existing policy. Similarly, the distribution of Lake Mead discharge was used to indicate the success or failure of the alternate policy of satisfying water demands at the location of water use. The values of average storage evaporation, TDS concentration, and power capacity were used to compare different policies on the basis of the potential costs or benefits that these values represent to the system.

8.4 Conclusions Derived from the Management Study

The results of the simulations performed show that operation under the existing policy is able to satisfy both the annual discharge of 8.23 MAF/yr and the ten year average discharge of 7.5 MAF/yr at Lake Powell only under the conditions of the lowest depletion level imposed, 3.8 MAF/yr. The existing policy is able to satisfy the ten year average discharge requirement, but not the annual discharge requirement at the 4.6 MAF/yr level of depletions. Neither requirement can be satisfied at the highest level of depletions, 5.5 MAF/yr.

In addition, at the higher two levels of depletions the attempts to meet the specified target discharge from the reservoir result in frequent reservoir drawdown and low values of average storage. The low values of average storage cause the power generating capacity at Lake Powell to fall 297 MW below the installed capacity of 900 MW, or a reduction of 33 percent.

By comparison, the water demand of 8.25 MAF/yr below Lake Mead is found to be met reliably at the lower two levels of depletions when no storage is provided by Lake Powell. At the highest level of depletions, this demand goes unmet roughly one year in every five, regardless of the storage permitted in Lake Powell.

The lower water demand of 7.0 MAF/yr below Lake Mead can be supplied at all three levels of depletions with and without the storage of water in Lake Powell.

Present consumption of Colorado River water downstream from Lake Mead exceeds 7.0 MAF/yr. However, this value is estimated to be the long-range limit on consumptive use as existing upstream water rights are developed. The results presented here show that the long-term demands for water in the basin can be supplied with less reservoir storage capacity than is presently installed.

Adhering to the existing policy of utilizing the full storage capacity of Lake Powell results in cost to the system in the form of evaporation, but reducing Powell storage to zero results in the loss of the 900 MW of installed hydroelectric power generating capacity.

A detailed economic analysis would be required to determine an optimum allocation of reservoir storage. However, as an example of one possible alternative to the existing management policy, the operation of Lake Powell at a storage of not more than 15 MAF is examined.

Depending upon the level of depletions imposed on the system, this policy would conserve between 0.14 and 0.25 MAF/yr of water that would be evaporated under the existing policy. Relative to conditions under the existing policy, the power capacity of the system would be reduced by six percent or less, depending, again, on the level of depletions.

It is shown that less than eight percent of the evaporation conserved by the alternate policy is sufficient to meet cooling tower requirements of thermal electric generation necessary to replace the foregone hydroelectric power. The remainder of the conserved water could be used in developing the vast energy resources in the Upper Colorado Basin.

The effect that the implementation of the alternate policy would have upon water quality is open to question. The two models developed for the passage of total dissolved solids through Lake Powell produce divergent results. Total dissolved solids concentrations may be increased or decreased by as much as 20 mg/ℓ. Arrangements for the validity of either model are given, and a suggestion is made for further research in this area.

From the standpoint of the water resource management concerns addressed above, the major trade-off inherent in adopting the alternate policy is between the installed hydroelectric power capacity and the potential development of the energy resources in the basin. As the upper region of the basin continues to develop its alloted water rights, efficient management of the water resources of the basin will become a necessity. The management study performed here indicates ways in which added efficiency could possibly be attained.

The simulation model developed here provides the type of information required for comparing management alternatives and for making decisions regarding the future operation and development of the Colorado River Basin.

8.5 Suggestions for Further Research

Suggestions for further research involve all of the areas addressed in this study.

In the area of Colorado River Basin modeling, improvement should be sought in the area of streamflow modeling, water quality modeling, and reservoir modeling.

The form of the streamflow model used in this study, and coincidently by the U.S. Bureau of Reclamation, reproduces month-to-month serial correlation of the historical streamflows. As indicated in Chapter 6, streamflow patterns covering several years have a great effect upon the behavior of the large reservoirs in the Colorado River system. It is suggested that analyses of runs may provide a method for selecting synthetic sequences whose long-term flow patterns are characteristic of those observed in the Colorado Basin. The fractional noise streamflow generation models, presently in a state of development, may offer a means for including this type of information directly into the model.

Studies of climatic change may also be fruitful by indicating possible ranges of future water resource conditions in the basin.

As discussed at some length in this paper, more data than is presently available will be required to model adequately the relationship between the water quality in Lake Powell and the volume of storage in the reservoir. The members of the Lake Powell Research Project are presently studying the chemical processes occurring in Lake Powell and attempting to develop good predictive models (Reynolds, 1975).

In order to make use of these improved lake models it will be necessary to model the flows of particular ions from each upstream tributary rather than the total dissolved solids flows as in this research.

In the context of Colorado River Basin Management several areas of future research can be identified. The selective simulation presented in the paper provide information regarding possible directions to be taken in managing the river basin. To be able to compare management alternatives more rigorously, an economic model must be developed and combined with the hydrologic simulation model developed here. Changes to the existing model could include the incorporation of the economic-based reservoir discharge rules presented in Chapter 4.

Finally, the model could be used to determine the impacts of energy resource development in the Upper Colorado River Basin. Preliminary work in this area should include a compilation of presently uncommitted water available for the extraction and processing of these energy resources. Western water law requires that the most recently acquired water rights are the first to be denied during periods of low runoff. For this reason the legal aspects of water use for energy development should be examined.

The presently expected future development of Colorado River water resources raises serious doubts as to the ability of the system to provide a reliable supply of water to all users under the existing framework of institutional constraints. It appears that the original division of water and the location of water deliveries specified by the 1922 Colorado River Compact must eventually be reevaluated. A study of possible alternative water allocation agreements should be undertaken, leading toward proposals for governmental or geographically defined regulatory agencies. For example, a single basin agency consisting of representatives from the states and individual water and energy interests might be considered. The potential value of such an agency is demonstrated by the success of the Colorado River Salinity Control Forum in determining a program of salinity control acceptable to many interested parties.

Each of the areas of research suggested above are not limited in application to Colorado River Basin. As further development of water resources taxes man's ability to manage those resources wisely and efficiently, better models and their imaginative use will become a necessity.

REFERENCES

CHAPTER 1

Askew, Arthur J. (1974) Optimum reservoir operating policies and the imposition of a reliability constraint. Water Resources Research 10(1):51-55.

Buras, Nathan. (1972) Scientific allocation of water resources. New York:American Elsevier Publishing Company, Inc.

Colorado River Board of California (CRBC). (1974) Annual Report, Year ending December 31, 1973. Los Angeles, California:CRBC.

Dixon, N. P.; Hendricks, D. W.; Auber, A. L.; and Bagley, J. M. (1970) Developing a hydro-quality simulation model. Report PRWG 67-1: 23-27, 73-82. Logan, Utah:Utah Water Resources Laboratory.

Dixon, N. P. and Hendricks, D. W. (1970) Simulation of spatial and temporal changes in water quality within a hydrologic unit. Water Resources Research 6(4):483-497.

Emshoff, James R. and Sisson, Roger L. (1970) Design and use of computer simulation models. London:Macmillan Company.

Fiering, Myron B. (1961) Queueing theory and simulation in reservoir design. Journal of the Hydraulic Division. ASCE Paper 2981:39-69.

Flack, Ernest J. and Howe, Charles W. (1974) Salinity in Water Resources Proceedings of the 15th Annual Western Resources Conference at the University of Colorado July 1973. Boulder, Colorado:Merriman Publishing Company.

Flucher, M. Kenneth et al. (1975) U. S. Bureau of Reclamation models, panel moderator, at Seminar on Colorado River Basin Modeling Studies, 17 July 1975, at Utah State University at Logan, Utah.

Grantham, George R.; Schaake, John C., Jr.; and Pyatt, Edwin E. (1971) Water quality simulation model. Journal of the Sanitary Engineering Division. ASCE (SA5):569-583.

Hall, Warren A.; Butcher, William S. and Esogbue, Austin. (1968) Optimization of the operation of a multiple-purpose reservoir by dynamic programming. Water Resources Research 4(3):471-477.

Hendrick, John D. and Gibbs, Albert E. (1974) Application of stochastic hydrology to simulate stream flow and salinity in the Colorado River. U. S. Bureau of Reclamation.

Howe, Charles W. and Orr, Douglas V. (1974a) Effects of agricultural acreage reduction on water availability and salinity in the Upper Colorado River Basin. Water Resources Research 10(5): 893-897.

Howe, Charles W. and Orr, Douglas V. (1974b) Economic incentives for salinity reduction and water conservation in the Colorado River Basin:In Salinity in Water Resources. Boulder, Colorado:Merriman Publishing Company.

Hyatt, M. Leon; Riley, J. Paul, McKee M. Lynn; and Israelson, Eugene K. (1970) Computer simulation of the hydrologic-salinity flow system within the Upper Colorado River Basin. Logan, Utah: Utah Water Research Laboratory.

Kindswater, C. E. (1964) Organization and methodology for river basin planning. Atlanta, Georgia:Georgia Institute of Technology.

Linsley, Ray D. and Franzini, Joseph B. (1972) Water resources engineering. New York:McGraw-Hill, Inc.

Loucks, Daniel P. (1968) Computer models for reservoir regulation. Journal of the Sanitary Engineering Division. ASCE Paper 6075: 657-669.

Maas, Arthur; Hufschmidt, Maynard M.; Dorfman, Robert; Thomas, Harold A.; Marglin, Stephen A.; and Fair, Gordon M. (1962) Design of water-resource systems. Cambridge, Mass.:Harvard University Press.

Maletic, John T. (1974) Current approaches and alternatives to salinity management in the Colorado River Basin. In Salinity in Water Resources: Proceedings of the 15th Annual Western Resources Conference at the University of Colorado July, 1973. Boulder, Colorado:Merriman Publishing Company.

Mann, Dean E.; Weatherford, Gary D.; and Nichols, Phillip. (1974) Legal-Political History of Water Resource Development in the Upper Colorado River Basin. Lake Powell Research Project Bulletin, No. 4. Los Angeles Regents of the University of California.

McBean, E. A. and Schaake, J. C., Jr. (1973) A marginal analysis system simulation technique to formulate improved water resource configurations to meet multiple objectives.

Metropolitan Water District of Southern California. (1968) Report for the fiscal year July 1, 1967 to June 30, 1968. Los Angeles, California:MWD.

Moran, P. A. P. (1970) Simulation and evaluation of complex water systems-A brief report. Water Resources Research. 6(6):1737-1742.

