January 1979

Estimation of water surface elevation probabilities and associated damages for the Great Salt Lake

L. Douglas James

David S. Bowles

W. Robert James

Ronald V. Canfield

ESTIMATION OF WATER SURFACE ELEVATION PROBABILITIES AND ASSOCIATED DAMAGES FOR THE GREAT SALT LAKE

By
L. Douglas James, David S. Bowles, W. Robert James,
and Ronald V. Canfield

The work on which this report is based was supported in part with funds from the Office of Water Research and Technology, U. S. Department of the Interior, under the Water Resources Research Act of 1964, as amended, P.L. 88-379, Project No. B-153-UTAH, Contract No. 14-34-0001-8122.

WATER RESOURCES PLANNING SERIES

UWRL/P-79/03

Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah 84322

March 1979

ABSTRACT

Rising water surface elevations in perennial terminal lakes threaten major damages to shoreline industrial plants, transportation routes, and wetlands. Falling elevations increase pumping costs for industries extracting minerals from the lake water and reduce the quality of shoreline recreation. The managers of these properties need information on future lake level probabilities for planning, and public agencies need information on both probabilities and damages to determine whether lake level control is justified.

Standard methods for estimating flood frequency and damages in riverine areas do not work well for terminal lakes because of the interdependency in annual peaks and the long advanced warning and duration of flood events. For this reason, the methods of operational hydrology were used to simulate lake level and shoreline damage sequences for the Great Salt Lake. Both ARMA (1,0) and ARMA (1,1) models were tried in generating multivariate sequences of precipitation, evaporation, and three river flows for 1937-1977. The multivariate Markov model was the only one able to preserve historical sequences, but recommendations for improved parameter solution techniques for the ARMA (1,1) model are made to help future users take better advantage of its theoretically greater ability to preserve hydrologic persistence.

The Markov model was used to generate 100 and 125-year lake sequences as inputs to a lake water balance model which used them to generate 125-year lake stage sequences. The generated sequences showed lake level probabilities for current land and water use conditions in the tributary area to be affected by known present conditions for about 35 years after which they stabilize in a normal distribution of mean 4196.42 and standard deviation of 4.56. The one-percent high event has a value of 4207.0, and the one-percent low event is 4185.8. Historical stages (1851-1977) varied between 4211.8 and 4191.5, and the amount by which these values exceed the forecast stages is indicative of the long term downward trend in lake stage caused by increasing upstream water use.

The model developed with the capability of estimating low future lake level probabilities would be affected by upstream water development and by pumping water from the lake during high stages into the western desert. Data on damages to 21 cost centers were collected, and a damage simulation model was developed to use them to estimate average annual damages under current conditions and benefits from lake level control efforts. Average annual damages to the mineral industry, railroads, highways, wetlands, and other properties were estimated to be currently $1,550,000.

The computer programs for multivariate stochastic flow generation, lake water level simulation, and damage estimation are reproduced and documented in the appendices. The models will be available for future use in re-estimating probabilities and damages as initial lake stages and lake use conditions change, additional years of input data are collected, and the state of the art of stochastic flow generation is refined.

ACKNOWLEDGMENTS

The authors are particularly indebted to Dr. Norman Stauffer and Mr. Lloyd Austin of the Utah Division of Water Resources for their help in providing much of the hydrologic data used in this study, making their water balance model available, and in generally assisting the investigators and providing valuable comments on a review draft of this report. Dr. Stephen Burges made valuable contributions in setting up the initial modeling effort and in critiquing the resulting model.

Dr. Ed Bradley and others of the Bureau of Business Research at the University of Utah provided valuable assistance in collecting the damage data as part of a study funded by the Utah Department of Developmental Services and the Four Corners Commission. The State of Utah has also provided funding to the Utah Water Research Laboratory to use the flow and damage simulation models developed as part of the research in planning a cost effective lake level control program. Dr. J. Paul Riley provided material for these studies for Chapter 5 as background for defining control methods to be used in the modeling.

The authors are also very much indebted to Donna Falkenborg for editorial assistance, Barbara South for manuscript preparation, and Susan Bissland for drafting help.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (CONTINUED)

LIST OF TABLES (CONTINUED)

CHAPTER 1

PROBLEMS CAUSED BY WATER LEVEL FLUCTUATIONS IN TERMINAL LAKES

Introduction

After its 1963 low of 4191.5 feet above mean sea level, the water surface level of the Great Salt Lake rose steadily. It passed the 1950 high of 4201, and by 1976 reached 4202.3, the highest level since 1928. Damages exceeded $4 million (Bureau of Economic and Business Research, Section I, 1977), and further rise was feared. The concern generated by threatened losses to the $65-million-per-year (BEBR, Section I, 1977) mineral extraction and other lakeside industries, the railroad company whose causeway across the lake was experiencing serious erosion, shoreline recreation enterprises, and the wildlife agencies managing the marsh areas near the lake for use as feeding areas by migratory waterfowl developed into strong political pressure for action. Those threatened recognized that a rise of only a few more feet would cost millions and could cost billions of dollars in damages. Such a rise may still occur in the near future and is almost certain in the long run.

In this sort of situation, the public and government officials expect the water resources engineers and planners in the responsible agencies to provide leadership in selecting and developing functional remedies. The planners in turn look to the literature or seek specialized expertise for the necessary methodology. When they did so, those faced with developing a strategy for water level control in the largest terminal lake in the United States found a state of the art that could tell them neither the probability of future rise nor the benefits that would result from any of the various measures proposed for lake level control. Specifically, the technical problems were lacks of 1) a method for estimating the probability of future water levels in a situation where levels from year to year were not the statistically independent events assumed in analyzing riverine flood peaks, and 2) a method for estimating expected damages in a situation where slowly rising levels give years of advance warning of danger and inundation can continue for many more years before the water recedes.

General Problem Statement

Fresh water lakes achieve a natural balance between inflow and outflow. Runoff from the tributary watershed keeps the lake level from dropping below the outlet elevation. A rock ledge or some similar erosion-resistant formation provides a natural outlet control over which small increases in head mean large increases in discharge. During flood periods, outflow rises to discharge the largest inflow flood volumes with only a small rise in lake level; and the maximum lake level is seldom much higher than the minimum level.

In an arid climate, runoff entering a lake may not be enough to raise the surface elevation to the top of a drainage divide over which outflow could then occur. Before that can happen, the rising surface elevation caused by high flows increases the lake surface area and hence evaporation. When the evaporation exceeds the inflow (which often quickly drops to near zero after the occasional storms which cause much of the runoff), the lake level begins to recede. One has a terminal lake in which so much water is lost to the atmosphere that no overland discharge occurs.

Terminal lakes vary along a continuum from those which may only be terminal during very dry periods when evaporation exceeds inflow, through those which discharge after a sequence of very wet years raises the water level to the outlet elevation (Tulare and Goose Lakes, California), through those which always contain water but never have surface outflow (Great Salt Lake, Utah), to those which only contain water immediately after floods (Sevier Lake, Utah). The lakes on the wet end of this continuum do not fluctuate much in surface level because evaporation does not cause large drawdowns. Those on the dry end do not fluctuate much because inflows are seldom large enough to cause high water. It is lakes with intermediate positions on the continuum where levels fluctuate most.

At many locations with porous soils or underlying cavernous limestone, lakes lose substantial water through subsurface discharge. This loss, when added to evaporation, may prevent the lake from reaching the level required for surface outflow. At these sites, the discharge does not increase as rapidly with head as it does at the natural weirs at the outlets of fresh water lakes, but rather remains relatively constant. Inflows must largely be contained by lake storage capacity, and hence the lake level can rise very high before stabilizing. If the lake bed (natural depression) is generally dry, new construction can easily become exposed to the problem unawares. For example, houses may fill what the pioneers once called buffalo wallows on the Great Plains. This is a distinctly different but very real problem of terminal lake flooding.

The economic consequences of water-level fluctuation are most severe along the shores of lakes where slopes are flat, water levels fluctuate over a wide range, and economic factors attract development. Lakes attract recreation development that needs to be close to the water and is hurt as either the lake recedes in the distance or rises to damage facilities. Many terminal lakes attract an important mineral extraction industry that needs to be close to obtain brine from the lake and yet requires substantial investment that can be damaged by flooding. Highway and railroad bridge costs increase geometrically as structures must be built higher above a fluctuating water surface or have to be closed as waters rise over them. Shore-area wetlands, which may be ecologically very valuable for waterfowl and related species, may suffer if inundated by rising salt water or if dried as the lake recedes. If urban areas exist near the lake, property may be developed closer to the lake during long periods of low levels (50 years for the Great Salt Lake near Salt Lake City) only to be inundated when the lake rises again.

The Nature of the Needed Hydrologic and Economic Information

The manager of property or business located near the shore of a terminal lake needs better information on the probability of the lake rising (or falling) to various levels within various planning horizons. Investors, who seek some minimum return on their investment over a certain period of time, want to know the probability, during that period, of the lake level moving out of a range in which they can earn the desired return. Managers of existing property can take certain measures to protect themselves against rising or falling water and need information on expected levels to use in deciding what to do and for designing the measures of their choice.

Government decision makers have a broader perspective. Before too many property managers find it necessary to go to considerable expenditure to protect themselves against rising water, economies of scale may enable a single water level control program to protect everyone for much less than the sum of the costs that would be required for each to protect himself individually. Government water resources planners need to be able to identify such situations so that they can implement an effective program before pending danger motivates unnecessary private-sector expenditure.

In addition to this structural perspective, government decision makers should consider lake levels in land use zoning programs. They need to know the risk at various elevations to keep certain types of property out of unnecessary danger. Insurance programs need information on risk in order to set reasonable actuarial flood insurance rates for those who own property in the risk area. The national flood insurance program could be faced with billions of dollars in claims if the Great Salt Lake were to return to its historic (1873) high of 4211.6 feet above msl.

The responsibility of the hydrologist in this situation is to develop probability information for the above planning needs. The probability associated with various lake levels is not simply determined and is not constant with time. A terminal lake is not like a river where the probability of a flood of given magnitude is the same this year as it will be next year as it will be ten years from now. Given that a lake is now at some known elevation, the probability of a particular high water level during the next year is not the same as the probability of the same water level occurring during the second year, etc. In fact, one would expect that a lake level having some rare probability of occurrence (say 0.01 in the first year) would have an even greater probability of occurring in the second year than in the first and greater yet in subsequent years, by virtue of the fact that large terminal lakes can neither rise nor fall very rapidly. The Great Salt Lake has fluctuated over a range of 20 feet since 1850 but never more than 5 and seldom more than 2 feet in any one year.

The information on probable lake levels that might be developed for planning purposes could thus reasonably be expected to take the form of Figure 1. Each year into the future, the maximum and minimum lake levels expected with any probability would grow further apart until some date, n years in the future, when the estimates would stabilize given the assumption that climatic and anthropologic influences become stationary. Each user would be interested in this information from the present up to some planning horizon. Industry commonly uses 10 to 20 years, and public works are generally designed on the basis of 50 or 100 years.

The number of years required for the probability curves to stabilize (become horizontal) would logically be influenced by the range over which the lake fluctuates and the current level within that range. A shorter period would be expected were the range small or the lake currently at near average levels, and a longer period would be expected were the range large or the lake currently either extraordinarily high or extraordinarily low. If recent trends as well as the current lake level influence probabilities, trend parameters also need to be introduced. If long term climatic cycles can be predicted quantitatively, long term future levels may be better predicted by an undulating curve than a horizontal line.

For planning purposes, one would like to be able to translate information on probable lake levels into expected economic losses. Rising lake levels inundate shoreline property and dilute salt brines to make mineral extraction more expensive. Other economic losses occur as falling lake levels necessitate additional pumping of salt brines to evaporation ponds and expose large unsightly areas between recreation facilities and the beach. Translation of Figure 1 into damage estimates, however, is complicated by the fact that damages are highly dependent on lake level sequences as well as level heights. A lake may rise to a level that it has only one chance in a hundred of reaching and stay that high for three years. One would grossly overestimate damages by assuming that the inundated property would be destroyed three times. A different procedure is needed than the one used for estimating the average annual damages from riverine flooding which essentially assumes that all damaged property will be restored by the end of each year in which a flood occurs.

Technical Problem Statement

Information of the sort shown on Figure 1 is needed for the selection and design of terminal lake water level control programs, terminal lake shore area land use control measures, setting flood insurance rates for property near terminal lakes, and by private property owners making land use and development choices for specific parcels. The technical problem is to derive and then to present this information.

Solution Strategy

Hydrologists determine riverine flood probabilities for rare events by fitting the Log Pearson Type III or some other suitable distribution to a historical series of annual flood peaks (U.S. Water Resources Council, Bulletin 17, 1976). This method, however, is inappropriate for estimating probabilities from a time sequence such as the 130-year record of Great Salt Lake levels for three reasons.

1. Lake levels in consecutive years are not independent events and in fact have a very high serial correlation ($r^2 = 0.96$).

2. The Log Pearson Type III and other distributions used to fit riverine sequences are unlikely to fit recorded lake stage data.