NAS-NRC Committee on Water. (1968) Water and Choice in the Colorado River Basin. Publication 1689. Washington, D. C.:National Academy of Sciences.

O'Brien, James J. (1975) Total water management concept in the Colorado River Basin. Paper presented at the Seminar on Colorado River Basin Modeling Studies, 17 July 1975 at Utah State University, Logan, Utah.

Orlob, Gerald T. (1973) Introduction to simulation techniques. In Models for environmental pollution controls. Edited by Rolf A. Deininger. Ann Arbor, Michigan:Ann Arbor Science Publishers, Inc.

Reader's Digest Association. (1963) Reader's Digest Great World Atlas. New York:Reader's Digest Association.

Ribbens, Richard W. and Wilson, Robert F. (1973) Application of a river network model to water quality investigations for the Colorado River. Denver, Colorado:U. S. Department of the Interior, Bureau of Reclamation Engineering and Research Center.

Sigualdason, O. T.; de Lucia, R. J.; and Biswas, A. K. (1972) The Saint John Study: An example of complementary usage of optimization and simulation modeling in water resources planning. International symposium on mathematical modeling techniques in water resources systems. Proceedings. Vol. 3, May 9-12. Ottawa, Canada.

Upper Colorado Region, State-Federal Inter-Agency Group. (1971) Upper Colorado Region comprehensive framework study - main report.

U. S. Bureau of Reclamation. (1971) Quality of Water-Colorado River Basin. Progress Report No. 5. Washington, D. C.:Government Printing Office.

U. S. Bureau of Reclamation. (Undated) Upper Colorado River Water Uses with Projected Depletions at Lee Ferry (Received upon request 19 August 1971 from L. M. Butterfield, Acting Regional Supervisor of Water and Land Operations, USBR Regional Office - Region 9, Salt Lake City, Utah).

U. S. Congress. (1902) Federal Reclamation Act of 1902. Public Law 161. 57th Congress, 1st Session.

U. S. Congress. (1928) Boulder Canyon Project Act, HR#5773. 70th Congress, 2nd session. ch. 42, p. 1058.

U. S. Congress. (1949) Upper Colorado River Basin Compact, S790. 81st Congress, 1st session, ch. 48, p. 33.

U. S. Congress. (1956) Senate. Colorado River Storage Project Act, S500. Public Law 84-485. 84th Congress, 2nd session.

U. S. Congress. (1968) Senate. Colorado River Basin Project Act. S1004. Public Law 90-537. 90th Congress, 1st session.

U. S. Congress. (1972) Federal Water Pollution Control Act. Public Law 90-500. 90th Congress, 2nd session.

U. S. Congress. (1974) Colorado River Basin Salinity Control Act. Public Law 93-320. 93rd Congress.

U. S. Department of the Interior. Notices. (1970) Colorado River Reservoirs, Coordinated Long-Range Operation. Federal Register 35(112):8951-8952.

U. S. Environmental Protection Agency. Rules and Regulations (1974) Water Quality Standards. Federal Register 39(244):43721-43723.

U. S. Supreme Court. (1963) Report of the Special Master: Arizona vs. California. Supreme Court Reporter 83A(372-374), U. S. 546.

Utah State University. (1975) Seminar on Colorado River Basin Modeling Studies, 16-18 July 1975. Utah State University, Logan, Utah.

Weber, Ernest M. (1975) Private communication.

Weber, Ernest M.; Donabedian, Christopher S.; and Tostrud, Merlin B. (1975) Models applied to salinity projections. Paper presented at the Seminar on Colorado River Basin Modeling Studies, 17 July 1975, at Utah State University, Logan, Utah.

CHAPTER 2

Bendat, Julius S. and Piersol, Allan G. (1971) Random data: analysis and measurement procedures. New York:Wiley-Interscience.

Benjamin, Jack R. and Cornell, C. Allin (1970) Probability, statistics, and decisions for civil engineers. New York:McGraw-Hill.

Benson, M. A. and Matalas, N. C. (1967) Synthetic hydrology based on regional statistical parameters. Water Resources Research 3(4): 931-935.

Brittan, Margaret R. (1961) Probability analysis applied to the development of synthetic hydrology for the Colorado River Basin. Boulder, Colorado:University of Colorado.

Bryson, Reid A. (1975) The lessons of climatic history. Environmental conservation. 2(3):163-170.

Clinton, M. and Hendrick, J. (1972) Personal communication during a visit to the USBR Region 9 Office, Salt Lake City, Utah.

Fiering, Myron B. (1961) Queueing theory and simulation in reservoir design. Journal of the Hydraulic Division. ASCE Paper 2981:39-69.

Fiering, Myron B. (1964) Multivariate technique for synthetic hydrology. Journal of the Hydraulic Division. ASCE Paper 4027: 43-60.

Fiering, Myron B. (1967) Streamflow synthesis. Cambridge, Mass.: Harvard University Press.

Fiering, Myron B. and Jackson, B. B. (1971) Synthetic streamflows. American Geophysical Union Water Resources Monograph 1. Washington, D. C.:American Geophysical Union.

Garnsey, Morris E.; Brittan, Margaret R.; Julian, Paul R.; Crow, Loren W.; Schlensener, Richard A.; and Yevdjevich, Vujica M. (1961) Past and probable future variations in streamflow in the Upper Colorado River Part 1. Summary and conclusion. Boulder, Colorado:University of Colorado.

Hendrick, John (1973) Techniques for modeling reservoir salinity. Hydrology Papers, #62. Fort Collins, Colorado:Colorado State University.

Hendrick, John D. and Gibbs, Albert E. (1974) Application of stochastic hydrology to simulate streamflow and salinity in the Colorado River. Denver, Colorado:Bureau of Reclamation Engineering and Research Center, Division of Planning Coordination, Water Utilization Section.

Howe, Charles W. and Orr, Douglas V. (1974a) Effects of agricultural acreage reduction on water availability and salinity in the Upper Colorado River Basin. Water Resources Research 10(5):893-897.

Howe, Charles W. and Orr, Douglas V. (1974b) Economic incentives for salinity reduction and water conservation in the Colorado River Basin. In Salinity in Water Resources: Proceedings of the 15th annual Western Resources Conference, edited by C. W. Howe and J. E. Flack. Boulder, Colorado:Merriman Publishing Company.

Hyatt, M. Leon; Riley, J. Paul; McKee, M. Lynn; and Israelson, Eugene K. (1970) Computer simulation of the hydrologic-salinity flow systems within the Upper Colorado River. Logan, Utah:Utah Water Research Lab.

Jackson, Barbara Bund. (1975a) The use of streamflow models in planning. Water Resources Research 11(1):54-63.

_______. (1975b) Markov mixture models for drought lengths. Water Resources Research 11(1):64-74.

_______. (1975c) Birth-death models for differential persistence. Water Resources Research 11(1):75-95

Jacoby, Gordon C., Jr. and Anderson, Orson L. (1972) Secular trends in streamflow. In Lake Powell Project-Final Report of Activities. Flagstaff, Arizona:Museum of Northern Arizona.

Julian, Paul R. (1960) A synthetic hydrology for the Colorado River. In Papers of the Western Resources Conference. University of Colorado Press.

Julian, Paul R. (1961) A study of the statistical probability of stream-runoff in the Upper Colorado River Basin. Boulder, Colorado:University of Colorado.

Leopold, Luna B. (1959) Probability analysis applied to a water-supply problem. USGS Circular 410. Washington, D. C.:Government Printing Office.

Linsley, Ray K. and Franzini, Joseph B. (1972) Water resources engineering. New York:McGraw-Hill Inc.

Mandelbrot, Benoit B. and Wallis, James R. (1969) Computer experiments with fractional Gaussian noises, 1, averages and variances.

Mandelbrot, Benoit B. and Wallis, James R. (1968) Noah, Joseph, and operational hydrology. Water Resources Research 4(5):909-918.

Matalas, N. C. (1967a) Time series analysis. Water Resources Research 3(3):817-829.

. (1967b) Mathematical assessment of synthetic hydrology. Water Resources Research 3(4):937-945.

Pegram, G. G. S. and James, W. (1972) Multi-lag multivariate auto-regression model for the generation of operational hydrology - A brief report. Water Resources Research 8(4):1074-1076.

Randkivi, A. J. and Lawgun, N. (1974) Simulation of rainfall sequences. Journal of Hydrology 22:271-294.

Reader's Digest Association. (1963) Reader's Digest Great World Atlas. New York:Reader's Digest Association.

Rodriguez-Iturbe', Ignacio; Mejia, Jose M.; and Dawdy, David R. (1972a) Streamflow simulation: 1.A new look at Markovian models, fractional Gaussian noise, and crossing theory. Water Resources Research 8(4):921-944.

________. (1972b) Streamflow simulation: 2. The broken line process as a potential model for hydrologic simulation. Water Resources Research 8(4):931-944.

Thomas, H. A., Jr., and Fiering, Myron B. (1963) The nature of the storage-yield relationship. Operations research in water management report of the Harvard Water Group to the USPHS. Cambridge, Mass.:Harvard University Press.

U. S. Bureau of Reclamation (1969) Report of the Committee on Probabilities and Test Studies to the Task Force on Operating Criteria for the Colorado River. (Received from USBR Regional Office - Region 9, Salt Lake City, Utah.)

U. S. Bureau of Reclamation. (1971a) "Computation of Virgin Flow-Colorado River at Lee Ferry". Region 9 Office, Salt Lake City, Utah.

U. S. Bureau of Reclamation. (1971b) Quality of Water: Colorado River Basin, Progress Report No. 5. Washington, D. C.:Government Printing Office.

U. S. Geological Survey (1973) Surface water supply of the United States, Colorado River Basin

Water Year	Water Supply paper No.	Water Year	Water Supply Paper No.
1930	704	1946	1059
1931	719	1947	1089
1932	734	1948	1119
1933	749	1949	1149
1934	764	1950	1179
1935	789	1951	1213
1936	809	1952	1243
1937	829	1953	1283
1938	859	1954	1343
1939	879	1955	1393
1940	899	1956	1443
1941	929	1957	1513
1942	959	1958	1563
1943	979	1959	1633
1944	1009	1960	1713
1945	1039	1961-65	1925-1926
		1966-70	2124-2126

1966-70 Part 9. Colorado River Basin, Vol. 1, 2, 3, Water Supply Paper No. 2125, U. S. Government Printing Office, Washington, D. C.:1973.

Accuracy of Field Data: Vol. 1 pp. 7, 512
Vol. 2 pp. 7, 435, 463, 605.

Weisbecker, Leo W. (1974) Snowpack, cloud-seeding, and the Colorado River. Oklahoma:University of Oklahoma Press.

Willmore, Paul and Lazenby, Gerald. (1973) Personal communication with the USBR Region 9 Office, Salt Lake City, Utah.

Yevdjevich, Vujica M. (1961) Some general aspects of fluctuations of annual runoff in the Upper Colorado River Basin. Fort Collins, Colorado:Colorado State University.

Yevjevich, Vujica M. (1972) Probability and statistics in hydrology. Fort Collins, Colorado, Water Resources Publications.

Young, G. K. and Pisano, W. C. (1968) Operational hydrology using residuals. ASCE Proceedings 94(HY4):909.

CHAPTER 3

Colorado River Board of California (CRBC). (1974) Annual Report, year ending December 31, 1973. Los Angeles, California:CRBC.

Flack, Ernest J. and Howe, Charles W. (1974) Salinity in water resources: Proceedings of the 15th Annual Western Resources Conference at the University of Colorado. Boulder, Colorado: Merriman Publishing Company.

Hall, F. R. (1970) Dissolved solids-discharge relationships, 1, mixing models. Water Resources Research 6(3):845-850.

Hall, F. R. (1971) Dissolved solids-discharge relationships, 2, applications to field data. Water Resources Research 7(3):591-601.

Holburt, Myron B. and Valentine, Vernon E. (1972) Present and future salinity of the Colorado River. Journal of the Hydraulic Division ASCE(HY3):503-520.

Hyatt, M. Leon; Riley, J. Paul; McKee, M. Lynn; and Israelson, Eugene K.; (1970) Computer simulation of the hydrologic-salinity flow system within the Upper Colorado River Basin. Logan, Utah: Utah Water Research Laboratory.

Iorns, W. V.; Hembree, C. H.; and Oakland, G. L. (1965) Water resources of the Upper Colorado River Basin - technical report. U.S.G.S. Professional Paper 441 and 442 (data). Washington, D. C.:Government Printing Office.

Johnson, N. M.; Likens, G. E.; Borman, F. H.; Fisher, D. W.; and Pierce, R. S. (1969) A working model for the variation in stream water chemistry at the Hubbard Brook Experimental Forest. Water Resources Research 5(6):1353-1363.

Langbein, W. B. and Dawdy, D. R. (1964) Occurrence of dissolved solids in surface waters in the U. S. USGS Professional Paper 501-D, pp. 115-117. Washington, D. C.:Government Printing Office.

Ledbetter, J. O., and Gloyna, E. F. (1964) Predictive techniques for water quality inorganics. Journal of the Sanitary Engineering Division. ASCE 90(1):127-151.

Maletic, John T. (1974) Current approaches and alternatives to salinity management in the Colorado River Basin. In Salinity in water resources Proceedings of the 15th Annual Western Resources Conference at the University of Colorado, July 1963. Boulder, Colorado:Merriman Publishing Company.

O'Connor, Donald J. (1974) The concentration of dissolved solids and river flow: Part A. steady state conditions. Part B. time variable conditions. Unpublished manuscript.

Pinder, George F. and Jones, John F. (1969) Determination of the ground water component of peak discharge from the chemistry of total run-off. Water Resources Research 5(2):438-445.

Pionke, H. B.; Nickes, A. D.; and Schoof, R. R. (1972) Estimating salinity of streams in the Southwest U. S. Water Resources Research 8(6):1597-1604.

Ribbens, Richard W. and Wilson, Robert F. (1973) Applications of a river network model to water quality investigations for the Colorado River. Denver, Colorado: U. S. Department of the Interior, Bureau of Reclamation Engineering and Research Center.

U. S. Bureau of Reclamation. (1971) Quality of Water-Colorado River Basin: Progress Report No. 5, Washington, D. C.:Government Printing Office.

Utah State University.(1975) Seminar on Colorado River Basin modeling studies, 16-18 July 1975. Utah State University, Logan, Utah.

Valentine, Vernon E. (1974) Impacts of Colorado River salinity. Journal of the Irrigation and Drainage Division. ASCE (Dec): 495-510.

Weber, Ernest, M. (1975) Personal communication with the Colorado River Board of California.

Weber, Ernest M.; Donabedian, Christopher S.; and Tostrud, Merlin B. (1975) Models applied to salinity projections. Paper presented at the Seminar on Colorado River Basin Modeling Studies, 17 July 1975, at Utah State University, Logan, Utah.

CHAPTER 4

Askew, Arthur J. (1974) Optimum reservoir operating policies and the imposition of reliability constraints. Water Resources Research 10(1):51-66.

Beard, Leo R. (1967) Optimization techniques for hydrologic engineering. Water Resources Research. 3(3):809-815.

Bower, Blair T.; Hufschmidt, Maynard M.; and Reedy, William W. (1962) Operating proceedures: Their role in the design of water-resource systems by simulation analyses. In Design of water-resource systems, pp. 443-458. By Maas, Arthur; Hufschmidt, Maynard M.; Dorfman, Robert; Thomas, Harold A. Jr.; Marglin, Stephen A.; and Fair, Gordon M.; Cambridge, Mass.:Harvard University Press.

Clinton, Michael J. and Others (1970) Colorado River Simulation Model: a digital computer system to model the major surface storage features of the Colorado River Basin. Salt Lake City, Utah, U. S. Department of the Interior, Bureau of Reclamation.

Feeny, C. (1975) Personal communication.

Hall, Warren A. (1964) Optimum design of a multi-purpose reservoir. Journal of the Hydraulics Division. ASCE 90(HY4):141-149.

Hall Warren A.; Tauxe, G. W.; and Yeh, W. W-G. (1969) An alternate proceedure for the optimization of operations for planning with multiple river, multiple purpose systems. Water Resources Research 5(6):1367-3172.

Harbeck, G. Earl; Kohler, Max A.; Loberg, Gordon E. and others (1958) Water-loss investigations: Lake Mead Studies. USGS Professional Paper 298. Washington, D. C.:Government Printing Office.

Hendrick, John (1973) Techniques for modeling reservoir salinity. Hydrology Papers, #62. Fort Collins, Colorado:Colorado State University.

Howard, C. S. (1949) Chemical limnology in Lake Mead, comprehensive survey 1948-1949. Part 7: Limnology. U.S.G.S. Preliminary Report. Washington, D. C.:Government Printing Office.

Hutchinson, G. E. (1957) A treatise on limnology. Vol 1 and II. New York:John Wiley and Sons.

Iorns, W. V.; Hembree, C. H.; and Oakland, G. L. (1965) Water resources of the Upper Colorado River Basin - technical report. U. S. G. S. Professional Paper 441 and 442. Washington, D. C.: Government Printing Office.

Irelan, Burdge. (1971) Salinity of surface water in the Lower Colorado River - Salton Sea area. U. S. G. S. Professional Paper 486-E. Washington, D. C.:Government Printing Office.

Langbein, W. B.; Smith, W. O.; Votter, C. P.; Cummings, G. B.; and others. (1960) Comprehensive survey of sedimentation in Lake Mead, 1948-1949. U.S.G.S. Professional Paper 295; pp. 95 Washington, D. C.:Government Printing Office.

Loucks, Daniel P. (1968) Computer models for reservoir regulation. Journal of the Sanitary Engineering Division. ASCE 94(SA4):657-669.

Mejia, Jose M.; Egli, Paul; and Leclerc, Andre. (1974) Evaluating multi-reservoir operating rules. Water Resources Research. 19(6):1090-1098.

O'Connor, Donald J. and Mueller, John A. (1970) A water quality model for chlorides in Great Lakes. Journal of the Sanitary Engineering Division ASCE 96(SA4):955-975.

O'Melia, Charles R. (1971) An approach to the modeling of lakes. Unpublished Manuscript.

Orlob, Gerald T. and Selna, Lawrence G. (1970) Temperature variations in deep reservoirs. Journal of the Hydraulics Division. ASCE 96(HY2):391-410.

Rahman, M. and Marcotte, N. (1974) On thermal stratification in large bodies of water. Water Resources Research 10(6):1143-1147.

Reynolds, R. C. (1973) Lake geochemistry. In Second Progress Report Lake Powell Research Project. Los Angeles, California: University of California. pp. 56-58.

Rechard, P. A. (1965) Determining bank storage of Lake Mead. Journal of the Irrigation and Drainage Division. ASCE 91(IR1):141-157.

Reynolds, R. C. (1975) Personal communication. (October, 1975).

Reynolds, R. C. Jr. and Johnson, N. M. (1974) Major element geochemistry of Lake Powell; Lake Powell Research Project Bulletin, No. 5 Los Angeles, California:Institute of Geophysics and Planetary Physics.

Ribbens, Richard W. and Wilson, Robert F. (1973) Application of a river network model to water quality investigations for the Colorado River Denver, Colorado:U. S. Department of the Interior, Bureau of Reclamation Engineering and Research Center.

Ryan, Patrick J. and Harleman, Donald R. (1971) Prediction of the annual cycle of temperature changes in a stratified lake or reservoir: mathematical model and user's manual. MIT Department of Civil Engineering Report #137. Cambridge, Mass. MIT.

Schweig, Z. and Cole, J.A. (1968) Optimal control of linked reservoirs. Water Resources Research. 4(3):479-497.

Shoemaker, Eugene M. (1975) Personal communication. November, 1975.

Thomas, Harold A. Jr. and Watermeyer, Peter. (1962) Mathematical models: a stochastic sequential approach. In Design of water resources systems, pp. 540-545. My Maas, Arthur; Hufschmidt, Maynard M.; Dorfman, Robert; Thomas, Harold A., Jr.; Marglin, Stephen A.; and Fair, Gordon M. Cambridge, Mass:Harvard University Press.

U. S. Army Corps of Engineers (1968) Report on reservoir regulation for flood-control storage at Hoover Dam and Lake Mead. 1955, revised 1968.

U. S. Bureau of Reclamation (1963a) Reservoir losses, Lake Powell Colorado River Storage Project (evaporation tables). Mimeographed. Salt Lake City, Utah:U. S. Department of the Interior, Bureau of Reclamation.

U. S. Bureau of Reclamation (1963b) Colorado River Storage Project. Glen Canyon Unit. Lake Powell: Area and Capacity Tables. Salt Lake City, Utah:U. S. Department of the Interior, Bureau of Reclamation.