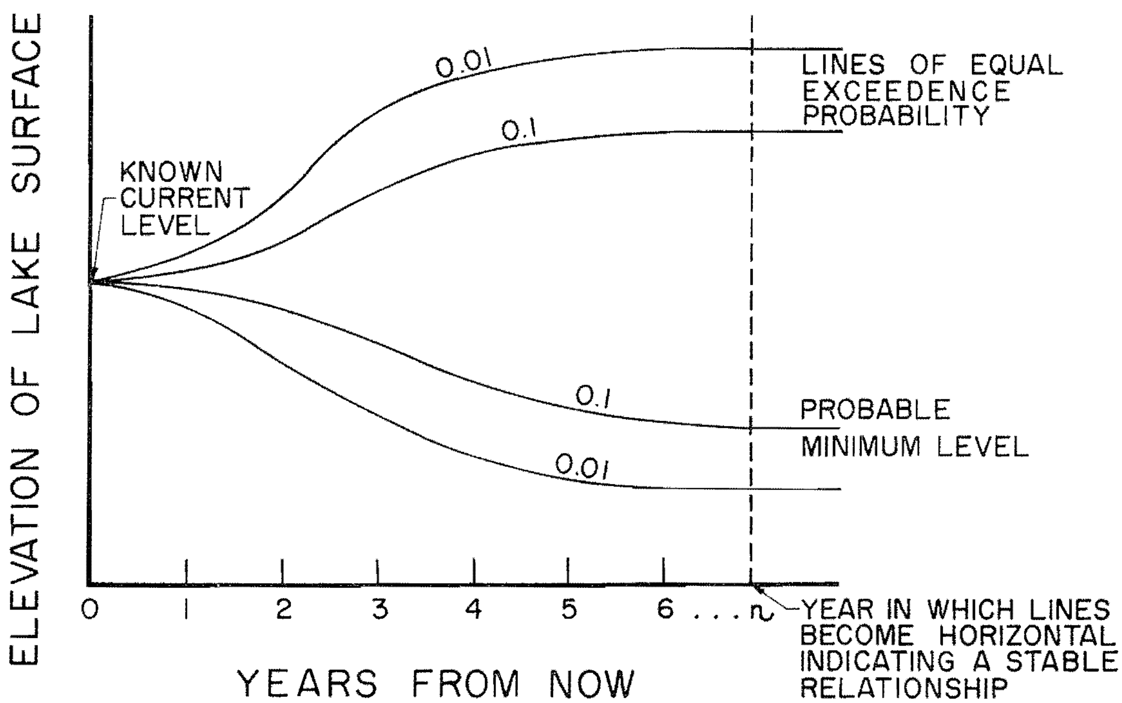


Figure 1. Expected terminal lake levels.

3. A fitted distribution would at best only provide the probabilities to the right of year n in Figure 1 and would not provide the planner nearer term probabilities for short run planning.

A promising technical approach for estimating the probability of terminal lake levels is to use operational hydrology (Fiering, 1967) as developed for estimating reservoir yield. The methods previously used to estimate reservoir yield, such as the Rippl diagram, determined the yield which could be developed from historical flows but provided no information on the probability of shortages (frequency of the design drought). Their use thus caused reservoirs built on rivers for which the period of record happened to include a very severe drought to be designed much more conservatively than were reservoirs on rivers for which the period of record had by chance not been one of severe low flows.

One important consideration in developing a method for relating drought yield to probability is that the duration of the design drought depends on the size of the reservoir and, for a large reservoir, is considerably longer than one year. The probability of a given drought can thus not be determined by analyzing the magnitudes of the volumes of annual runoff but requires information on the persistence properties of sequences of annual flows as well. The procedure of operational hydrology is to use stochastic methods to generate a sequence of synthetic flows having the same statistical properties as the recorded flows and then use this sequence to size a water supply reservoir for a probability of the lake running dry at some maximum acceptable level. For given flows and facility design, that probability is estimated by a method that combines a stochastically generated flow sequence with a reservoir water balance model and can be used directly to compute the stabilized probable minimum levels on Figure 1. As to probable maximum levels, a terminal lake differs from a reservoir in that it has no spillway that can quickly discharge large volumes of inflow to damp rising surface levels. The water level instead continues to rise. This difference, however, has no effect on the operational hydrology used to generate flows but only on the water balance model in which those flows are used. All that is needed to expand the method for application to terminal lakes is to change the water balance model so that rising levels are limited only by the storage-elevation relationship. One needs to estimate outflow from evaporation data rather than water demand and spillway discharges.

Application of a stochastically generated flow sequence in a water balance model to derive the needed probability relationships requires:

1. Data on the historical sequences of inflow and outflow affecting lake levels. For terminal lakes, these include streamflow into the lake (potentially gaged at several sites and including additional flow from ungaged watersheds), subsurface flow into the lake (probably not recorded in a historical time sequence and dependent on aquifer geology and withdrawals from wells), precipitation on the lake (as averaged from gages in nearby communities, none of which sites are likely to be on the lake), and evaporation from the lake (as estimated from nearby evaporation pan data that need to be adjusted for atmospheric conditions over the lake and for salinity conditions and currents within a lake whose salinity changes as lake levels rise and dilute the salt content).

2. Analysis of the historical data sequences for significant cross and serial relationships and to describe those relationships in terms of parameters to be preserved.

3. A model that can generate simultaneous synthetic sequences of the various types of data affecting the lake water balance and having desired distributional, persistence, and cross correlation properties.

4. Calibration and use of the model to generate sets (simultaneous surface flow, subsurface flow, precipitation, and evaporation) as needed.

5. A water balance model that uses these sets to generate equally likely sequences of lake levels. With such a model, one can begin from known present conditions, simulate many possible future time sequences (traces) of lake levels, and perform a frequency analysis of the results year by year into the future to develop information of the sort shown in Figure 1.

6. A damage simulation model that uses a simulated sequence of lake levels to generate a sequence of consequent damages and estimate an equivalent average annual value.

7. A procedure for adjusting the models of steps 5 and 6 to determine the effects of various water level control measures on lake levels and damages. The principal control measures proposed for the Great Salt Lake are levees, pumping from the lake into adjacent desert areas during periods the lake is high, and new water projects to increase consumptive use of water that would otherwise flow into the lake.

The immediate objective of this study was to execute these seven steps to study the specific problems of the Great Salt Lake. The results would then be generalized to other terminal lakes.

Working Out the Details

The third step in the above strategy would require breaking new ground in operational hydrology methodology. Other steps would require additional innovations. In order to begin at the current state of the art, the study first identified important issues that it would be necessary to resolve in implementing the seven-step strategy and followed by reviewing the literature relevant to those issues. Seventeen specific issues were identified in the categories of stochastic hydrologic modeling, water balance modeling, and damage estimation. Additional issues are discussed in the areas of model generalization and information presentation.

Stochastic Hydrologic Modeling

The problems that would need to be overcome in developing a stochastic hydrologic model that would accurately represent lake inflow and outflow sequences were identified by reviewing the current state of the art of stochastic flow generation, the sorts of stochastic flows that would have to be generated, and the adequacy of the available data. This review identified the following potential problems in trying to generate the desired flow sequences with existing model formulations given the available data.

1. Preserving Historical Correlations. While a number of models for multivariate stochastic streamflow generation are proposed in the literature, few have been successfully applied to real situations. For the Great Salt Lake, five or six variables including precipitation, evaporation, and streamflow would be needed. The correlation statistics could be expected to vary significantly from those encountered by other modelers, concerned only with streamflow measured at two or more sites, and this could be expected to lead to problems in trying to preserve statistics in new ranges. For terminal lakes, evaporation is always the largest single item in the water balance since over the long run it must equal the sum of all the inflows. For a very large shallow lake such as the Great Salt Lake, precipitation on the lake surface will also be relatively large. Furthermore, both evaporation and precipitation were observed to vary enough from year to year so that it would be undesirable to treat either as annual constants. Therefore, both meteorological series would have to be generated; the question was whether the correlation between these series and of each with streamflow would be large enough to require all to be included in one multivariate model or whether independent univariate models could be used.

2. Preserving Hydrologic Persistence. In hydrologic data sequences, large values are more likely to follow other large values than to follow small values and vice versa. The historical sequences of both precipitation and streamflow data from natural watersheds in the Salt Lake area exhibit high serial correlation (lag-one correlation coefficient of 0.35 for precipitation and 0.65 for streamflow) and persistence properties (Hurst coefficient of 0.61 for precipitation and 0.74 for streamflow). A model would be needed that could preserve these levels of correlation and persistence.

3. Achieving Data Homogeneity. Flows into the Great Salt Lake have been greatly altered over the years of record by reservoir storage, runoff changes caused by urban development along the Wasatch Front, and groundwater pumping and surface water diversions that increase consumptive use in the tributary basin. Consequently, historical annual flow sequences are not homogeneous but contain trends with calendar time. In order to have streamflow amounts for a combination of historical climatic fluctuations and present watershed conditions and consumptive use rates, the Utah Division of Water Resources (1974) has converted the historic flows to a homogeneous sequence assuming present conditions. The difficulty with using these sequences is that present conditions are associated with a damping of extremes by reservoir storage that greatly increases flow persistence and creates statistics more difficult to preserve in a flow generation model.

4. Missing Data. Stochastic simulation requires fairly long sequences of simultaneous measurements at each site where flow is to be represented in order to obtain accurate estimates of flow distributions, cross correlations, and persistence. Historical sequences often contain gaps which are more extensive in some series than in others and worsen as one attempts to go farther back in time. Particular problems for this study were that data were very sparse for estimating runoff into the lake from the smaller basins and from subsurface flow, the evaporation data covered only summer months, and the pan locations did not seem to represent the lake very well.

5. Length of Record. A simulation model is calibrated to generate flow sequences whose statistical properties match those of the historical flow population. The statistics for defining the distribution shapes, correlations, and persistences of the historical flows can be estimated more reliably if longer data series are available. The longer series, however, extend back to a time when records tend to be intermittent and imprecise. One needs to determine whether the information available in older and less reliable records or such indirect indicators as tree ring data actually improves estimation of the desired statistical properties of the historical flows. The answer is likely to vary from one parameter to another with how reliably it can be estimated from a short record. The effort one can justify in improving an estimate also depends on how sensitive the results are to errors in its measurement.

6. Initial Persistence Situation. Lake levels and damages for the near future certainly depend on the current lake level, but it is not clear as to whether or not they al-

so depend on the recent trend in lake levels. If the lake level is passing through 4200 while rising, is it more likely to continue to rise than it would be to rise if it had just recently fallen to 4200? The answer to this question governs the number of parameters needed to define the current state in order to project near-future probabilities.

Water Balance Modeling

The water balance model used to translate inflows and outflows into lake levels poses additional potential problem areas. Some relate to how well the historical period of record used as a basis for the stochastic generation represents long term conditions and others relate to difficulties in achieving accurate stages.

7. Climatic Cycles. Since the levels of large terminal lakes vary with average inflow amounts over periods of many years, they will fluctuate with any natural cycles of wet and dry years such as might be related to sunspot patterns or other cyclic physical phenomena. If such cycles indeed exist and follow a predictable pattern, information on that pattern should be used to improve advance estimation of high or low lake levels.

8. Evaporation-Streamflow Feedback. The geographical setting of the Great Salt Lake, just upwind from a major mountain range where most of the runoff into it originates, led to speculation that the extraordinarily high persistence in downwind precipitation and runoff values might be caused by a positive feedback effect associated with the relationship between lake levels and evaporation. Perhaps the extra evaporation during periods when the lake was high was adding significantly to the precipitation totals on the Wasatch Mountains rising 7000 feet above the lake less than 30 miles downwind. If so, high lake levels would increase precipitation that would in turn increase runoff and contribute to the lake level remaining high. Conversely, low lake levels would reduce evaporation, precipitation, and runoff and contribute to dry-cycle persistence.

9. Non-Level Lake Surface. A lake water balance model would compute lake elevations assuming a level surface. In the special case of the Great Salt Lake, a causeway crossing the middle of the lake causes higher elevations in the south than in the north arm. A water balance model preserving these two elevations would have to be split into two parts by separating each inflow and outflow by lake portion and computing flows through the causeway between them. Also, winds blowing across a lake cause seiches with downwind elevations higher than upwind elevations and generate waves that ride up sloped beaches. Therefore, sloped, downwind water surface elevations are higher during storm periods than is the level elevation during periods of calm. Since lake levels follow the annual pattern of highs immediately after spring runoff and lows in the late fall, one also needs to consider the joint probabilities of strong winds occurring during spring lake elevation maximums.