U. S. Bureau of Reclamation (1967) Boulder Canyon Project, Arizona-Nevada. Lake Mead: area and capacity tables. Boulder City, Nevada:U. S. Department of the Interior, Bureau of Reclamation.

U. S. Bureau of Reclamation (1970) Glen Canyon Dam and Powerplant. Technical record of design and construction. Denver, Colorado: U. S. Department of the Interior, Bureau of Reclamation.

U. S. Bureau of Reclamation (1971) Quality of Water-Colorado River Basin. Progress Report No. 5. Washington, D. C.:Government Printing Office.

U. S. Bureau of Reclamation (1973) Quality of Water-Colorado River Basin. Progress Report No. 5. Washington, D. C.:Government Printing Office.

Varga, Louis P. and Falls, C. Paul (1972) Continuous system models of oxygen depletion in a eutrophic reservoir. Engineering, Science and Technology 6(2):135-142.

Vemuri, V. (1974) Multiple-objective optimization in water resource systems. Water Resources Research. 10(1):44-48.

CHAPTER 5

Feeny, C. (1975) Personal communication.

Hendrick, John (1973) Techniques for modeling reservoir salinity. Hydrology Papers, #62. Fort Collins, Colorado:Colorado State University.

Hoffman, Dale A. (1967) Water quality study of Lake Mead. Report No. CMI-70. Denver, Colorado:U.S. Bureau of Reclamation.

Hyatt, M. Leon; Riley, J. Paul; McKee, M. Lynn; and Israleson, Eugene K. (1970) Computer simulation of the hydrologic-salinity flow system within the Upper Colorado River Basin. Logan, Utah:Utah Water Research Laboratory.

Iorns, W. V.; Hembree, C.H.; and Oakland, G. L. (1965) Water resources of the Upper Colorado River Basin-technical report. U.S.G.S. Professional Paper 441 and 442 (data). Washington, D.C.: Government Printing Office.

Ribbens, Richard W. and Wilson, Robert F. (1973) Application of a river network model to water quality investigations for the Colorado River. Denver, Colorado:U.S. Department of the Interior, Bureau of Reclamation Engineering and Research Center.

U.S. Bureau of Reclamation (1969) Meeting of Federal and State Representatives for Review of Basin Data Pertinent to the Preparation of Operating Criteria for the Colorado River Pursuant to Section 602 of Public Law 90-537. Washington, D.C.:U.S. Department of the Interior.

U.S. Bureau of Reclamation (1971a) Quality of Water--Colorado River Basin: Progress Report No. 5, Washington, D.C. Government Printing Office.

U.S. Bureau of Reclamation (1971b) Upper Colorado River water uses with projected depletions at Lee Ferry (undated, received Aug. 1971). USBR, Denver, Colorado.

Upper Colorado Region, State-Federal Inter-Agency Group. (1971) Upper Colorado Region comprehensive framework study--main report.

U.S. Congress. (1974) Colorado River Basin Salinity Control Act. Public Law 93-320. 93rd Congress.

U.S. Department of the Interior. (1970) Colorado River Reservoirs, Coordinated Long-Range Operation. Federal Register 35(112):8951-8952.

U.S. Environmental Protection Agency (1971) The mineral water quality problem of the Colorado River Basin. Washington, D.C.:Government Printing Office.

U.S. Geological Survey (1966-1970) Surface Water Supply of the United States, Colorado River Basin.

Water Year	Water Supply Paper No.	Water Year	Water Supply Paper No.
1941	942	1956	1453
1942	950	1957	1523
1943	970	1958	1574
1944	1022	1959	1645
1945	1030	1960	1745
1946	1050	1961	1885
1947	1102	1962	1945
1948	1133	1963	1951
1949	1163	1964	1958
1950	1189	1965	1965
1951	1200	1966	1994
1952	1253	1967	2015
1953	1293	1968	2098
1954	1353	1969	2148
1955	1403	1970	2158

Weber, Ernest M.; Donabedian, Christopher S.; and Tostrud, Merlin B. (1975) Models applied to salinity projections. Paper presented at the Seminar on Colorado River Basin Modeling Studies, 16-18 July 1975, at Utah State University, Logan, Utah.

CHAPTER 6

Emshoff, James R. and Sisson, Roger L. (1970) Design and use of computer simulation models. London:MacMillan Company.

Hendrick, John (1973) Techniques for modeling reservoir salinity. Hydrology Papers, #62. Fort Collins, Colorado:Colorado State University.

Jackson, Barbara Bund. (1975) The use of streamflow models in planning. Water Resources Research. 11(1):54-63.

Jacoby, Gordon C., Jr. (1975) Personal communication.

Mandelbrot, Benoit B. and Wallis, James R. (1968) Noah, Joseph, and operational hydrology. Water Resources Research 4(5):909-918.

Melentijevich, Mirko J. (1965) The analysis of range with output linearly dependent upon storage. Hydrology Papers #11. Fort Collins, Colorado:Colorado State University.

Mize, Joe H. and Cox, J. Grady (1968) Essentials of simulation. New Jersey:Prentice-Hall,Inc.

Stockton, Charles W. (1975) River flow synthesis from tree-ring data. Paper presented at the Seminar on Colorado River Basin Modeling Studies, 17 July 1975, at Utah State University, Logan, Utah.

U.S. Geological Survey (1973) Surface water supply of the United States, Colorado River Basin. Water Supply Paper #2125.

Vicens, Guillermo J. and Schaake, John C., Jr. (1972) Simulation criteria for selecting water resource system alternatives. Report No. 154. Cambridge, Mass.:Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics.

Yevjevich, Vugica (1972a) Stochastic processes in hydrology. Fort Collins, Colorado:Water Resources Publications.

. (1972b) An objective approach to definitions and investigations of continental hydrologic droughts. Hydrology Papers #23. Fort Collins, Colorado:Colorado State University.

CHAPTER 7

Anderson, Orson L. and Perkins, Pricilla (1973) Some consequences of restricting the maximum elevation of Lake Powell. Lake Powell Research Project Progress Report. Los Angeles, California: University of California.

Beard, Leo R. (1967) Optimization techniques for hydrologic engineering. Water Resources Research 3(3):809-815.

Buras, Nathan (1972) Scientific allocation of water resources. New York:American Elsevier Pub. Co.

Clyde, Calvin (1974) Energy production and water supply-background. In Proceedings of the Universities Council on Water Resources, Energy, environment, and water resources. Logan, Utah: Utah State University.

Conway, R. W. (1963) Some tactical problems in digital simulation. Management Science 10(1):47-61.

Linsley, Ray K. and Franzini, Joseph B. (1972) Water resources engineering. New York:McGraw-Hill, Inc.

Mejia, Jose M.; Egli, Paul; and LeClerc, Andre (1974) Evaluating multireservoir operating rules. Water Resources Research 10(6):1090-1098.

Metz, William D. (1974) Oil shale: A huge resource of low-grade fuel. In Energy: use, conservation, and supply. Philip H. Abelson (ed.). New York:American Association for the Advancement of Science.

Monarchi, David E.; Kisiel, Chester C.; and Duckstein, Lucien (1973) Interactive multiobjective programming in water resources: a case study. Water Resources Research 9(4):837-850.

Reynolds, R. C. (1975) Personal communication.

Schweig, Z. and Cole, J. A. (1968) Optimal control of linked reservoirs. Water Resources Research 4(3):479-497.

Stamm, Gilbert G. (1975) Salinity control on the Colorado. Water Interantional July 1975:9-14.

Walsh, John (1974) Problems of expanding coal production. In Energy: use, conservation, and supply. Philip H. Abelson (ed.) New York:American Association for the Advancement of Science.

Weber, Ernest M. (1975) Personal communication.

Weisbecker, Leo W. (1974) Snowpack, cloud-seeding, and the Colorado River: a technology assessment of weather modification. Norman, Oklahoma:University of Oklahoma Press.

CHAPTER 8

Reynolds, R. C. (1975) Personal communication.

Thomas, Harold A., Jr. and Fiering, Myron B. (1962) The mathematical synthesis of streamflow sequences. In The Design of water resource systems, Arthur Maas et al. (Editors). Cambridge, Mass.:Harvard University Press.

Appendix A: Details of Statistical Computations

§A-1 Determination of lag-one month serial correlation coefficients, ${}_t a_m$. (Refer to Section 2.2.3.2 for details of applications.)

Equation (2.5), reproduced below, displays the lag-one month serial correlation coefficient. The notation used has been introduced in Section 2.2.3.

(A1) $$ {}_t\varepsilon_m^y(1) = ({}_t a_m)\cdot {}_t\varepsilon_{m-1}^y(1) + {}_t\varepsilon_m^y(2) $$

(The tributary subscript, t, is omitted for the remainder of this section.)

The first term on the right represents the estimate of $\varepsilon_m^y(1)$ based upon the value of $\varepsilon(1)$ from the previous month. The coefficient, a_m, is to be chosen so as to minimize the mean square error of the estimate, or equivalently, the variance of $\varepsilon_m^y(2)$, the step two residual.

Recalling that the residuals have zero mean,

(A2) $$ \mathrm{VAR}[\varepsilon_m^y(2)] = \overline{[\varepsilon_m^y(2)]^2} $$

$$ = \overline{[\varepsilon_m^y(1)-(a_m)\cdot \varepsilon_{m-1}^y(1)]^2} $$

Minimizing the expression in (A2) and solving for a_m,

(A3) $$ \frac{\partial \mathrm{VAR}[\varepsilon_m^y(2)]}{\partial a_m} = 0 $$

$$ = -2\cdot\overline{\varepsilon_m^y(1)\cdot\varepsilon_{m-1}^y(1)} + 2\cdot(a_m)\cdot\overline{[\varepsilon_{m-1}^y(1)]^2} $$

or,

(A4) $$ a_m = \frac{\mathrm{COVAR}[\varepsilon_m^y(1),\ \varepsilon_{m-1}^y(1)]}{\mathrm{VAR}[\varepsilon_{m-1}^y(1)]} $$

In this application,

$$\text{COVAR}[\varepsilon_m^y(1),\ \varepsilon_{m-1}^y(1)] = \frac{\sum_{y=1}^{n} [\varepsilon_m^y(1) \cdot \varepsilon_{m-1}^y(1)]}{n-1}, \tag{A5}$$

for m = 1, 2, ... , 12.

Also,

$$\text{VAR}[\varepsilon_{m-1}^y(1)] = \frac{\sum_{y=1}^{n} [\varepsilon_m^y(1)]^2}{n-1}, \tag{A6}$$

for m = 1, 2, ... , 12.

§A-2 Determination of the cross-correlation coefficients, b_{ts}. (Refer to Section 2.2.3.3 for details of application.)

Equation (2.7), reproduced below, displays the cross-correlation structure used in modeling tributary streamflows.

$$\text{(A7)} \qquad {}_t\varepsilon_m^y(2) = \sum_{s\varepsilon S} [(b_{ts})\cdot {}_s\varepsilon_m^y(2)] + {}_t\varepsilon_m^y(3),$$

where S is the set of tributaries with which tributary t is cross-correlated, and b_{ts}, $s\varepsilon S$, are the cross-correlation coefficients.

As in Section A-1, the coefficients are to be determined so as to minimize the variance of ${}_t\varepsilon_m^y(3)$, the step three residual. Estimating one variable by a multiple linear correlation of other variables typically involves the assumption that the constituent variables are independent. Since this assumption is not necessarily valid in the present context, the following formulation was adopted.

Proceeding as in Section A-1,

$$\text{(A8)} \qquad \text{VAR}[{}_t\varepsilon_m^y(3)] = \overline{\{{}_t\varepsilon_m^y(2) - \sum_{s\varepsilon S} [(b_{ts})\cdot {}_s\varepsilon_m^y(2)]\}^2}.$$

For a particular element of S, designated r, minimizing the above expression and solving for b_{tr} yields

$$\text{(A9)} \qquad \frac{\partial \text{VAR}[{}_t\varepsilon_m^y(2)]}{\partial b_{tr}} = 0$$

$$= -2 \cdot \overline{{}_t\varepsilon_m^y(2)\cdot {}_r\varepsilon_m^y(2)}$$

$$+2 \sum_{\substack{s\varepsilon S \\ s\neq r}} (b_{ts})\cdot \overline{{}_r\varepsilon_m^y(2)\cdot {}_s\varepsilon_m^y(2)}$$

$$+2(b_{tr})\cdot \overline{[{}_r\varepsilon_m^y(2)]^2},$$

or,

$$(A10) \qquad b_{tr} = \frac{\overline{{}_t\varepsilon_m^y(2) \cdot {}_r\varepsilon_m^y(2)} - \sum\limits_{\substack{s\varepsilon S \\ s\neq r}} (b_{ts}) \cdot \overline{{}_r\varepsilon_m^y(2) \cdot {}_s\varepsilon_m^y(2)}}{\overline{[{}_r\varepsilon_m^y(2)]^2}}$$

Using the definitions in Section A-1,

$$(A11) \qquad b_{tr} = \frac{\text{COVAR}[{}_t\varepsilon_m^y(2),\ {}_r\varepsilon_m^y(2)] - \sum\limits_{\substack{s\varepsilon S \\ s\neq r}} (b_{ts}) \cdot \text{COVAR}[{}_r\varepsilon_m^y(2),\ {}_s\varepsilon_m^y(2)]}{\text{VAR}[{}_r\varepsilon_m^y(2)]}$$

An analogous relationship may be formed for each element of S, and the resulting set of linear equations solved for the values of each b_{ts}.