10. Effects of Control Measures on Lake Level. There are three basic structural approaches to lake level control. One is to pump water out of the lake into nearby areas where it can be held either until it evaporates or until the lake recedes. For the Great Salt Lake, the flat desert areas to its west have often been mentioned when rising levels threaten damage. A second approach is to reduce inflow to the lake by diverting streamflow out of the basin or for consumptive use in the basin. Lake level control provides additional benefits for economic justification of the diversion or irrigation projects in such cases. The third approach is to build levees around damage prone areas. In order to analyze the desirability of these possibilities, one must determine their effects on the lake water balance and on damages. The first method adds to evaporation in the water balance and poses the problems of developing an operating rule for deciding when and how much to pump to maximize cost effectiveness within the constraints posed by the ability of the holding areas to store water. The second method reduces inflow in a pattern determined by the use made of the diverted water and requires careful coordination of the lake level control with use of water for other needs to maximize combined benefits. The optimized rules for pumping from the lake or for diverting water before it enters the lake would then in these respective cases be incorporated into the lake water balance model to determine consequent lake stage traces. The functional relationship between stages and damage would be unchanged. The levee alternative would change the stage-volume relationship for the lake and eliminate damages in protected areas until the levee is overtopped. Specific quantitative relationships would be needed for all of these cases to determine how control measures would affect lake levels.

11. Number of Traces. The frequency distribution of the lake levels in any particular year becomes better defined as the water balance model is used to generate more traces, but each trace takes computer time to generate and more traces require more computations to analyze. The trade off between cost and improved resolution needs to be examined in deciding how many traces to generate.

12. Effect of Salinity on Evaporation. Salinity is known to suppress lake evaporation. For water balance modeling, one needs to express this relationship and determine whether one can use average salinity in the lake for estimating evaporation or whether one needs to account for the fact that surface waters are generally fresher than the heavier salt water which settles to the bottom.

Damage Modeling

The damage model used to translate stage sequences into damage sequences poses what are perhaps the most difficult conceptual issues of all. In addition, such a model requires considerable additional empirical data whose collection poses more difficulties. Five major issues in this model component are described below.

13. Behavior Forecasts. The damages caused by a given rise in lake levels depend on how people respond. When will property owners seek to protect and when will they abandon structures? How does recreation visitation respond to changing lake levels? How is the wildlife population supported by feeding areas adjacent to the lake affected? Once property is abandoned because of rising lake levels, to what level and for what duration does the lake surface have to drop before its former site is again developed?

14. Viewpoint. Decision makers in government may consider damages from the viewpoint of revenues and expenditures to a particular government, to all the citizens of the governmental jurisdiction, or to whomsoever may be affected. Private sector decisions are more likely to be made only in consideration of effects on the decision maker. The viewpoint(s) from which the damages are to be estimated must be selected for a model; and for the results to be meaningful, the viewpoint(s) used should be widely held among the people who will be making decisions on lake level control.

15. Projected Futures. The damages from rising water depend on the use of the inundated land and can be expected to increase with shoreline industrial and recreational development. Even if no land use change occurs, the value of shoreline facilities can be expected to increase with recreation demand from growing populations and tourism and with the demand for minerals extracted from the lake. If shoreline zoning is used to restrict development in hazard areas, one needs a policy for balancing damages prevented against the opportunity cost of idle land near urban areas or of foregoing the advantages of shoreline location. Since structural lake level control measures can be designed to function for 50 years or more, one needs to project changes in demands for lakeshore products and in property at hazard and the consequences of its loss in order to estimate benefits.

16. Environmental and Social Effects. Lake level changes have a number of economic effects that are difficult to estimate (either because of theoretical problems or because of empirical problems in working with limited data). Other important effects cannot be reliably measured in monetary units. What are the more important environmental and social factors? How should these be integrated in lake level control decisions?

17. Scheduling Control Measures. Some measures for lake level control can be applied quickly when it is feared that a lake is about to rise to a dangerous level, but other measures (particularly upstream water development projects) require much longer to implement. Waiting until danger threatens and then relying on short-term measures reduces the possibility of making a large investment only to find it unneeded for many years. Immediate action including long-term measures provides surer security against becoming trapped in a situation where it is too late to take the most effective remedy.

Model Generalization

While the research goal is to develop a general method for estimating water level probabilities and consequent damages, the specific numerical analyses will be for the Great Salt Lake. The methodology developed is intended to be general so that it can be applied to other terminal lakes from information on their surface inflows, precipitation, evaporation, lake geometry, etc. The computer programs developed will be presented in a manner that allows their ready application with other data for studies at other sites. Despite these good intentions, however, other sites will no doubt have local pecularities requiring model adjustment.

Information Presentation

One can visualize the analysis and modeling described above as yielding 1) probability information such as that on Figure 1, and 2) a present worth or a discounted average annual value for damages. Both the probability information and the damage estimate, though, would only be good for one year. The next year, the known current lake level would be different, another year of data would change the estimates of the statistical parameters for the historical flow population, and all estimates would change.

Two approaches could be used to deal with the annual change in known initial conditions. One would be to develop a method for normalizing the curves and damage estimates so that one could read values for any lake level. The other would be to develop a computer program that could make the desired estimates from initial conditions read as input data. To minimize computer time, the computer program should store the results of the previous model calibration so that it would not be necessary to repeat the entire modeling effort for every new initial condition. Every five to ten years, however, the model should be recalibrated to take advantage of the information in the additional years of record.

Report Organization

The work done to provide terminal lake level probabilities and damage estimates is described in seven following chapters. The next chapter examines the literature describing the current state of the art for dealing with the issues listed above in order to build a foundation for the methodology to be developed. Chapter 3 describes the data collected, the iterative data time series considered, and how the data were tested for adequacy and prepared into suitable form. Chapter 4 compares the results from the generating methods attempted, and presents the method used to preserve the desired properties in generating a set of five time series of physical events. The fifth chapter describes the lake level control alternatives. Chapter 6 presents the lake water balance model used to convert generated inflows and outflows to lake stages and describes the results of applying the model to estimate lake stage probabilities in various time frames with and without two selected control measures. Chapter 7 presents the damage simulation model and illustrates its use to estimate benefits from the two selected control measures. The final chapter presents how the methodology can be generalized to cover other terminal lakes, evaluates the research accomplishments, and recommends future studies.

CHAPTER 2

LITERATURE REVIEW

Development of the stochastic hydrologic model, water balance model, and damage estimation model has been identified in the first chapter with 17 specific problems. The next task was to review the literature to establish a foundation that could be used for building each model by collecting the best available thinking for resolving the 17 problems. The three major sections of this chapter, one for each of the three models, are each divided into a part on the state of the modeling art followed by a second part on studies providing insight for dealing with the specific problems.

Stochastic Generation of Hydrologic Sequences

Steps in Stochastic Generation

The hydrologic data sequences needed to determine terminal lake level probabilities quantify inflows and outflows. The inflows are streamflow, subsurface flow, and precipitation on the lake surface. For large terminal lakes, the outflow is entirely by evaporation, but subsurface discharge occurs at some sites. Each inflow and outflow varies by location on or around the lake and over time. Stochastic modeling to derive lake level fluctuation probabilities requires compiling measurements in time series for indexing these inflows and outflows, selecting how to aggregate the inflow and outflow time series (e.g., should inflows from individual rivers be combined or modeled separately?), converting the measurements obtained into time-period totals of the selected aggregations, selecting relationships among and within the time series that need to be preserved to model important trends in the lake water balance, and deriving a model that will preserve these, or at least as many of them as possible, relationships.

State of the Art for Univariate Models

Stochastic flow simulation began with the univariate models of the Harvard water program (Maass, 1962). The criterion of success was generation of flows whose mean, distribution, and serial relationships matched corresponding values in a single recorded sequence. The Markov generating function proposed by Thomas and Fiering (1962) was

$$X_t = \overline{X} + \beta(X_{t-1} - \overline{X}) + T_t \,\sigma \sqrt{1-\rho^2} \quad . \quad . \quad . \quad . \quad (1)$$

where a flow X in time period t is generated from the flow in previous time period t-1, a single-lag serial regression slope β which for single-lag serial correlations has the same numerical value as the correlation coefficient ρ, a mean flow $\overline{X}$, a standard deviation of flows σ, and a variate T_t taken at random from a normalized distribution of the flows. Through the three terms on its right side, the equation generates flows from a mean value, a regression estimating the deterministic effect of the previous value, and a term whose value is picked at random from a distribution representing variance not explained by the regression.

The second term on the right side of Equation 1 provides memory of past flows, only the immediately preceding flow is remembered, and the influence of the memory as opposed to the random component increases with the value of ρ. Conceptually, one could lengthen the memory by expanding the second term to the series

$$\beta_1 \; (X_{t-1} - \overline{X}) + \beta_2 \; (X_{t-2} - \overline{X}) + \ldots. + \beta_n \; (T_{t-n} - \overline{X}) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Multiple autocorrelation analysis would then be used to determine the linear association within the historic time series through estimates of values for the β_s. The ρ in the third term of Equation 1 would be the correlation coefficient in the multiple regression. Mathematically, Series 2 would be terminated with the last ρ before the first one that did not prove to be significantly different than zero. Physically, the maximum lag is limited by the maximum duration of storage routing through aquifers making significant contribution to base flow. Some authors (Fiering and Jackson, 1971) describe tests for the significance of lag effects from periods t-2, t-3, etc. and Markov models using Series 2 in Equation 1 for preserving the associated β_s, but the first order model of the single-lag process was found adequate for most applications.

One issue in stochastic flow generation is the distribution to use in selecting values for T_t in Equation 1 as the best representation of flows being modeled. The normal distribution is easily applied by taking variates at random from a normal distribution of zero mean and unit variance and can be used for hydrologic variables found to be normally distributed. For most hydrologic variables, however, a better match is achieved by assuming the logarithms rather than the data to be normally distributed; and, in addition, the log normal distribution eliminates generation of negative flows.

If the log normal distribution is to be used, the parameters $\bar{X}$ or μ, σ, and ρ used in Equation 1 should not be calculated directly from log-transformed data because that does not preserve the parameters of the data when the generated logs are transformed back. If μ_x, σ_x, and ρ_x are used to denote the mean, standard deviation, and serial correlation coefficient, respectively, calculated from the untransformed or raw data, one can solve for values of μ_y, σ_y, and ρ_y to be used in Equation 1 from the relationships (Matalas, 1967):

$$\mu_x = e^{\left(\frac{\sigma_y^2}{2} + \mu_y\right)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

$$\sigma_x^2 = e^{2(\sigma_y^2 + \mu_y)} - e^{\sigma_y^2 + 2\mu_y} \quad . \; . \; . \; . \; . \; . \; . \quad (4)$$

$$\rho_x = \frac{e^{\sigma_y^2 \rho_y} - 1}{e^{\sigma_y^2} - 1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

The parameters σ_y and μ_y can be determined by simultaneous solution of Equations 3 and 4, and ρ_y can then be determined as the one unknown in Equation 5.

Charbeneau (1978) showed that by making the transform

$$\psi = 1 + (\sigma_x/\mu_x)^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

One can solve directly for the y parameters as

$$\sigma_y^2 = \log \psi \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (7)$$

$$\mu_y = \tfrac{1}{2} \log \left[\sigma_x^2 / (\psi^2 - \psi)\right] \quad . \; . \; . \; . \; . \; . \; . \quad (8)$$

$$\rho_y = \{\log \left[\rho_x(\psi - 1) + 1\right]\}/(\log \psi) \quad . \; . \; . \quad (9)$$

These y parameters would then be used with Equation 1 to generate flows having a log-normal distribution.

Many hydrologic data series are skewed in their log transforms or are from a population whose minimum value is nonzero. For such cases, the three parameter log normal distribution (3PLN) can be used (Burges and Lettenmaier, 1975). Values X_t in a sequence that follows a 3PLN can be transformed to a normally distributed sequence Y_t by

$$Y_t = \ln (X_t - a) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (10)$$

in which a is the "third parameter" and defines a lower value for the distribution. The transformed sequence Y_t is then used in the stochastic models where appropriate. If a is not known on the basis of some physical lower limit, it can be estimated from observed data as

$$a = \mu_x \left(1 - \frac{\eta_x}{\eta_y}\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (11)$$

in which η is the coefficient of variation or σ/μ. η_y can be estimated from the equation (Yevjevich, 1972):

$$\eta_y = \left[\frac{\sqrt{\gamma_x^2 + 4} + \gamma_x}{2}\right]^{1/3} - \left[\frac{-\sqrt{\gamma_x^2 + 4} + \gamma_x}{2}\right]^{1/3} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (12)$$

in which γ_x is the coefficient of skewness of the untransformed data.

Then μ_y' and σ_y' and ρ_y', for use in Equation 1 to generate flows having a 3PLN distribution, are estimated from the equations presented by Matalas (1967). His equations for μ_x, σ_x, and ρ_x when solved for the three needed terms give:

$$\sigma_y' = \sqrt{\ln \left(\frac{\sigma_x}{(\mu_x - a)^2} + 1\right)} \quad . \; . \; . \; . \; . \quad (13)$$

$$\mu_y' = \ln \left[\mu_x - a\right] - \frac{\sigma_y'^2}{2} \quad . \; . \; . \; . \; . \; . \quad (14)$$

$$\rho_y' = \frac{\ln \left[\rho_x(e^{\sigma_y'^2} - 1) + 1\right]}{\sigma_y'^2} \quad . \; . \; . \; . \; . \quad (15)$$

For this study, an estimated skew coefficient exceeding 0.1 as computed from the untransformed data was taken as large enough to justify preservation of the skewness by using the 3PLN distribution (Yevjevich, 1972).

Before applying Equation 1 to highly serially correlated data, one should recognize that for a sequence which exhibits serial correlation, the sample variance underestimates the population variance. The sample variance may be adjusted to eliminate this bias by applying the relationship (Matalas, 1966):

$$\sigma^2 = S^2 \left\{1 - \frac{2\rho}{n(n-1)} \left[\frac{n(1-\rho) - (1-\rho^n)}{(1-\rho)^2}\right]\right\}^{-1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

in which

σ = population variance

S = sample variance of sequence

n = sequence length

ρ = serial correlation of sequence

When log normal or 3PLN transformations are used, S is taken as σ_y and ρ as ρ_y for substitution in Equation 16 to estimate σ for use in Equation 1.

These Markovian models (whether of first or higher order) assume that the parameters remain constant over time (a stationary series). If a long series is divided into several non-over-lapping sets and parameters ($\bar{X}$, σ, β_1, β_2, etc.) do not vary significantly from set to set, the time series is said to be stationary. Nonstationarity may be caused by a measurement change (e.g., moving a precipitation gage), change in the physical system (e.g., watershed urbanization), or long-term patterns in the underlying physical causes of precipitation (e.g., climate change). The first two sources of nonstationarity can be overcome by adjustments to assure homogeneous data. The long-term persistence that would follow from accepting the third possible source of nonstationarity has been a matter of speculation and discussion by hydrologists for years, and, if proved, would have very important implications for terminal lake control.

Hurst (1951) studied the related issues of stationarity and persistence from the perspective of long hydrologic records. He calculated the range (R) of cumulative departures from the mean, normalized by the standard deviation (S), as a statistic that represents long term persistence in hydrologic time series. He examined 690 annual series of streamflow, river and lake levels, precipitation, temperature, pressure, tree ring growth, mud varve, sunspot, and wheat price records for periods varying from 30 to 2000 years (Nile River streamflows). Hurst (1951) found that the range (R/S) can be rescaled as:

$$\frac{R}{S} = \left(\frac{n}{2}\right)^h \quad \ldots\ldots\ldots\ldots (17)$$

in which the exponent h is called the Hurst coefficient. The mean h for the 690 series was found to be 0.729 with a standard deviation of 0.092. Hurst compared his empirical coefficient, h, with results from series of numbers taken at random from a normal distribution and found the latter h to equal 0.5. Feller (1951), using the theory of Brownian motion, arrived at the same asymptotic results without assuming normality in the underlying process. The disagreement between the empirical K of 0.729 and the theoretical 0.5 has led to many following efforts to explain this observed nonrandomness or what came to be called the Hurst phenomenon. An understanding of any underlying physical relationship could add a great deal to a better understanding of the rises and falls of terminal lakes, a hydrologic time series whose Hurst coefficients have been observed to be among the largest of those for any hydrologic phenomena because of the way such lakes integrate inflows and outflows.

Mandelbrot and Wallis (1969) found that values of h calculated from Equation 17 for data generated by a white noise process tended to be somewhat eratic for series lengths (n) shorter than about 20. One would expect that for natural series having higher values of h that a longer record may be required to achieve a stable estimate. For this reason, the authors proposed plotting a pox diagram of R/S versus n on a log-log scale so that one could determine visually whether the estimate had stabilized for the length of record. The specific procedure is as follows:

1. Subdivide the total length of record (n) into equal shorter sequences of length n_s. The shorter sequences may overlap. The minimum n_s to use is 3, and the maximum is n. Several intermediate values should also be selected so that the values of n_s used are approximately uniformly spaced on a logrithmic scale.

2. For each sequence of length 3, calculate (Equation 17) the rescaled range, R/S. Compute the mean rescaled range for all sequences of length 3.

3. Repeat 2 in order to compute the mean rescaled range for each selected value of n_s.

4. Plot mean R/S versus n_s on log-log paper as shown in Figure 2.

5. Estimate h as the slope of a least squares line fit through the points on the linear portion of the log-log plot or between n_0 and n as shown on Figure 2.

Wallis and Matalas (1970) compared estimating h by the pox diagram method with estimating it by applying Equation 17 directly to the total length of record for independent processes, lag-one Markov processes, and an approximation to discrete fractional Gaussian noise. They found that the pox diagram method showed less bias but greater variance.

Markov models do not replicate the Hurst phenomenon. The first models to succeed in preserving a Hurst coefficient exceeding 0.5 were the fractional Gaussian noise (fGn) models introduced to synthetic hydrology by Mandelbrot and Wallis (1968, 1969a,b,c,d). These models preserve long term persistence by causing the autocorrelation function to die off increasingly slowly as h becomes larger than 0.5. The desired h is used as a model parameter and then preserved in the generated sequences. Fractional Gaussian noise sequences having h values not equalling 0.5 lie outside the Brownian domain in

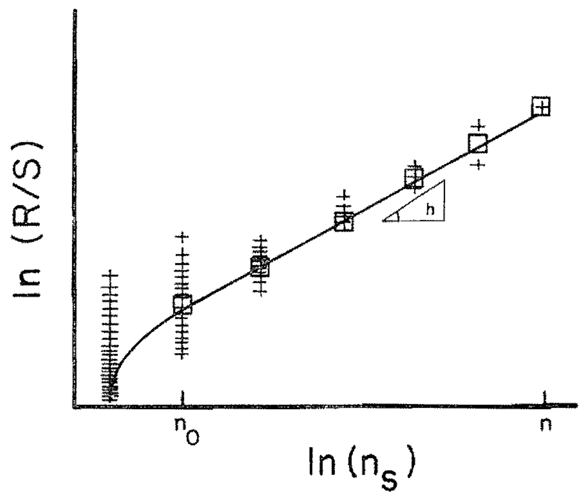


Figure 2. Pox diagram of logarithm of the rescaled range for various series lengths.

that they do not satisfy the mixing property of Brownian motion. Specifically, past and future averages of the process become independent as the sample size approaches infinity. Mandelbrot and Van Ness (1968) and Mandelbrot and Wallis (1969c) define fGn mathematically, and O'Connell (1971) reviews the relationship of fGn to the Hurst phenomenon. The principal drawback of the technique is that its complexity and consequent high computer cost make it impractical to apply to many design problems.

In efforts to develop a more practical generating method, others have tried such approximations to the fractional Gaussian noise model as 1) the autoregression integrated moving average (ARIMA) process which O'Connell (1971) patterned from techniques previously developed by Box and Jenkins (1970), and 2) the Broken Line process by Rodriguez-Iturbe, Mejia, and Dawdy (1972), and Mejia, Rodriguez-Iturbe, and Dawdy (1972). A detailed historical account of these efforts has been recorded by O'Connell (1974). The first of the above approximations, the ARIMA-Type model is computationally more practical.

Even though the fGn model and its approximations can preserve desired values of h other than 0.5, they do so purely as operational tools developed apart from understanding the underlying physical processes. As a caution to those who would accept these models as representing persistence in a geophysical system, Klemes (1974) noted: "It would be more realistic to say that: 1) fractional noises offer one possible explanation of the Hurst phenomenon; and 2) approximations to fractional noises provide a flexible operational tool for the simulation of series exhibiting the Hurst phenomenon. An ability to simulate, and even successfully predict, a specific phenomenon does not necessarily imply an ability to explain it correctly. A highly successful operational model may turn out to be totally unacceptable from the physical point of view" (Klemes, 1974, p. 675).

In support of this warning, Klemes showed that a zero memory as well as an infinite memory model can exhibit the Hurst phenomenon. Stochastic models that operate on stationarity of the mean can represent nonstationary time series for short time intervals, and stationarity or nonstationarity is a matter of time-series length. Experimentally, Klemes generated synthetic sequences from a distribution whose parameters were varied during the total simulation period but kept constant over shorter time periods called epochs. He showed that the infinite memory concept in fGn models can be a function of epoch length rather than of total series length in accounting for the Hurst phenomena.

As an alternative to explaining persistence from climatic epochs, Klemes (1974) noted the important role the conservation of mass and energy or the storage effect can have in causing hydrologic time series to exhibit values greater than 0.5 for the Hurst coefficient. This effect is dramatically seen in the extraordinarily high value of h (1.079) computed from the data on the Great Salt Lake stages. Specifically, Klemes attempted to show that a semi-infinite storage reservoir model with various and diverse input processes might also explain the Hurst phenomenon. While Klemes was not able to prove or disprove specific physical causes for a Hurst coefficient exceeding 0.5, he did show that in real world hydrologic systems, the Hurst phenomenon may be a result of one or more of several physical causes: long-term memory, nonstationarity in geophysical phenomena, or storage systems. Salas, Boes, Yevjevich, and Pegram (1977) have stated that the Hurst phenomenon might be explained by: "auto correlation, nonstationarity, and departure from normality which either individually or combined accentuate a transient behavior, which is present in independent time series." In conclusion, one finds the Hurst phenomenon to be a property of hydrologic time series that can be quantified numerically but for which the physical causes are poorly understood and much debated.

This uncertainty about hydrologic persistence places the would be modeler of terminal lake levels in a very dubious position. Terminal lake levels are determined by a water balance in a large storage system whose content is governed by cumulative inflows and outflows over long periods and hence is extremely sensitive to hydrologic persistence, a phenomenon whose physical causes are poorly understood. Since the modeler cannot make a conclusive theoretical case for either accepting or rejecting persistence as a hydrologic phenomenon, discretion suggests empirical replication of observed Hurst coefficients.

The current state of the art of univariate stochastic modeling seeks to match statistics computed from observed data sequences with corresponding statistics computed from generated data sequences. Since available models cannot guarantee preservation of all statistics of interest over the entire range of values encountered in nature, one must often sacrifice in matching some statistics in order to do a better job of matching others. The need for this sort of trade off becomes much greater for the multivariate modeling situations described in the next section than it is for the univariate models where the statistics are fewer.

The most practical models available for univariate generation preserving a Hurst coefficient greater than 0.5 are the moving-average type models and specifically the ARMA (1,1) (O'Connell, 1971, 1974) and the ARMA-Markov (Burges and Lettenmaier, 1975). These models force persistence into a generated series by varying average values from one epoch or period of time to the next while maintaining the desired average for the total period. The ARMA acronym stands for autoregressive integrated moving average, and the two numbers in parentheses indicate the order of the autoregression and moving average processes respectively. The equation for the ARMA (1,1) model is

$$X_t = \overline{X} + \phi\,(X_{t-1} - \overline{X}) - \theta\omega_{t-1} + \omega_t \quad . \quad . \quad . \quad . \quad (18)$$

where ω_t is the error term. Comparison of Equation 18 with Equation 1 shows the same form of relationship other than that memory of the preceding generated error term (ω_{t-1}) is added to maintain stability in the moving average. In terms of the ARMA (1,1) nomenclature, the X_{t-1} term provides the single lag autoregression, and the ω_{t-1} term provides a single lag moving average. The parameters (ϕ,θ) in Equation 18 vary with the values for h and ρ to be preserved; however, a major disadvantage of the ARMA (1,1) model is that the ϕ and θ required to preserve given values of ρ and h cannot be determined explicitly but have to be approximated empirically from curves plotted from completed simulations (Burges and Lettenmaier, 1975, p. 17).

In order to have a generating model in which the parameters are an explicit function of the statistics to be preserved, Lettenmaier and Burges (1977) proposed combining Equations 1 and 18 in what they called an ARMA-Markov model and having the form:

$$X_t = \rho_m X_{t-1} + \varepsilon_t + \phi X_{t-1} - \theta\omega_{t-1} + \omega_t \quad . \quad . \quad . \quad . \quad (19)$$

where the X is expressed in standardized normal form $[(X - \mu)/\sigma]$ and ε_t and ω_t are independent processes having different variances which can be established from the values of the statistics to be preserved. The authors also provide a method for establishing values for ϕ and θ for the values of μ, σ, ρ, and h of the series record.

Lettenmaier and Burges (1977) found the ARMA (1,1) and ARMA-Markov models to provide reasonable approximation of the fGn process for values of $h \leq 0.80$ but for the results to become quite poor for higher h. They also describe problems associated with estimating h from short records. Finally, they recommend using the ARMA models throughout their range of reliability because they are so easy to use computationally.

The Broken Line process, BL, was developed as an approximation to the discrete fractional Gaussian noise model by Mejia et al. (1972) and claims the advantage of having a second derivative of the autocorrelation function at the origin. Preservation of the second derivative, not possible in the fGn models, provides better results with respect to crossing properties, extreme events, run lengths, and run sums for continuous time series. For the discrete time series used in hydrologic modeling, these advantages disappear. Use of the model is further handicapped by the fact that the parameters for the Broken Line process are difficult to compute (O'Connell, 1974).