FIGURE B-1

COLORADO RIVER UPPER MAINSTEM NEAR CISCO, UTAH

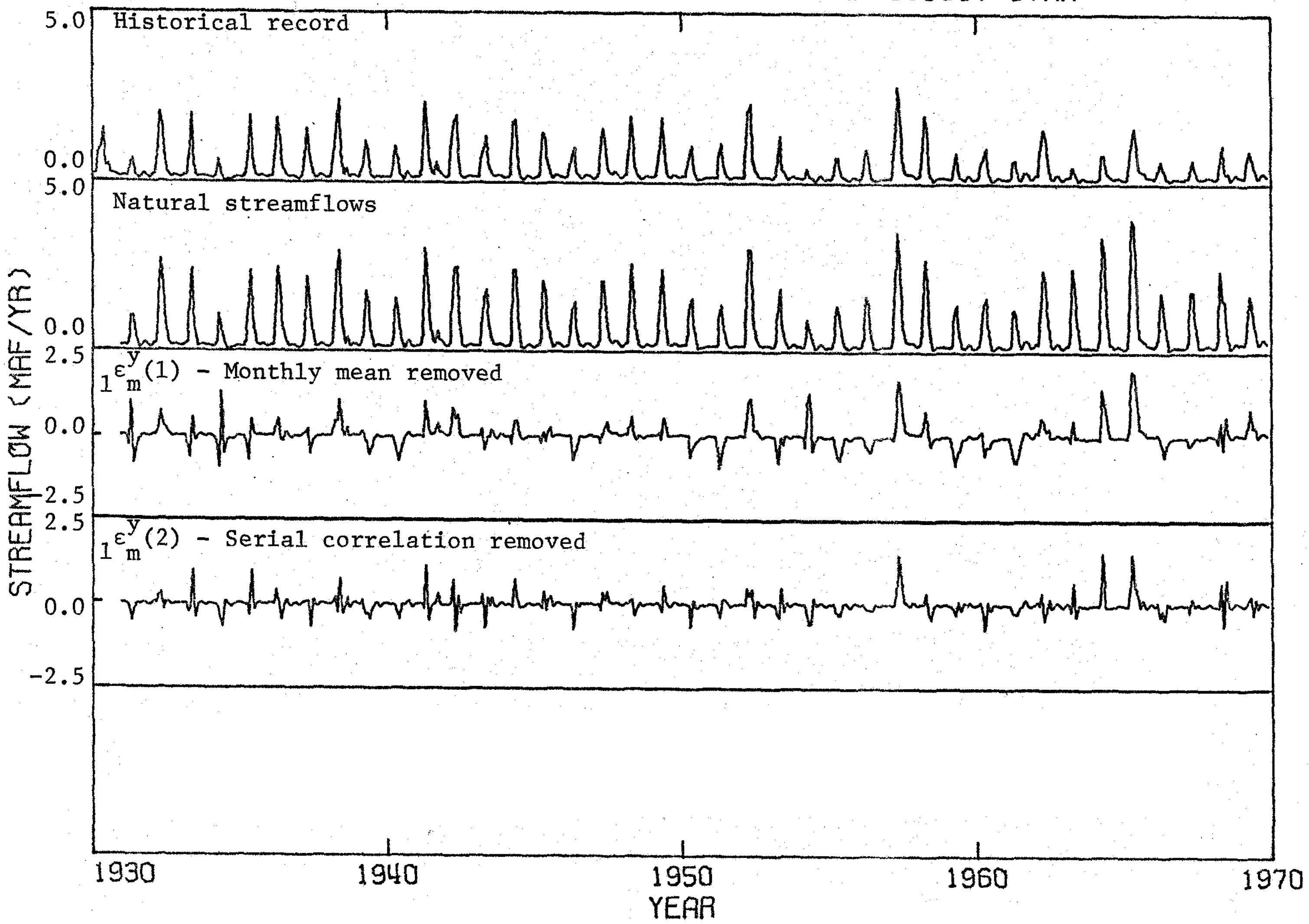


FIGURE B-2

GREEN RIVER NEAR GREEN RIVER, UTAH

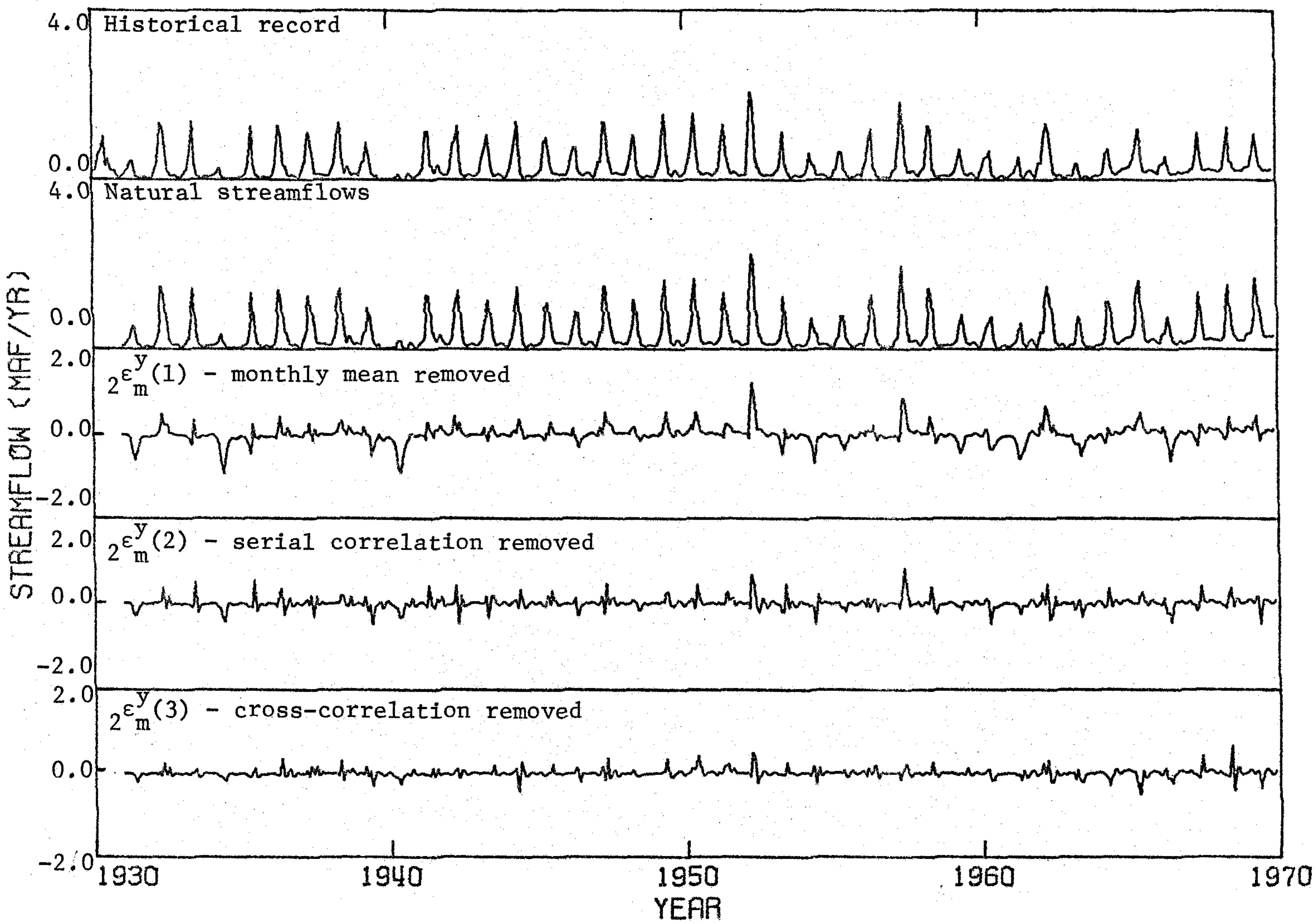


FIGURE B-3

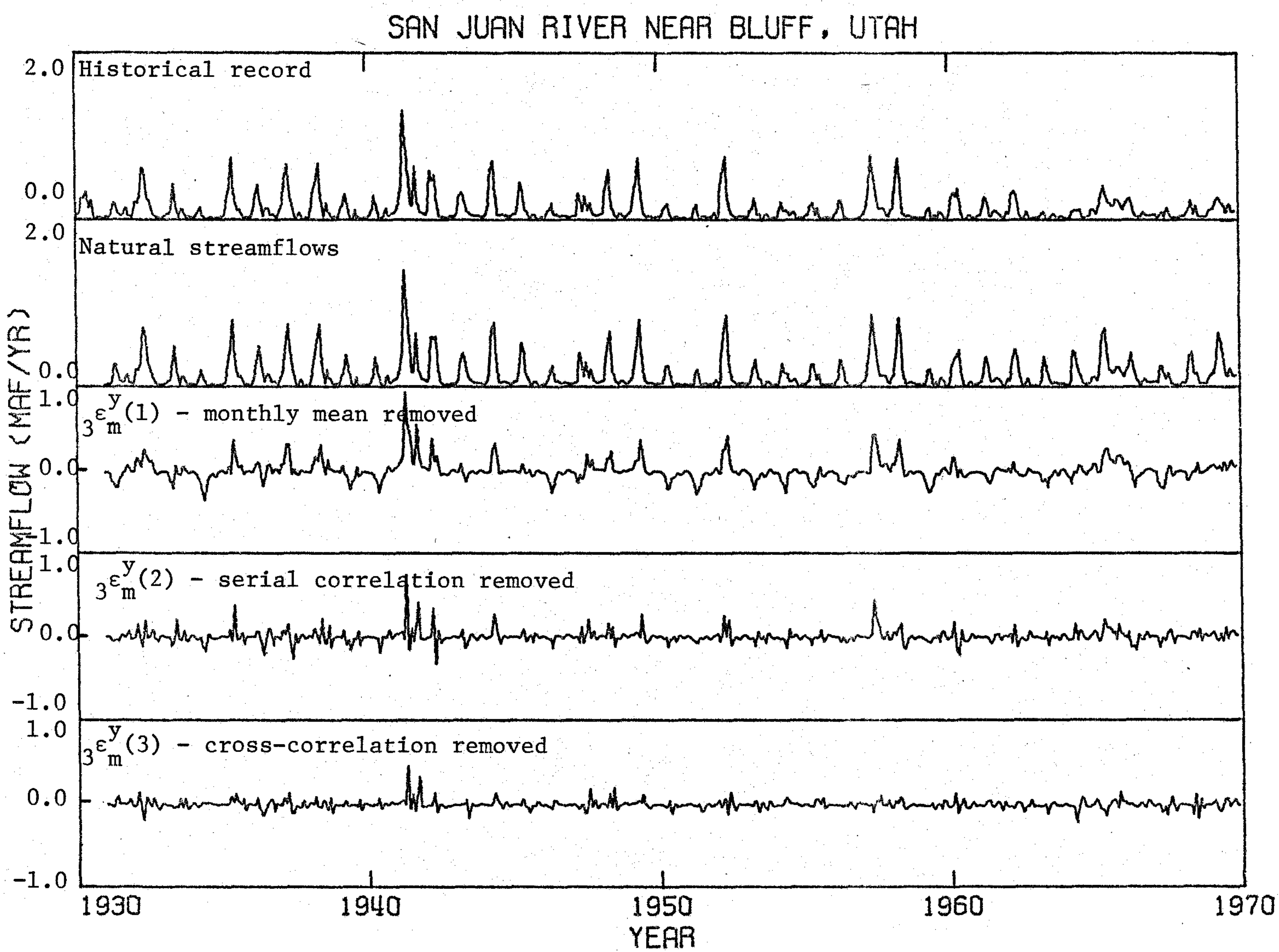

SAN JUAN RIVER NEAR BLUFF, UTAH
Historical record
Natural streamflows
$_3\varepsilon_m^y(1)$ - monthly mean removed
$_3\varepsilon_m^y(2)$ - serial correlation removed
$_3\varepsilon_m^y(3)$ - cross-correlation removed
2.0
0.0
1.0
-1.0
STREAMFLOW (MAF/YR)
1930
1940
1950
1960
1970
YEAR