State of the Art for Multivariate Models

The first attempt at preserving cross correlations between two synthetic sequences (X_t and Y_t) was that by Thomas and Fiering (1962), who combined the standardized normal form of the univariate lag-one Markov model:

$$X_t = \rho_x X_{t-1} + \varepsilon_t \sqrt{1 - \rho_x^2} \quad . \quad . \quad . \quad . \quad . \quad (20)$$

with an analogous cross correlation model:

$$Y_t = \rho_{xy} X_t + \omega_t \sqrt{1 - \rho_{xy}^2} \quad . \quad . \quad . \quad . \quad . \quad (21)$$

in which

- X_t = synthetic value of hydrologic sequence at station X at time t
- Y_t = synthetic value of hydrologic sequence at station Y at time t
- ρ_x = lag-one serial correlation at station X
- ρ_{xy} = lag-zero cross correlation between stations X and Y
- ε_t, ω_t = values of independent normally distributed random variables with zero mean and unit variance at time t

Both X_t and Y_t are expressed in standardized normal form. The model preserves the lag-zero cross correlation ρ_{xy} between X_t and Y_t and the lag-one serial correlation ρ_x but assigns a value $\rho_{xy}\,\rho_x$ to ρ_y and thus does not preserve the observed value for ρ_y. Fiering (1964) later remedied this situation by using principal components to preserve all three correlations and extended the model so that it could handle any number of sequences. The procedure, however, has the shortcoming that only the lag-one serial correlations are preserved.

In order to preserve higher order serial along with the cross correlations, Matalas (1967) introduced the lag-one autoregressive process:

$$\underline{X}_t = A\underline{X}_{t-1} + B\underline{\varepsilon}_t \quad \ldots\ldots\ldots\ldots (22)$$

in which

$\underline{X}_t$ = m-vector at time t of synthetic values of hydrologic sequences at m stations, each value expressed in standardized normal form, i.e. $(X_{i,t} - \mu_i)/\sigma_i$

$\underline{\varepsilon}_t$ = m-vector at time t of normally and independently distributed random variables with zero mean and unit variance. Elements of ε_t are independent of the elements of X_{t-1}

A = m x m coefficient matrix calculated as

$$A = M_1 M_0^{-1} \quad \ldots\ldots\ldots\ldots (23)$$

B = m x m coefficient matrix derived from

$$BB^T = M_0 - M_1 M_0^{-1} M_1^T \quad \ldots\ldots\ldots (24)$$

in which equations, M_0 is the lag-zero cross correlation matrix:

$$M_0 = \begin{bmatrix} 1 & & & \\ & 1 & & \rho_{ij}(0) \\ & & \ddots & \\ \rho_{ji}(0) & & & 1 \end{bmatrix} \quad \ldots\ldots (25)$$

and M_1 is the lag-one cross correlation matrix:

$$M_1 = \begin{bmatrix} \rho_1(1) & & & \\ & \rho_2(1) & & \rho_{ij}(1) \\ & & \ddots & \\ & \rho_{ji}(1) & & \rho_m(1) \end{bmatrix} \quad \ldots\ldots (26)$$

In the above matrices, i designates the row, j designates the column, and the first subscripted variable is lagged behind the second. The coefficient matrices A and B are estimated from the cross correlation matrices computed from the historical sequences using Equations 23 and 24 with the result that the multivariate synthetic sequences generated using Equation 22 will match the multivariate historical sequence values of $\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\gamma}_i$, $\hat{\rho}_i(1)$, $\hat{\rho}_{ij}(0)$, and $\hat{\rho}_{ij}(1)$, i,j = 1,2, ..., m, where the hat notation denotes values estimated for these parameters from the historical data.

The multivariate lag-one Markov model is a special case of the lag-one autoregressive process (Equation 22) in which A is defined as a diagonal matrix with lag-one serial correlation on the diagonal and the elements of M_1 are defined as (Matalas, 1967):

$$\rho_{ij}(1) = \rho_i(1)\rho_{ij}(0) \quad \ldots\ldots\ldots\ldots (27)$$

B is then calculated by solving the following expression:

$$BB^T = M_0 - AM_1^T \quad \ldots\ldots\ldots\ldots (28)$$

The multivariate lag-one Markov model preserves $\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\rho}_i(1)$, and $\hat{\rho}_{ij}(0)$ and approximates $\hat{\rho}_{ij}(1)$ as defined in Equation 27.

O'Connell (1974) formulated the multivariate ARMA (1,1) model:

$$\underline{X}_t = C\underline{X}_{t-1} + D\underline{\varepsilon}_t + E\underline{\varepsilon}_{t-1} \quad \ldots\ldots\ldots (29)$$

in which C is the m x m coefficient matrix given by

$$C = M_2 M_1 . \quad \ldots\ldots\ldots\ldots (30)$$

D and E are the m x m coefficient matrices obtained by simultaneously solving the equations:

$$DD^T + EE^T = M_0 - M_2 M_1^{-1} M_1^T + M_2 M_1^{-1} M_0 M_1^{T-1} M_2^T - M_1 M_1^{T-1} M_2^T \quad \ldots\ldots\ldots\ldots (31)$$

$$ED^T = CM_0 - M_1 \quad \ldots\ldots\ldots\ldots (32)$$

In Equations 30 and 31, M_2 is the lag-two cross correlation matrix:

$$M_2 = \begin{bmatrix} \rho_1(2) & & & \\ & \rho_2(2) & & \rho_{ij}(2) \\ & & \ddots & \\ \rho_{ji}(2) & & & \rho_m(2) \end{bmatrix} \quad \ldots\ldots (33)$$

While a general analytical solution to Equations 31 and 32 has not been found, O'Connell (1974) proposed an iterative numerical solution which preserves the entire M_0, M_1, and M_2 matrices and a less general solution which preserves M_0 and the diagonal elements of M_1 and M_2. O'Connell (1974) also suggested a variation of the iterative numerical solution, one that does not preserve the off-diagonal elements of the estimated M_2 matrix, through defining C to be a diagonal matrix with elements

$$c_i = \frac{\hat{\rho}_i(2)}{\hat{\rho}_i(1)}, \text{ with all } c_i < 1.0 \quad . \quad . \quad . \quad . \quad (34)$$

This variation has the advantage that the inversion of M_1 in Equation 31 is not required. In addition, since c_i equals ϕ_i in the univariate ARMA (1,1) model, this variation permits the selection of ϕ_i from tables presented in O'Connell (1974) such that $\rho_i(1)$ and h_i the Hurst coefficient, are preserved. The major disadvantage of the approach is that it does not apply to cases where lag-two correlations exceed lag-one correlations.

The writers are aware of no published descriptions of applications of multivariate ARMA models although O'Connell's multivariate ARMA (1,1) program has been applied by O'Connell (personal communication, 1978) and by Armbruster (personal communication, 1978).

For hydrologic sequences with a log-normal distribution, the Markov model of Equation 22 and the ARMA (1,1) model of Equation 29 can be used provided the statistics used to estimate the coefficient matrices are transformed according to procedures outlined in presenting Equations 7-9 and 13-15 as described by Matalas (1967) and O'Connell (1974).

In a multivariate model, one may have a mixture of normally and log normally distributed variables. Mejia, Rodriques-Iturbe and Cordova (1974) published expressions for obtaining the cross correlations between 1) two-log normal variables and 2) a mixture of a normal and a log normal variable. These expressions have been generalized in this study to cover the case of lagged cross correlations of general order as follows:

1. Cross correlation between the 3PLN variables[1]

$$\rho'_{ij} = \ln \{1 + \rho_{ij} [(\exp(\sigma_i'^2) - 1)(\exp(\sigma_j'^2) - 1)]^{\frac{1}{2}}\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

2. Cross correlation between a mixture of a normal and a 3PLN variable

   a. i is 3PLN and j is normal

$$\rho'_{ij} = \sigma_j [\exp(\sigma_j'^2) - 1]^{\frac{1}{2}} \rho_{ij} \quad . \quad . \quad . \quad . \quad . \quad (36)$$

   b. i is normal and j is 3PLN

$$\rho'_{ij} = \sigma_i [\exp(\sigma_j'^2) - 1]^{\frac{1}{2}} \rho_{ij} \quad . \quad . \quad . \quad . \quad . \quad (37)$$

A computer program for estimating cross correlation matrices and other parameters for a mixture of normal and 3PLN variables was prepared for this study and is documented in Appendix D.

Two other multivariate ARMA models are known to the writers. The first is by Gwilyn Jenkins and Partners Limited, a British consulting and contract research organization, who advertise a multivariate stochastic forecasting package. However, the details of this package are proprietary information. The second is described by Ledolter (1978), but it is not clear whether he has a working multivariate ARMA model. Ledolter reviews the development of a general multivariate ARMA model and efficient parameter approximate maximum likelihood estimation procedures developed by Wilson (1973) and Hillmer (1976).

Matalas and Wallis (1974) have proposed a multivariate filtered fractional Gaussian noise process which matches historic sequence estimates $\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\rho}_{ij}(0)$, h_i. A limitation of this technique is that the same value of the filtering parameter ρ must be assumed for each of the variables in the multivariate model. This assumption is necessary to keep the process stationary with respect to the cross correlations, but has the result that it may not be possible to preserve estimates $\hat{\rho}_i(1)$ and h_i for each variable.

The Broken Line model as recently extended to the multivariate case by Curry and Bras (1978) preserves the $\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\gamma}_i$, $\hat{\rho}_i(1)$, and h_i of the original time series. The model has been applied to the Nile River (Curry and Bras, 1978) in conjunction with a dissaggregation and monthly autoregressive streamflow model. One problem with the multivariate Broken Line model is that it may lend to an inconsistent cross-covariance matrix for the Broken Line sequences. Curry and Bras (1978) describe an empirical calibration procedure to obtain a consistent cross-covariance matrix. Further difficulty may be encountered in the preservation of skewness. The user needs to make trade offs

[1]To avoid an unnecessarily complex notation in Equations 35-37, the x and y subscripts used in Equations 3-15 to distinguish the normal and log normal distributed variables, respectively, have been omitted. However, the prime notation indicates transformed parameters for the case of two 3PLN variables or a cross correlation between variables where one or more has a 3PLN distribution.

in degree of preservation among the Hurst, lag-one, and skewness coefficients.

Specific Problems

1. Preserving Historical Correlations. The relationships within and among the data series that one tries to preserve in a multivariate stochastic hydrologic model can be expressed in time-lag matrices (Equations 25, 26, and 33) in which the serial correlations one tries to preserve for each series appear on the diagonal and the cross correlations one tries to preserve among them appear as off-diagonal elements. In addition, one tries to preserve the distribution of values within each series as indicated by its mean, variance, skewness, and persistence.

Ideally, one would like to preserve all of the correlation coefficients that are significantly different than zero, enough moments for each series to define its distribution, and the long-term persistence properties of each distribution. As can be seen from the preservation capabilities of available models as summarized in Table 1, available multivariate stochastic models are not able to preserve all these characteristics. The modeler is faced with a dilemma of which model to adopt when they vary in the combination of parameters preserved. For dealing with the dilemma, Fiering and Jackson (1971) suggest a decision theory procedure to evaluate the economic consequences of implementing a design if the assumptions of model and distribution type on which it is based are untrue. An example application of this procedure by Jettmar and Young (1975) compared Markov and FFGN models for sizing a reservoir on the Rappahannouk River, Virginia. Markovian methods yielded an optimal reservoir size close to that obtained from using the historical data whereas the FFGN approach resulted in a 215 percent smaller reservoir.

Although the decision theory approach to multivariate stochastic model selection is theoretically attractive, it requires an extensive effort for which resources were not available in this study. The ARMA (1,1) models developed by O'Connell (1974) were selected for this study because they preserve a wide range of parameters without the computational complexities of the fGn and Broken Line techniques.

The main difficulty with applying the ARMA (1,0) process is in obtaining a solution to Equation 24. As BB^T is symmetric, a unique solution for B does not exist. Matalas (1967) suggested the method of principal components for solving for B, and Young (1968) suggested a solution procedure based on a lower triangular form for B. With either technique, complex numbers are obtained in the B matrix unless M_0 (Equation 25) is positive definite (A matrix is positive definite if all its eigenvalues are positive). This is a necessary but not a sufficient condition for BB^T to also be positive definite.

Table 1. Parameters preserved by various multivariate stochastic models.

Model	Reference	Parameters Preserved
1. Interstation correlated Markov	Thomas and Fiering (1962)	$\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\rho}_i(1)$, $\hat{\rho}_{ij}(0)$, $\hat{\rho}_j(1)=\hat{\rho}_i(1)\ \hat{\rho}_{ij}(0)$ $i \neq j$
2. Principal components	Fiering (1964)	$\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\rho}_i(1)$, $\hat{\rho}_{ij}(0), i\neq 1$
3. Lag-one Autoregressive, ARIMA (1,0,0)	Matalas (1967)	$\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\gamma}_i$, $\hat{\rho}_i(1)$, $\hat{\rho}_{ij}(0)$, $\hat{\rho}_{ij}(1)$, $i \neq j$
4. Lag-one Markov	Matalas (1967)	$\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\gamma}_i$, $\hat{\rho}_i(1)$, $\hat{\rho}_{ij}(0)$, $\hat{\rho}_{ij}(1)=\hat{\rho}_i(1)\hat{\rho}_{ij}(0)$, $i \neq j$
5. Lag-one Autoregressive-lag-one moving average, ARIMA (1,0,1)	O'Connell (1974)	a) Iterative numerical solution: $\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\rho}_i(0)$, $\hat{\rho}_i(1)$, $\hat{\rho}_i(2)$, $\hat{\rho}_{ij}(0)$, $\hat{\rho}_{ij}(1)$, $\hat{\rho}_{ij}(2)$, $i \neq 1$ b) Less general solution: $\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\rho}_i(0)$, $\hat{\rho}_i(1)$, $\hat{\rho}_i(2)$, $\hat{\rho}_{ij}(0)$, $i \neq j$
6. Filtered fractional Gaussian Noise	Matalas and Wallis (1974)	$\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\rho}_{ij}(0)$, and h_i
7. Broken Line	Curry and Bras (1978)	$\hat{\mu}_i$, $\hat{\sigma}_i$, $\hat{\gamma}_i$, $\hat{\rho}_i(1)$, and h_i

For a two-dimensional multivariate ARMA (1,0) process, Matalas and Wallis (1971a) identified the specific constraints which when imposed on the elements of M_0 and M_1 would guarantee BB^T to be positive definite. If the constraints are violated in the historical data, the elements in the cross correlation matrices must be adjusted to values falling within the constrained region before simulation can proceed. Attempts by the writers to generalize the constraints to higher dimensional multivariate models led to results which are too complex to be helpful to the modeler in determining the adjustment needed to the cross correlations to overcome problems with M_0 and M_1 matrices that are not positive definite. In summary one can identify a matrix as not being positive definite, but one cannot determine what adjustments will make a matrix positive definite with minimal distribution to a model's replication of the historical statistics.

Anderson (1962) presents tests for the significance of serial correlation coefficients as a function of sample size. This can be used to choose the number of serial lags to use in a model, but does not resolve the question of what to do when some coefficients in a matrix are significant and others are not.

2. Preserving Hydrologic Persistence. Long-term persistence is measured by the Hurst coefficient. In the multivariate case, one must consider such additional issues as how to decide when different computed Hurst coefficients for two series are really significantly different and, if they are, how to preserve different Hurst coefficients for different series. With respect to the first issue, no significance tests for differences between Hurst coefficients estimated from different series are known to the authors. With respect to the second, different Hurst coefficients can be preserved for different series by applying the ARMA (1,1) model of Equation 29 and specifying elements in the diagonal of the C matrix according to different Hurst coefficients for different series through Equation 34.

3. Achieving Data Homogeneity. Where hydrologic time series may have been affected over time by human caused changes in actual values (streamflow changes by reservoir storage) or changes in measurement (moving of a rain gage), one needs a test to determine whether a given series is homogeneous and select a method to adjust identified nonhomogeneous series. Streamflow nonhomogeneities can occur because of reservoir construction, diversions for consumptive use, or changes in runoff characteristics with land use. Double mass plots or the nonparametric Mann-Whitney U-test (Mendenhall, 1971) can be used to evaluate homogeneity in the distribution of time series data.

Even though homogeneity can be achieved by estimating flows on the basis of any constant state of basin development, many (e.g., Burges, 1978) recommend converting flow series to natural conditions. Since natural conditions tend to be more stable over time than do human patterns of land and water use, one has less difficulty in obtaining homogeneous data over a long enough period of time to make reliable estimates of the desired parameters. One also avoids the influence of the operating policies for reservoirs, diversion works, etc., that depend on human choices determined by many factors other than natural processes within the hydrologic cycle. Finally, natural conditions tend to be associated with flows that are less highly correlated and easier to preserve in flow generation models.

The major disadvantage in using natural flows is that if current conditions have prevailed throughout most of the period of record, synthesis based on natural flows would require a model to convert measured flows to natural flows and then, after a natural flow series is generated, reverse application of the model to convert the generated natural flows back to current conditions. The modeling errors in the double transformation may be greater than those encountered in trying to preserve statistics representing current conditions.

For the contribution made by this effort to the Great Salt Lake Resource Management Study, the assumption of present land and water use conditions continuing into the future was made at the request of the Utah Department of Development Services which want the results of this study as inputs to the legislative decision-making process. However, both present condition and natural flow data were estimated and used for calibrating separate stochastic models in order that the quality of the preservation of the statistics could be compared between the two bases. In either case, the techniques used for modifying flows to a common basis may introduce into the flow sequences inconsistencies which are not indicated by statistical and other tests of time-series homogeneity.

4. Missing Data. Short gaps in individual records in a set of long data series are generally filled by using multiple regression relationships with series that were measured during the gap. The measured series to use in the regression are best selected by stepwise regression techniques that test which of the measured series make a significant contribution to explaining variation in the series with the missing data. Once a regression is established, one can use it to make deterministic estimates of the missing items or can add randomly selected values of the error term in a stochastic process. The stochastic estimates do a better job of preserving series variability (deterministic estimates vary over a smaller range), but the extra effort required for stochastic modeling may not be justified if

only a few points are missing or nearly all the variance is explained by the regression.

The problem caused by missing data becomes much more severe when a desired series has not been measured at all or when the measured series is too short to establish reliable regression relationships. Examples for the Great Salt Lake were the ungaged smaller streams and groundwater discharge into the lake. Records for small streams are, where they exist, of short duration; and estimates of groundwater flow to the lake are in the form of average values and not time series data.

Three methods are available for reconstructing missing series. One is to reconstruct them from secondary data such as may be used in rainfall-runoff models or depth-to-groundwater subsurface-flow models, calibrated on the basis of as many years of record as are available. A second method that can be used when one has lake stage information is to estimate the sum of the missing series as the residual flows needed to explain observed stages from observed flows in the water balance model. This method suffers from all the problems inherent in estimating from small differences in large numbers. The third method is to calibrate a model that estimates the unmeasured flows from measured flows and check the results against observed lake stages. Previous studies (UDWR, 1974) on the Great Salt Lake estimated the residual flows as fractions of several lagged series of measured lake inflows. Since the inflows from the missing series can be shown by the lake water balance to be small in comparison with the measured series, the work that would be required for more refined estimation of the minor series was not considered justified for this study.

5. Length of Record. Generally one finds that the problem of missing data becomes more serious as series are extended into the more remote past because more and more gaps have to be filled. Matalas and Jacobs (1964) and Fiering (1963) examined the use of correlation analysis to augment hydrologic data and provided guidelines for judging whether to do so. The modeler needs to consider how much is really being added to the information. Beard (1976) states that when short-record statistics are adjusted using long-record correlated data, the improvement in accuracy of the mean value is given by the expression:

$$N_1' = \frac{N_1}{1 - \frac{N_2 - N_1}{N_2} R^2} \quad . . . . (38)$$

in which

N_1 = number of items in the short record

N_2 = number of items in the long record

R = cross correlation coefficient

N_1' = number of items that would be needed in the short record to obtain an accuracy of the mean that is equivalent to that obtained by the adjustment

The number of inflows and outflows for the Great Salt Lake covered by measured time series increases as one draws closer to the present as shown in Table 2. A record 127-years in length is available for the lumped sum of the lake inflows from the three principal tributaries modified to a present condition basis. However, separate series for the three rivers, for precipitation, and for evaporation go back only 41 years. In this study, the 41-year period with five series was selected because 1) data collected more recently can be expected to be more reliable, 2) the modifications required to achieve a common basis are less severe, and 3) the 41-year series includes pan evaporation. The 35-year series with natural flows was also tried but rejected for reasons described later. Since evaporation is the only outflow from the lake, it is equivalent in magnitude to all the inflows combined. Since pan evaporation varies significantly from year to year, it is desirable to represent its variability and cross correlation with the inflow variables as well as possible. Some simulations were run with four 77-year series, beginning in 1901 and omitting evaporation, but the results were less satisfactory.

One other alternative considered was to use the full available length of each series in estimating its parameters and of each pair of series in estimating its cross correlations. This would mean that different numbers in the cross correlation matrices would be based on different lengths of record. The difficulty encountered with this approach was that using records of unequal

Table 2. Time periods for time series inputs to stochastic model.

Time Series Set	Time Period	Time Series	Number of Time Series
1	1851–1977	Lumped Streamflow	1
2	1875–1977	Lumped Streamflow Precipitation	2
3	1890–1977	Separate Streamflows (3) Precipitation	4
4	1937–1977	Separate Streamflows (3) Precipitation Evaporation	5
5	1943–1977	Separate Natural Streamflows (3) Precipitation Evaporation	5

length to estimate cross correlations decreases the probability of obtaining a positive definite BB^T matrix (Fiering, 1963). Since the study had already spent the available funds and effort and not developed fully satisfactory solutions to the matrix equations using the 41-year series, no solutions were attempted with data from unequal length series.

6. Initial Conditions. Any simulation must begin from some set of initial conditions, and the results in early years are strongly influenced by the conditions used. Because one purpose of the model sought in this study is to estimate lake level probability in the near term, it is essential to set the initial conditions to represent the current state of nature. For simulating lake stages in the near future, the initial conditions should be the total inflows and outflows in the water year most recently completed and the elevation of the lake water surface at the end of that year. For the probabilities forecast in this study, annual total streamflows, precipitation, and evaporation were taken for water year 1978 and the initial lake stage was taken as that of October 1, 1978, or 4198.6 feet. The lagged error term in the ARMA model is initialized with an independent random number.

Each new year of data changes the values of all the distribution parameters and the correlation matrices as well as the initial conditions. These changes could potentially cause significant changes to the generating relationships or even cause a different model to appear optimal. This kind of total model recomputation and review, however, is probably too much work to justify redoing every year. Future model users would be better advised to recompute the parameters and update and review the model every five years but to revise the flows and stages used to define the initial conditions every year.

Water Balance Models

State-of-the-art

Water balance models for reservoirs and lakes are based on the principle of the conservation of mass or

$$\bar{I}\Delta t - \bar{Q}\Delta t = \Delta S \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (39)$$

where average inflow $\bar{I}$ and outflow $\bar{Q}$ are established over a period Δt, and ΔS represents the change in lake volume over that period. For terminal lakes, the inflows are surface runoff (possibly subclassified by stream), subsurface runoff (possibly subclassified by aquifer), and precipitation on the lake surface.

Where the lake level fluctuates, one must remember that some of the precipitation that falls directly on the lake at high levels falls on exposed soil at low levels and runs off into the lake. The net gain to the lake from precipitation falling on its surface thus equals

$$P' = (1-k)P \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (40)$$

where P is the precipitation and k is a runoff coefficient. For the dry desert flats around the Great Salt Lake, the runoff coefficient is close to zero and P' was taken as P. Most of the inflow comes from melting mountain snows collected by larger rivers, and runoff from areas near the lake is low.

Some attempts to predict future levels of the Great Salt Lake have used short-term deterministic forecasting methods which do not provide stage-frequency information. A stochastic technique provides information on risks, and capability for making that information as reliable as possible by: 1) incorporating long-term persistence (measured by the Hurst coefficient) and short-term persistence (measured by the lag-one correlation coefficient), 2) conditioning stage-frequency distributions on previous lake stages; and 3) determining the sensitivity of stage-frequency distributions to management alternatives on the lake and/or major tributaries within the basin. Several alternative approaches to produce stage-frequency information or utilize stochastic models are evaluated below with respect to these criteria.

1. Frequency analysis of a single sequence of lake stages. The Utah Division of Water Resources (1974) estimated the stage-frequency relationship for the Great Salt Lake by fitting a frequency distribution to the historic record of lake stages. They also used a water balance model to estimate how the lake stages would have been affected if the lake inflows had, instead of being their historic values, reflected: 1) natural watershed conditions or 2) additional upstream water use. The two modified records were then used to obtain modified stage-frequency relationships.

The purpose of fitting a distribution to the historical record is to use the characteristic shape of the distribution (either directly by computations, or indirectly by extrapolating by eye from points plotted on paper scaled to represent that distribution) to estimate the magnitude of rare events from a short record. Extrapolation by curve fitting does not reflect the persistence of lake stages (criterion 1) nor the dependence of future lake stages on present known conditions (criterion 2). Furthermore, lake stages may not even follow the distributions used for riverine frequency analysis. The approach does, however, address the sensitivity of stage-frequency relationships to management alternative (criterion 3).

2. Markov modeling based on precipitation records. Glenne, Eckhoff, and Paschal (1977) predicted future stages of the Great Salt Lake by applying a third order Markov model that represented lake inflows from precipitation to a water balance model developed by Kalinin (1968). The model was verified by hindcasting the historic record. Apparently only one 1,000-year sequence of lake stages was generated. Although stage-frequency distributions for different planning horizons were not obtained, these distributions could be found by varying the seed number in the random number generator, generating many equally probable sequences, and analyzing the distribution of the resulting lake stages at various time horizons.

This technique could satisfy criterion 2 (if many sequences were generated) because the synthetic sequences are conditioned on the known initial lake stage; however, the Markov model does not preserve long-term persistence in the historic inflow sequence (criterion 1). Also, one cannot directly analyze the effects of management alternatives on stage-frequency distributions with this approach (criterion 3).