FIGURE B-4

SAN RAFAEL RIVER NEAR GREEN RIVER, UTAH

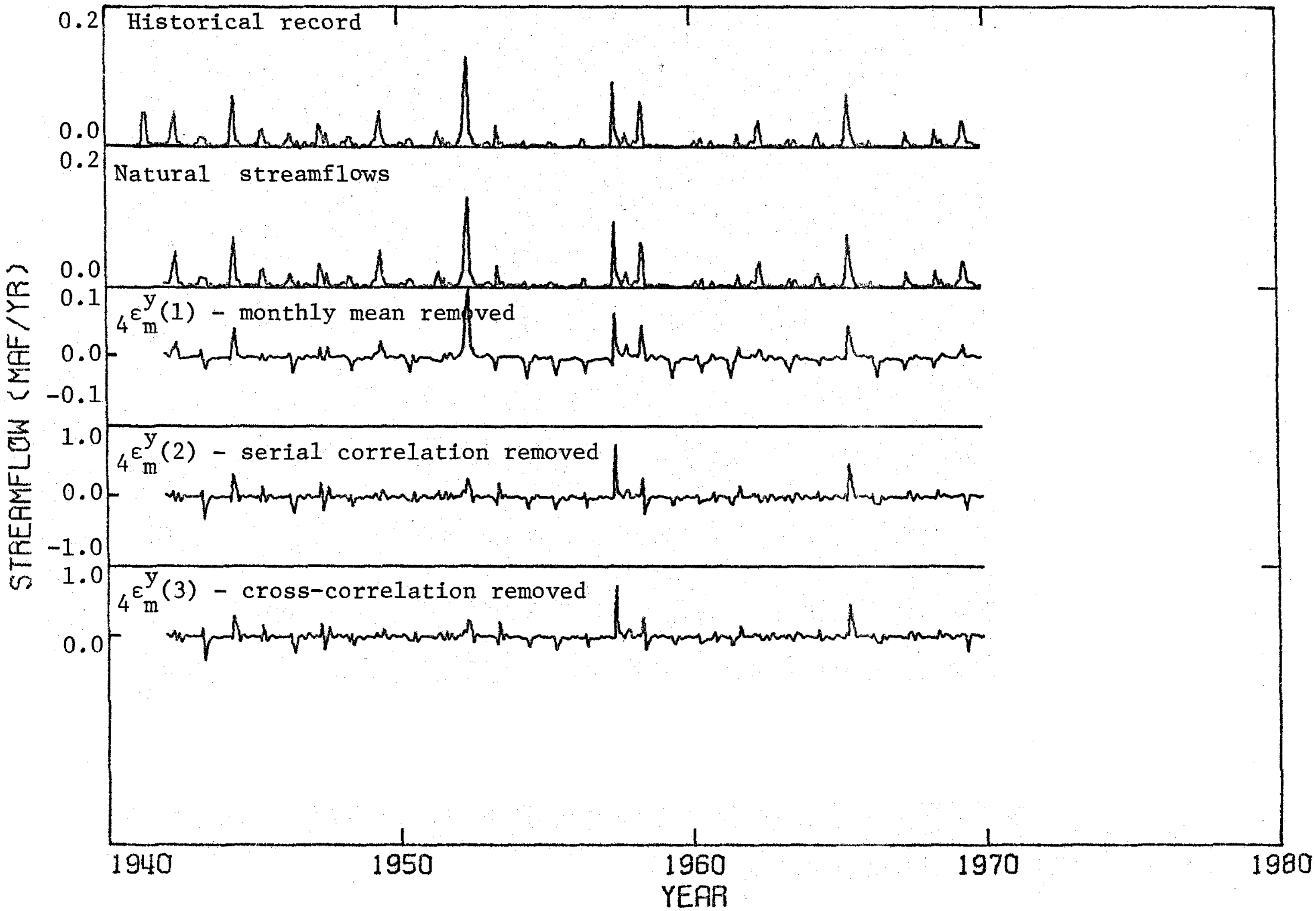


FIGURE B-5

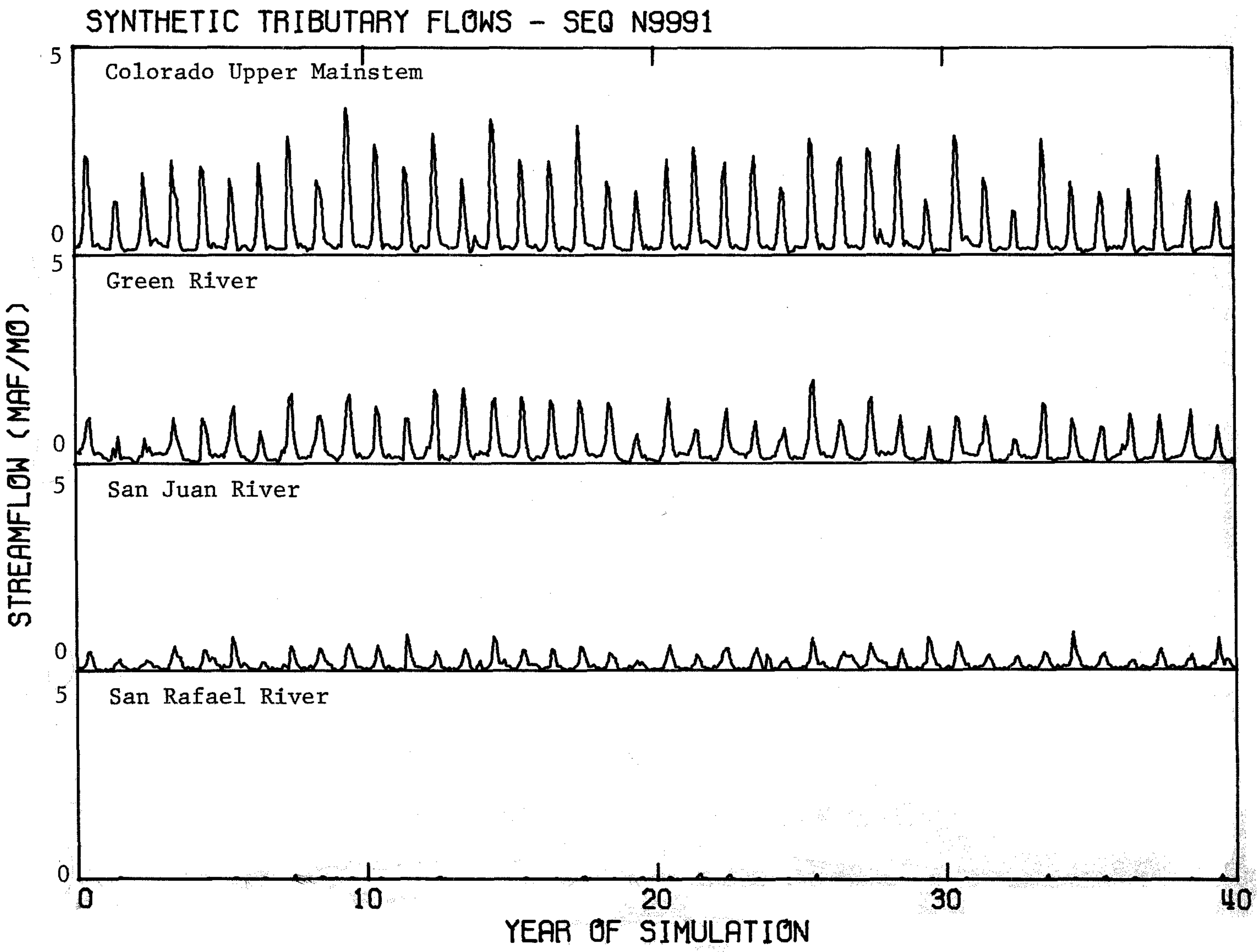

SYNTHETIC TRIBUTARY FLOWS - SEQ N9991
Colorado Upper Mainstem
Green River
San Juan River
San Rafael River
STREAMFLOW (MAF/MO)
YEAR OF SIMULATION
0
5
0
10
20
30
40

FIGURE B-6

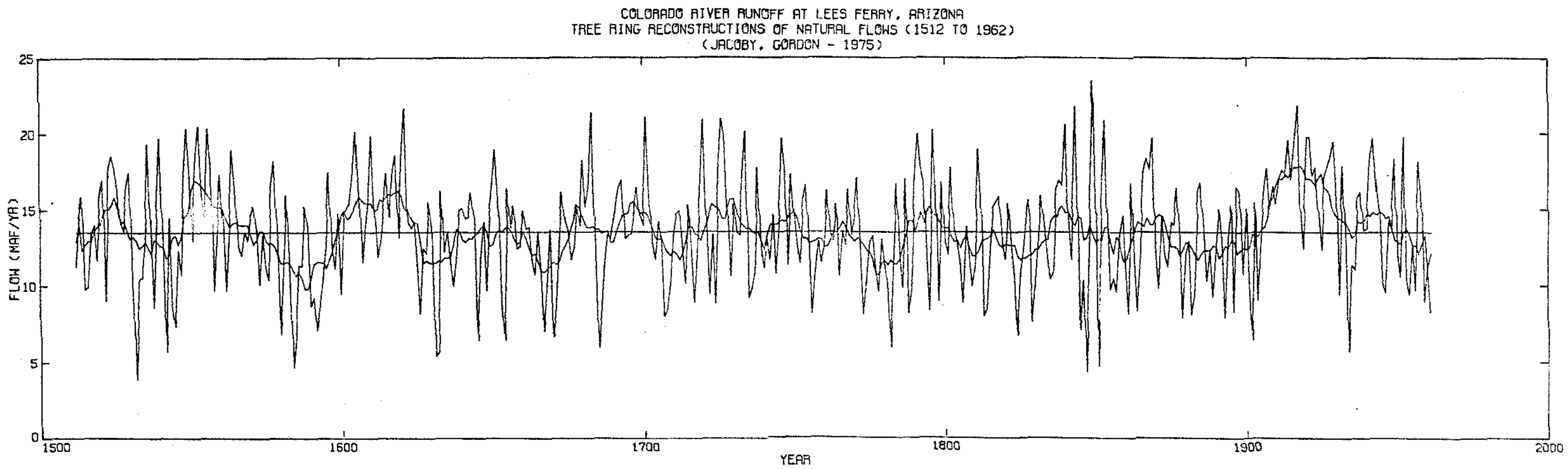

COLORADO RIVER RUNOFF AT LEES FERRY, ARIZONA
TREE RING RECONSTRUCTIONS OF NATURAL FLOWS (1512 TO 1962)
(JACOBY, GORDON - 1975)
FLOW (MAF/YR)
YEAR
0
5
10
15
20
25
1500
1600
1700
1800
1900
2000

TABLE C-1

Summary of Model Outputs for Lakes Powell and Mead

Depletion Level: DPL #1, 3.8 MAF/yr
Lake Powell Target Discharge, D_t = 8.23 MAF/yr
Lake Mead Target Discharge, D_t = 8.25 MAF/yr

			Maximum Allowed Powell Storage, SP_M					
			3 MAF		15 MAF		27 MAF	
ITEM X			$\overline{X}$	σ_X	$\overline{X}$	σ_X	$\overline{X}$	σ_X
POWELL:								
Inflow conc.,	C_i	(mg/ℓ)	600.		600.		600.	
Discharge conc.,	C_o	(mg/ℓ)	603.		619.		635.	
Inflow,	I_P	(MAF/yr)	9.88	3.14	9.88	3.14	9.88	3.14
Evaporation,	E	(MAF/yr)	0.06	0.01	0.31	0.08	0.56	0.09
Discharge,	D	(MAF/yr)	9.78	3.12	9.53	2.05	9.27	1.85
Withdrawal,	W	(MAF/yr)	0.05	0.00	0.05	0.00	0.05	0.00
Storage,	S	(MAF)	2.38	0.15	11.65	3.01	22.52	4.14
Power cap.,	P_c	(MW)	0.0	0.0	738.	247.	900.	7.
Power output	P_o	$(GWH)\times10^3$	0.0	0.0	3.77	0.22	4.09	0.18
MEAD:								
Inflow conc.,	C_i	(mg/ℓ)	670.		687.		704.	
Discharge conc.,	C_o	(mg/ℓ)	785.		810.		829.	
Inflow,	I_M	(MAF/yr)	10.34	3.12	10.09	2.05	9.83	1.85
Evaporation,	E	(MAF/yr)	0.96	0.13	0.98	0.02	0.94	0.12
Discharge,	D	(MAF/yr)	9.23	1.81	8.96	1.55	8.75	1.29
Withdrawal,	W	(MAF/yr)	0.13	0.00	0.13	0.00	0.13	0.00
Storage,	S	(MAF)	25.81	4.11	26.52	3.24	25.17	3.97
Power Cap.,	P_c	(MW)	1326.	11.	1328.	0.0	1328.	0.0
Power output	P_o	$(GWH)\times10^3$	4.58	0.90	4.45	0.77	4.34	0.64
TOTALS:								
Evaporation,	E_T	(MAF/yr)	1.02		1.29		1.50	
Storage,	S_T	(MAF)	28.19		38.17		47.69	
Power Cap.,	P_{cT}	(MW)	1326.		2111.		2228.	
Power output,	P_{oT}	$(GWH)\times10^3$	4.58		8.22		8.43	

Note: 1 MAF = 1.233 km^3; 1 GWH = one thousand MWH

TABLE C-2

Summary of Model Outputs for Lakes Powell and Mead

Depletion Level: DPL#2, 4.6 MAF/yr
Lake Powell Target Discharge, D_t = 8.23 MAF/yr
Lake Mead Target Discharge, D_t = 8.25 MAF/yr

ITEM X			Maximum Allowed Powell Storage, SP_M: 3 MAF $\bar{X}$	3 MAF σ_X	15 MAF $\bar{X}$	15 MAF σ_X	27 MAF $\bar{X}$	27 MAF σ_X
POWELL:								
Inflow conc.,	C_i	(mg/ℓ)	655.		655.		655.	
Discharge conc.,	C_o	(mg/ℓ)	657.		674.		687.	
Inflow,	I_P	(MAF/yr)	9.21	3.09	9.21	3.09	9.21	3.09
Evaporation,	E	(MAF/yr)	0.05	0.01	0.27	0.10	0.44	0.17
Discharge,	D	(MAF/yr)	9.00	3.07	8.77	1.76	8.60	1.23
Withdrawal,	W	(MAF/yr)	0.15	0.0	0.15	0.0	0.15	0.0
Storage,	S	(MAF)	2.35	0.16	10.14	3.75	17.44	7.00
Power cap.,	P_c	(MW)	0.0	0.0	690.	323.	803.	233.
Power output	P_o	(GWH)x10^3	0.0	0.0	3.16	0.21	3.45	0.16
MEAD:								
Inflow conc.,	C_i	(mg/ℓ)	727.		744.		758.	
Discharge conc.,	C_o	(mg/ℓ)	838.		856.		866.	
Inflow,	I_M	(MAF/yr)	9.56	3.07	9.33	1.76	9.15	1.24
Evaporation,	E	(MAF/yr)	0.76	0.24	0.71	0.24	0.63	0.19
Discharge,	D	(MAF/yr)	8.52	1.08	8.35	0.53	8.26	0.10
Withdrawal,	W	(MAF/yr)	0.26	0.0	0.26	0.0	0.26	0.0
Storage	S	(MAF)	19.14	7.52	17.83	7.62	15.32	5.95
Power cap.,	P_c	(MW)	1100.	432.	1038.	503.	989.	517.
Power output,	P_o	(GWH)x10^3	3.60	1.49	3.30	1.61	3.13	1.62
TOTALS:								
Evaporation,	E_T	(MAF/yr)	0.81		0.98		1.07	
Storage,	S_T	(MAF)	21.49		27.97		32.76	
Power cap.,	P_{cT}	(MW)	1100.		1728.		1792.	
Power output,	P_{oT}	(GWH)x10^3	3.60		6.46		6.58	

Note: 1 MAF = 1.233 km^3; 1 GWH = one thousand MWH

TABLE C-3

Summary of Model Outputs for Lakes Powell and Mead

Depletion Level: DPL#3, 5.5 MAF/yr
Lake Powell Target Discharge, D_t = 8.23 MAF/yr
Lake Mead Target Discharge, D_t = 8.25 MAF/yr