3. Stochastic modeling of lake stage. Direct stochastic modeling of lake stage could be attempted through an approach that would 1) develop a stochastic model to replicate the statistical properties of historical lake stages, 2) generate many synthetic sequences, and 3) analyze the results to obtain stage-frequency distributions at different time horizons. The approach appears insufficient for three reasons. First, the integration of the separate phenomena of surface inflow, subsurface inflow, precipitation on the lake, and evaporation attenuates some of the stochasticity in these four sequences and probably thereby reduces the ability of the model to preserve the desired distributional properties. Second, this approach does not provide for investigation of the effects on stage-frequency distributions (through changes in inflow) of changes in land and water use in the tributary basin (criterion 3). Third, long-term persistence and serial correlation appear to be higher in lake stages than in the four component sequences and may be too high for available generating techniques to preserve (Lettenmaier and Burges, 1977).

An example of this approach is by Allen (1977), who used Box-Jenkins (1970) techniques to "forecast" future trends of the Great Salt Lake based on an ARIMA (1,1,1) model calibrated to match the historic sequence of peak lake stages. The difference between an ARMA and an ARIMA model is that the ARIMA process adds one or more integrating terms. The middle number in the designation indicates that Allen added a first order integration process to the first order autoregression and moving average processes indicated by the first and third numbers respectively. Allen also identified a seasonal ARIMA (1,1,0) x (0,1,1) model to represent fluctuation in lake stage during the year. The models were selected based on residual testing techniques and concepts of parsimony described by Box and Jenkins (1970). Several weaknesses in Allen's approach, with respect to the above criteria are:

1. No demonstration of capability to preserve hydrologic persistence. Based on O'Connell (1974), it is questionable whether these ARIMA models can perserve persistence statistics satisfactorily in the range of the very high values of these statistics for the Great Salt Lake stages.

2. As part of the justification for selecting the ARIMA (1,1,1) model over the ARIMA (1,1,0) model, it is stated that "the inclusion of the moving average flow, while not statistically significant, should make the forecast somewhat less dependent on the initial level of the series." However, this dependency is a desirable feature as stated in criterion 2.

3. No provision is made for varying management alternatives to meet criterion 3.

4. No stage-frequency distributions were calculated apparently because the question of future lake levels was reviewed as a "forecasting" operation rather than a "simulation."

5. The nonstationarity in the historical lake stage series due to the changing influence of man through time was not removed by adjusting the historical series to either natural or present conditions. In his conclusion, Allen points out the need for a stochastic model of the lake with similar capabilities for studying management alternatives to the model developed in our study.

4. Stochastic modeling from multivariate series. The approach described in this report satisfies all three criteria by coupling 1) a multivariate stochastic model for generating long sequences of sets of inflow (precipitation on the lake, surface inflows, and subsurface inflow) and outflow (pan evaporation), and 2) a water balance model for calculating lake stages from the sequence sets. Stage-frequency distributions at any desired planning horizon can then be estimated directly from corresponding points in the generated long synthetic sequences of lake stage.

Specific Problems[2]

7. Climatic Cycles. Since solar radiation is the energy source for terrestial

---

[2]Problem numbering continues to follow that used in Chapter 1.

weather, some reason exists for suspecting that weather changes correlate with the sunspot activity which causes emitted radiation to vary by about one percent between high and low years (Landsberg, 1962, 116-120). Sunspots have been observed since 1749 and follow an approximate 11-year cycle (Landsberg, 1962). Earlier European observations go back to 1610, suggest additional longer cycles of various periods, and show a long period in the 17th century of low sunspot activity associated with cold-wet weather. During this time according to Willett (1977), the Great Salt Lake reached an elevation of 4222 feet and overflowed into the western desert. Based on analysis and extrapolation of these various cycles, Willett forecasts a rise in lake level to 4205 by 1981 and to around 4217 by 2002. To the degree that these forecasts are true, a purely stochastic simulation process will not represent future lake level probabilities. A deterministic component would have to be added.

In order to justify incorporating solar weather cycles into hydrologic forecasting, one should show that they are associated with a significant portion of the relevant variability. Weakly (1965) identified drought periods from tree rings in Nebraska over the period from 1220 to 1957, but did not find sufficient regularity in his wet-dry pattern to forecast cycles. Snellman (1977) states that almost all alleged climatic cycles are associated with only a small fraction of the total observed variance and/or are artifacts of statistical sampling. He also states that climatologists are skeptical about using sunspot cycles for predicting future climatic cycles for two reasons: 1) there is no conclusive evidence of the existence of these cycles in earlier centuries; and 2) there is no physical explanation of a correlative relationship between these solar changes and atmospheric changes. The conclusion is that a relationship may exist, is probably weak, and is yet to be modeled quantitatively. For these reasons, no attempt was made in this study to superimpose trends or cycles suggested by sunspot data for the purpose of establishing probabilities of lake levels for present decisions among management alternatives.

8. <u>Evaporation-Streamflow Feedback</u>. Large lakes have been observed to increase precipitation downwind. Landsberg (1962, p. 303) reports annual precipitation averaging 31 inches upwind and 36 inches downwind of the Great Lakes. The heavy snowfall belts downwind of Lake Ontario in New York state are one of the best known examples of this phenomenon. If lakes increase downwind precipitation, one could reasonably expect larger lakes to bring larger increases and that when the surface area of a lake varies over as wide a range, as does the Great Salt Lake, significant variation in downwind precipitation may occur too. Where the precipitation concentrates in a small mountain area and where runoff from that area is the principal source of water for the lake, one has good grounds for suspecting a possible feedback relationship. While this study did not have funds to explore this possibility quantitatively, such a positive feedback process may contribute to the extraordinarily high persistence of annual streamflow in some of the downwind tributaries to the Great Salt Lake.

9. <u>Non-Level Lake Surface</u>. In 1959, Southern Pacific constructed a railroad causeway across the lake from sand and gravel capped with boulder-sized riprap. The permeable causeway, breached by two box culverts each 15-feet wide, separates the lake into two parts; about 40 percent of the lake to the north and remaining 60 percent south of the causeway. As the recipient of most of the fresh water inflow, the slow rate at which water can pass through the culverts and seep through the causeway to the north arm causes the south arm to be somewhat higher. In 1975, a maximum difference of 2.35 feet occurred during a period of rising stages.

Waddell and Bolke (1973) developed an empirical relationship for estimating the elevation difference between the two arms from variable inflow relative to volume, area, evaporation, and two-way flows through the causeway affected by salinity difference. A graphical version of Waddell and Bolke's relationship presented by the Utah Division of Water Resources (1977) was used in this study.

Winds create a non-level lake surface by causing the water to surge toward the leeward shore and thereby generating what is called setup or a wind tide of height estimated from the formula

$$Z_s = \frac{V_w^2 F}{1400d} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (41)$$

where Z_s is the height of the tide above still lake level in feet, V_w is the windspeed in miles per hour, F is the length of the fetch of water over which the wind is blowing in miles, and d is average lake depth in feet (Linsley and Franzini, 1964). In estimating wind tide, one must remember that winds blow faster over water, because of reduced surface friction, than over land. For fetches longer than 6 miles, Saville, McClendon, and Cochran (1962) estimated velocity over water as 1.31 times that over land. For the south arm of the Great Salt Lake, the peak average wind speed parallel to the maximum fetch over the 12-hour period required to cause windtides on the Great Salt Lake during the spring high water months was 39 mph in 1975 measured 20 feet above ground level. Multiplying by 1.31 to estimate the faster velocity over water gives 51 mph. With a 35-mile fetch and 20-foot mean depth, Equation 41 estimates a wind tide of 3.25 ft. Smaller wind tides would be estimated at other points around the lake with shorter fetches in directions of lower wind speeds.

Lin (1977) has specifically studied wind surge heights, the harmonic properties of wind-induced seiches in the Great Salt Lake. His published results for a storm in January 1969 (Figure 3) show a maximum amplitude for the first harmonic of 2.4 ft at Silver Sands. The maximum wind speed during this storm at Salt Lake City was 36 knots or 41 mph. These gaged data thus indicate that Equation 41 estimates wind tides at about twice the level experienced on the Great Salt Lake.

The wind also generates short frequency waves whose tops rise somewhat higher than the wind tide and which may have enough momentum to run up the beach to elevations above their tops. Linsley and Franzini (1964) give for estimating wave height:

$$Z_w = 0.034\, V_w^{1.06} F^{0.47} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (42)$$

Substitution of the 1975 Great Salt Lake values for V_w and F in Equation 42 gives a Z_w of 11.7 ft. For the very flat shoreline

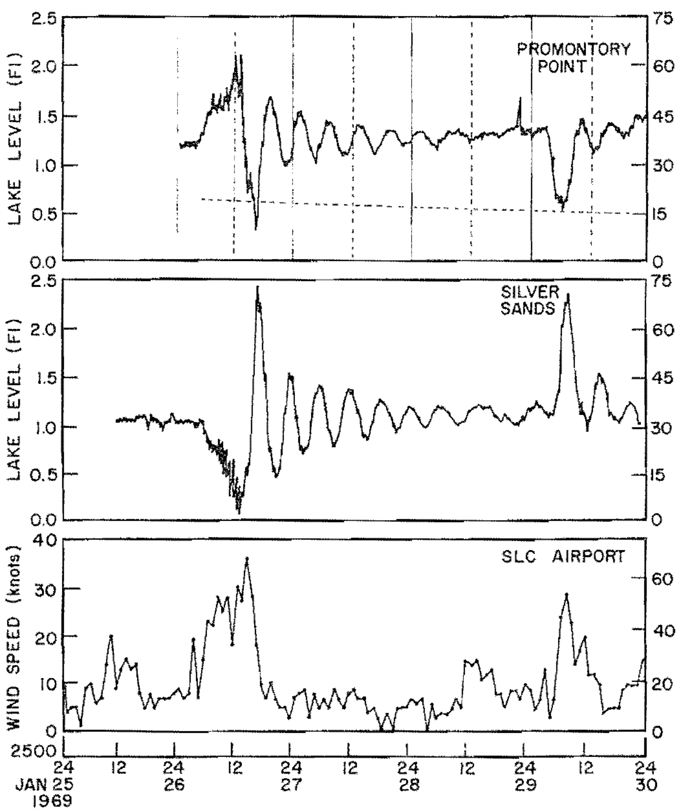


Figure 3. Typical time pattern of wind tides and associated wind speeds on the Great Salt Lake, January 25-30, 1969. Source: Lin (1977).

slopes of the Great Salt Lake (flatter than 1:30), the runup Z_r would be only about 0.2 Z_w (2.3 ft). For levees (slope of 1:6), Z_r would be slightly larger than Z_w. Chapter 7 of the U.S. Army Coastal Engineering Research Center (1973) Shore Protection Manual suggests even higher values. The above relationships are for average wave height; the 1.0 percent wave height (the average of the highest one percent of all waves) is at least 50 percent higher (reaching 17.5 ft).

The above 1975 Great Salt Lake figures for windtide plus runup suggest that a levee sloped six horizontal to one vertical at the most exposed lakeshore points may have to have a freeboard as high as 20 feet to prevent wave-splash topping. A somewhat lower level could be constructed without endangering the levee, particularly if its lakeside surface were protected with a scour-resistant material. Nevertheless, these figures give one an appreciation for the magnitude of lakeshore damages possible during storm periods.

10. <u>Effects of Control Measures on Lake Level</u>. To date, economic evaluation of the alternatives for lake level control have utilized historic time series for lake inflows. In a preliminary use of stochastic methods to evaluate the effects on flooding damages of different-size causeway openings, a stochastic model comprised of two multivariate models, one of lake precipitation and the other of lumped streamflow, was tried. This model would not be expected for a simulate extreme lake stages since precipitation and streamflow are not correlated in the model as they are of course in nature. Table 3 summarizes the results of using this model in conjunction with the water balance and damage simulation models presented in later chapters in terms of the resulting expected values of reduction in flooding damages over the N years following 1977 for different causeway openings (BERB, 1977). The conclusion was that since the average annual cost of placing a 100-foot opening in the causeway exceeds the benefits shown on Table 3, the opening could not be economically justified by lake level control benefits alone.

The effect of levees on lake levels can be analyzed in a straight forward manner in a water balance model by merely adjusting the volume-area relationship to deduct volumes and surface areas that will no longer be inundated by rising water.

The effects of control by pumping into evaporation areas are more complicated to quantify because they depend on the operating rules used to decide when to start and stop the pumps. Theoretically, rules can be devised to maximize net benefits (James and Lee, 1971, p. 469-70). The Utah Division of Water Resources (1977) compared several alternative operating rules for pumping from the lake, and the results of their work are described in Chapter 4.

Table 3. Expected values of the reduction in flooding damages from present (1977) values over the next N years for different causeway openings. Damage reduction is expressed as a discounted equivalent uniform annual amount in thousands of dollars.