ITEM X			Maximum Allowed Powell Storage, SP_M: 3 MAF		15 MAF		27 MAF	
			$\overline{X}$	σ_X	$\overline{X}$	σ_X	$\overline{X}$	σ_X
POWELL:								
Inflow conc.,	C_i	(mg/ℓ)	696.		696.		696.	
Discharge, conc.,	C_o	(mg/ℓ)	698.		712.		719.	
Inflow,	I_P	(MAF/yr)	8.35	3.02	8.35	3.02	8.35	3.02
Evaporation,	E	(MAF/yr)	0.05	0.01	0.21	0.11	0.29	0.16
Discharge,	D	(MAF/yr)	8.15	3.01	8.02	1.40	7.94	0.91
Withdrawal,	W	(MAF/yr)	0.15	0.0	0.15	0.0	0.15	0.0
Storage,	S	(MAF)	2.31	0.15	7.84	3.85	10.93	6.58
Power cap.,	P_c	(MW)	0.0	0.0	505.	364.	603.	354.
Power output,	P_o	(GWH)x10^3	0.0	0.0	2.24	0.19	2.52	0.14
MEAD:								
Inflow conc.,	C_i	(mg/ℓ)	756.		771.		778.	
Discharge conc.,	C_o	(mg/ℓ)	854.		854.		852.	
Inflow,	I_M	(MAF/yr)	8.66	3.01	8.53	1.40	8.45	0.91
Evaporation,	E	(MAF/yr)	0.49	0.22	0.32	0.16	0.22	0.05
Discharge,	D	(MAF/yr)	7.93	0.80	7.95	0.79	7.96	0.77
Withdrawal,	W	(MAF/yr)	0.26	0.0	0.26	0.0	0.26	0.0
Storage,	S	(MAF)	10.89	6.64	5.88	4.69	3.16	1.29
Power cap.,	P_c	(MW)	612.	585.	289.	504.	0.0	0.0
Power output,	P_o	(GWH)x10^3	1.97	1.85	0.94	1.63	0.0	0.0
TOTALS:								
Evaporation,	E_T	(MAF/yr)	0.54		0.53		0.51	
Storage,	S_T	(MAF)	13.20		13.72		14.09	
Power cap.,	P_{cT}	(MW)	612.		794.		603.	
Power output,	P_{oT}	(GWH)x10^3	1.97		3.18		2.52	

Note: 1 MAF = 1.233 km^3; 1 GWH = one thousand MWH

TABLE C-4

Summary of Model Outputs for Lakes Powell and Mead

Depletion Level: DPL#1, 3.8 MAF/yr
Lake Powell Target Discharge, D_t = 8.23 MAF/yr
Lake Mead Target Discharge, D_t = 7.00 MAF/yr

ITEM X			Maximum Allowed Powell Storage, SP_M: 3 MAF $\overline{X}$	3 MAF σ_X	15 MAF $\overline{X}$	15 MAF σ_X	27 MAF $\overline{X}$	27 MAF σ_X
POWELL:								
Inflow conc.,	C_i	(mg/ℓ)	600.		600.		600.	
Discharge conc.,	C_o	(mg/ℓ)	603.		619.		632.	
Inflow,	I_P	(MAF/yr)	9.88	3.14	9.88	3.14	9.88	3.14
Evaporation,	E	(MAF/yr)	0.05	0.01	0.31	0.08	0.56	0.09
Discharge,	D	(MAF/yr)	9.78	3.12	9.53	2.05	9.27	1.85
Withdrawal,	W	(MAF/yr)	0.05	0.0	0.05	0.0	0.05	0.0
Storage,	S	(MAF)	2.38	0.15	11.65	3.01	22.52	4.14
Power cap.,	P_c	(MW)	0.0	0.0	783.	247.	900.	7.
Power output,	P_o	(GWH)x10^3	0.0	0.0	3.78	0.21	4.09	0.18
MEAD:								
Inflow conc.,	C_i	(mg/ℓ)	670.		687.		704.	
Discharge conc.,	C_o	(mg/ℓ)	792.		818.		841.	
Inflow,	I_M	(MAF/yr)	10.34	3.12	10.09	2.05	9.83	1.85
Evaporation,	E	(MAF/yr)	1.04	0.03	1.07	0.01	1.07	0.00
Discharge,	D	(MAF/yr)	9.17	2.48	8.89	2.05	8.63	1.85
Withdrawal,	W	(MAF/yr)	0.13	0.0	0.13	0.0	0.13	0.0
Storage,	S	(MAF)	28.72	1.16	29.75	0.15	29.76	0.10
Power cap.,	P_c	(MW)	1328.	0.0	1328.	0.0	1328.	0.0
Power output,	P_o	(GWH)x10^3	4.55	1.23	4.41	1.02	4.28	0.92
TOTALS:								
Evaporation,	E_T	(MAF/yr)	1.09		1.38		1.63	
Storage,	S_T	(MAF)	31.10		41.40		52.28	
Power cap.,	P_{cT}	(MW)	1328.		2111.		2228.	
Power output,	P_{oT}	(GWH)x10^3	4.55		8.19		8.37	

Note: 1 MAF = 1.233 km^3; 1 GWH = one thousand MWH

TABLE C-5

Summary of Model Outputs for Lakes Powell and Mead

Depletion Level: DPL #2, 4.6 MAF/yr
Lake Powell Target Discharge, D_t = 8.23 MAF/yr
Lake Mead Target Discharge, D_t = 7.00 MAF/yr

ITEM X			Maximum Allowed Powell Storage, SP_M					
			3 MAF		15 MAF		27 MAF	
			$\bar{X}$	σ_X	$\bar{X}$	σ_X	$\bar{X}$	σ_X
POWELL:								
Inflow conc.,	C_i	(mg/ℓ)	655.		655.		655.	
Discharge conc.,	C_o	(mg/ℓ)	657.		674.		687.	
Inflow,	I_P	(MAF/yr)	9.21	3.09	9.21	3.09	9.21	3.09
Evaporation,	E	(MAF/yr)	0.05	0.01	0.27	0.10	0.44	0.17
Discharge,	D	(MAF/yr)	9.00	3.07	8.77	1.76	8.60	1.24
Withdrawal,	W	(MAF/yr)	0.15	0.0	0.15	0.0	0.15	0.0
Storage,	S	(MAF)	2.35	0.16	10.14	3.75	17.44	7.00
Power cap.,	P_c	(MW)	0.0	0.0	690.	323.	803.	233.
Power output,	P_o	$(GWH)x10^3$	0.0	0.0	3.16	0.21	3.45	0.16
MEAD:								
Inflow conc.,	C_i	(mg/ℓ)	727.		744.		758.	
Discharge conc.,	C_o	(mg/ℓ)	862.		892.		913.	
Inflow,	I_M	(MAF/yr)	9.56	3.07	9.33	1.76	9.15	1.24
Evaporation,	E	(MAF/yr)	1.00	0.08	1.05	0.05	1.06	0.02
Discharge,	D	(MAF/yr)	8.30	2.04	8.02	1.61	7.83	1.20
Withdrawal,	W	(MAF/yr)	0.26	0.0	0.26	0.0	0.26	0.0
Storage,	S	(MAF)	27.29	2.86	28.90	1.70	29.59	0.64
Power cap.,	P_c	(MW)	1328.	0.0	1328.	0.0	1328.	0.0
Power output,	P_o	$(GWH)x10^3$	4.12	1.01	3.98	0.80	3.88	0.60
TOTALS:								
Evaporation,	E_T	(MAF/yr)	1.05		1.31		1.50	
Storage,	S_T	(MAF)	29.64		39.04		47.03	
Power cap.,	P_{cT}	(MW)	1328.		2018.		2131.	
Power output,	P_{oT}	$(GWH)x10^3$	4.12		6.54		7.33	

Note: 1 MAF - 1.233 km^3, 1 GWH = one thousand MWH

TABLE C-6

Summary of Model Outputs for Lakes Powell and Mead

Depletion Level: DPL#3, 5.5 MAF/yr
Lake Powell Target Discharge, D_t = 8.23 MAF/yr
Lake Mead Target Discharge, D_t = 7.00 MAF/yr

ITEM X			Maximum Allowed Powell Storage, SP_M: 3 MAF $\bar{X}$	3 MAF σ_X	15 MAF $\bar{X}$	15 MAF σ_X	27 MAF $\bar{X}$	27 MAF σ_X
POWELL:								
Inflow conc.,	C_i	(MAF/yr)	696.		696.		696.	
Discharge conc.,	C_o	(MAF/yr)	698.		712.		719.	
Inflow,	I_P	(MAF/yr)	8.35	3.02	8.35	3.02	8.35	3.02
Evaporation,	E	(MAF/yr)	0.05	0.01	0.21	0.10	0.29	0.16
Discharge,	D	(MAF/yr)	8.15	3.01	8.02	1.40	7.94	0.91
Withdrawal,	W	(MAF/yr)	0.15	0.0	0.15	0.0	0.15	0.0
Storage,	S	(MAF)	2.31	0.15	7.84	3.85	10.93	6.58
Power cap.,	P_c	(MW)	0.0	0.0	505.	364.	604.	354.
Power output,	P_o	(GWH)x10^3	0.0	0.0	2.24	0.19	2.52	0.14
MEAD:								
Inflow conc.,	C_i	(mg/ℓ)	756.		771.		778.	
Discharge conc.,	C_o	(mg/ℓ)	895.		920.		936.	
Inflow,	I_M	(MAF/yr)	8.66	3.01	8.53	1.40	8.45	0.91
Evaporation,	E	(MAF/yr)	0.86	0.19	0.90	0.17	0.96	0.13
Discharge,	D	(MAF/yr)	7.51	1.29	7.32	0.85	7.18	0.42
Withdrawal,	W	(MAF/yr)	0.26	0.0	0.26	0.0	0.26	0.0
Storage,	S	(MAF)	22.64	6.10	23.99	5.57	25.86	4.46
Power cap.,	P_c	(MW)	1263.	209.	1313.	52.	1324.	19.
Power output,	P_o	(GWH)x10^3	3.59	0.86	3.61	0.44	3.56	0.21
TOTALS:								
Evaporation,	E_T	(MAF/yr)	0.91		1.11		1.25	
Storage,	S_T	(MAF)	24.95		31.83		36.79	
Power cap.,	P_{cT}	(MW)	1265.		1818.		1928.	
Power output,	P_{oT}	(GWH)x10^3	3.59		5.85		6.08	

Note: 1 MAF = 1.233 km^3; 1 GWH = one thousand MWH