Causeway Opening (feet)	N (years)	Damage Reduction ($1000) State	Industry	Other	Total
	10	114	430	283	828
	14	92	344	524	659
	25	95	262	211	568
100	50	91	313	244	648
	75	87	307	239	634
	100	86	305	237	628
	125	86	304	237	628
	10	160	637	286	1083
	14	129	511	226	866
	25	131	335	234	699
300	50	121	391	276	788
	75	118	391	288	797
	100	117	386	285	790
	125	116	387	285	789
	10	165	658	339	1162
	14	133	529	268	930
	25	137	350	279	766
600	50	127	407	314	848
	75	124	407	325	855
	100	123	403	322	848
	125	123	403	322	847

The effects of control by augmenting upstream consumptive use are the most complicated to quantify because of the complexity of the alterations to hydrologic processes, the difficulty in determining the optimum system operation policy, and the factors constraining operation. The hydrologic complexity comes in determining how much of the diverted flow will reappear as return flow and how water use will affect storm runoff. The optimization difficulty comes in determining benefits from the uses in which the water is consumed and how to reckon fixed costs which continue during periods when water is unavailable for diversion into the calculations. The constraining factors come in institutionalizing an agricultural system that will willingly shift back and forth between irrigated and dryland agriculture.

This study did not attempt upstream consumptive use system optimization. The approach was to start with liberal assumptions on system efficiency with the idea that if augmenting upstream consumptive use could not be justified under very favorable assumptions, it should be rejected without further study. Specifically, if the lake rises above a control elevation, the idealized operating plan will use upstream storage to reduce inflow from the Bear River to the minimum flow that will satisfy such requirements such as flow through the Bear River bird refuge. Specific storage sites are not specified, but lake stages will be reduced and a benefit will be achieved through reducing flooding damages. The value of this benefit will be a maximum that could be achieved and the maximum benefit lake level control could contribute to upstream water development project justification.

11. Number of Traces. Probability distributions for lake levels such as that suggested by Figure 1 are developed by generating many sequences or traces of lake levels. The marginal gain in information as more traces are generated diminishes as more runs are made. Burges (1970) studied the number of traces required to reach a stable storage distribution in a reservoir design study. He found that 300 traces may suffice for a stream exhibiting low variability but that 1000 traces may be needed for streams with high variability. Since the marginal cost of generating a trace is quite small, one is normally justified in generating the traces required to make stable estimates.

12. Effect of Salinity on Evaporation. Jones (1933) developed Figure 4 expressing the effect of sodium chloride content on evaporation from salt water brine as a fraction of evaporation from fresh water. It was assumed that the effect of other dissolved minerals would be similar and that total salt content could be used in place of the sodium chloride content to read the evaporation ratio.

Vertical sampling to determine salinity profiles in the south arm indicates that a

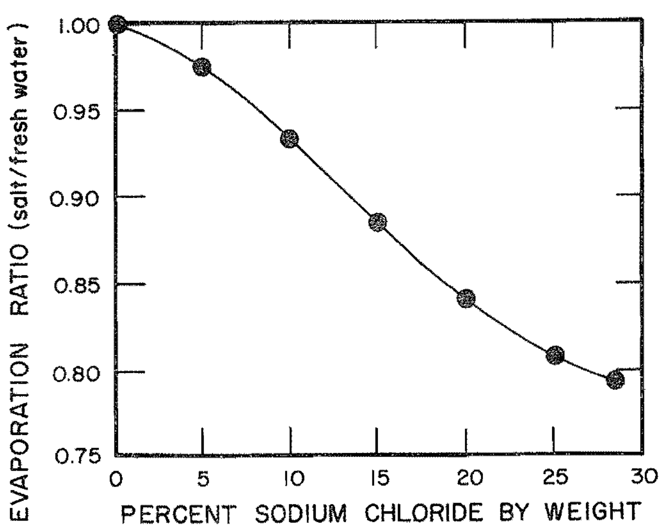


Figure 4. Ratio of salt water evaporation to fresh water evaporation as a function of salt content, after Jones (1933).

fresher water tends to float on top of the denser brines and thus that the salinity of the surface waters which control evaporation is somewhat less than the average for the total lake volume. In the Great Salt Lake, this effect is at least partially offset by the fact that the brines in the north arm are denser than the average salinity for the entire volume. Assaf (1977) estimated the total salt content of the Great Salt Lake to be 4.7×10^9 tons. The Utah Division of Water Resources (1974) lake water balance model converts an average freshwater equivalent evaporation of 52 inches per annum to saline water evaporation using the mean salinity of the lake estimated by dividing the total salt content by the total water content and using the resulting fraction to read an evaporation ratio from Figure 4.

Damage Models

State-of-the-art

Two hundred years of changing procedures to meet changing needs in water resources planning and management practice in the United States (James and Rogers, 1976) have lead to the Principles and Standards in which the Water Resources Council (1973) officialized a multiple objective methodology for federal water resources planning. While the recommended methodology for pursuing the goals of national economic development, environmental quality, and social well-being will in turn be superceded by new guidelines, the Principles and Standards provide a reasonable statement of the current state-of-the-art. Economic analysis is shown as an established quantitative procedure in which the details are being refined by research, and application is constrained by politically established water policy. In contrast, the methodologies for environmental and social assessment are in much more rudimentary states, far from concensus in either performance or application.

The focus of this study is to use the best available methodology to develop a damage simulation model to evaluate terminal lake control alternatives. The literature review needs to abstract relevant principles from the planning literature and identify empirical data that can contribute to better estimation of specific economic effects. Individual topics are discussed in the following sections.

Flood control damage models have normally associated an amount of damage with a flood stage and not considered the dynamics of the time pattern in which a flood rises or falls from the peak. The only known exception is the dynamic riverine flood damage simulation model developed by Breaden (1973) where damages were simulated as they occurred with time and varied with such factors as the length of time since the last flood, the duration of flooding, and the time of year.

Transportation Effects

Railroads and highways are threatened by closure when water levels rise toward their roadbed elevation. Economic theory would say that the damages caused to such facilities equals the economic costs, to whomsoever they may accrue, of the least-cost response to the problem, whether it is to close the route, protect the route at its location, or move the route to a higher alignment (James and Lee, 1971, p. 274-7).

Damage estimation can thus be performed as a two step process of predicting a response to a given state of the lake surface and of then estimating the costs inherent in that response. One might predict response by economic optimization, but other management goals usually dominate travel decisions. Both highway and railroad location and relocation decisions are influenced by many factors outside the benefit-cost framework, but the decisions follow generally predictable patterns.

Of the alternative responses, one may generally expect:

1. Closure to be favored where traffic is too light to justify route protection, where the lake level is expected to remain so high as to be threatening for long periods of time, or where the closure is expected to be of too short a duration to justify structural remedy. Closures that only occur during overtopping by storm-driven waves are a good example of this last case. The duration of closure is important because economic losses increase with the length of time traffic is interrupted.

2. Protection to be favored if the maximum expected lake level is not so high above the route elevation as to make protection more closely than realignment. A protection decision is in part a gamble that the terminal lake will not soon afterwards rise above the protection elevation. The wisdom of a protection decision can be evaluated in terms of whether the protection would pay for itself before it is overtopped or in terms of the probability of overtopping before the end of a required payback period for the investment.

3. Movement of the route to be favored if traffic is great enough to justify the cost and if the maximum lake level is expected to be high enough to make realignment less costly than protection. Sometimes a route moved to a higher elevation should be moved back down after a lake level recedes in order to take advantage of a shorter alignment or flatter grades or to reestablish access to temporarily abandoned areas. Where later return seems probable, one should delay moving to a new higher alignment until sure that it will be necessary. In deciding when to move, management must balance a trade off between a) protecting a route near the lake too long only to find it suddenly closed

during a storm and kept closed as the lake continues to rise, and b) moving to a higher route too early when moving itself is expensive and longer routes and steeper grades increase transport cost.

The information transportation planners should weigh in choosing among these three alternatives can be divided between 1) information on lake level probabilities, and 2) information on the costs and benefits of implementing various decision alternatives. The information on costs and benefits can in turn be divided between 1) empirical information on specific designs with estimates of their costs, and 2) general information on road user cost, the value of travel time, accident losses, etc.

The empirical information on the costs of specific designs needs to cover the maintenance measures one takes to protect a roadway against wave scour and settlement and how their costs vary with rising water, repair measures required after storms and how their costs vary with lake level, designs and costs (installation and maintenance) for levees between a route and the lake and for raising roadway elevation. All such information is site specific and must largely be obtained from the railroad or highway department that operates and maintains the transportation route.

Shifting traffic from one route to another changes the cost of vehicle operation and the time required in transit. Vehicle operating costs vary with distance, vertical and horizontal alignment, character of the roadway surface, and traffic congestion. Curves for estimating these costs are available (Winfrey, 1969; AASHO, 1960; Claffey, 1965). The curves can be used to estimate the average operating costs over an alignment of known characteristics, and that average can then be multiplied by a traffic volume to get a total vehicle operating cost for the route. The time of travel can be estimated from distances and velocities, and an economic value of a vehicle hour can be inferred from commuter choices (Nelson, 1968; Thomas, 1967). Haney (1967) estimated the value of travel time to be $2.82 per vehicle hour based on commuter choice studies in the San Francisco area. Cesario (1976) compared the value of travel time with wages and recommended evaluating travel time at one third the wage rate. Similar principles can be used to estimate costs of rail transport and the value of time for moving trains. It is also necessary to account for any interference of high water or wave conditions on operating cost and travel time. This is a significant problem for rail traffic moving across the Great Salt Lake causeway.

No generally acceptable method has been found for assigning an economic value of road access (Winfrey, 1969, p. 609-610). The usual procedure is to allocate costs residual to road user benefits to landowners, but that practice is not much help in the problem at hand. Fortunately, access closure, other than to Antelope Island, is not a major problem associated with rising water in the Great Salt Lake.

Recreation Effects

Recreation on the Great Salt Lake includes use of shoreline areas for swimming, picnicking, camping, sightseeing, and related activities and use of the lake for boating. These activities are supported by facilities (bath houses, boat launching and docking areas, picnic tables, places to purchase food and supplies, etc.) near the shoreline and by beach areas with reasonably short distances from parking to the water. Because shoreline areas are relatively flat, the vertical lake level changes that occur on the Great Salt Lake cause large changes in the shoreline position horizontally and major problems in keeping the facilities near the beach. Recreation facility management issues include 1) how to design shoreline recreation areas to minimize their sensitivity to fluctuating lake levels and 2) when to move facilities toward or away from the lake. The first issue thus deals with the question of site selection, and the second deals with the facility location at a given site.

Economic comparison of site alternatives would show the first issue to involve trade offs between a less accessible recreation site at a location of steeper slope and a more accessible site where the lake level fluctuation means greater horizontal shoreline movement because of flatter slope. Where the lake level can fluctuate over a range of 20 feet, as it does for the Great Salt Lake, and where horizontal shoreline movement can be measured in miles, recreation facilities are best designed not as permanent structures but so they can be moved as lake levels fluctuate. The decision on moving recreation facilities toward or away from the lake can be analyzed in much the same way as are the transportation alternatives of closure, protection, and movement. The goal would be to keep them as close to the lake as possible without unnecessary exposure to wave damage during storm periods.

One type of useful information on lake level probabilities would be, given an existing facility elevation, what probability of wave damage (or distribution of possible amounts of wave damage) can be expected during the coming recreation season. The facility manager could make the best use of this information about October 1, when the summer recreation period is over and the winter season of rising lake levels and storms is about to begin. If the risk of damages during the coming winter is excessive, the facilities should be moved to higher ground. In the spring, the facility will have survived the time of greatest hazard, and the lake level will be falling during the summer period of high evaporation and low inflow. It would make little sense to move the facilities away from a falling lake just as recreationists who want to be near the water begin coming. In the spring, the recreation facility manager is more interested in the expected level (or distribution of expected levels) to which the lake will drop before the season ends.

An economic analysis of these alternatives requires site specific information on the costs of moving various types of facilities closer or further from the lake, costs of storm damage repair, how one can modify facility design to increase movability or reduce damageability, and estimates of the costs of developing various alternative sites. More general information from the literature (Clawson and Knetsch, 1966; Seckler, 1966; Seneca, 1969; Dwyer et al., 1977) can be used to construct a theory and collect the supporting information needed to estimate recreation benefits.

Estimates of visitation must then be combined with a value assigned to a visitor day for economic evaluation and with estimates of visitor expenditures for economic impact studies (James and Lee, 1971, p. 411-412). One needs to consider the effects of shoreline fluctuation (Carson, 1972) and the salinity of the water (saturation produces salt deposition that causes discomfort to swimmers and crusts the bottom with deposits that hurt pleasure craft). One can expect changes in lake levels and lake quality to affect numbers of visitors (Holman and Bennett, 1973), the value of a recreation day, and the expenditures per visitor. One could reasonably expect that greater difficulty of access, even for an international attraction such as the Great Salt Lake, would reduce visitation with the major decrease being because local visitors would return less often. More of the visitors would be people coming from a distance for a one-time experience. One-time visitors would probably not be numerous enough to provide the necessary revenue to maintain a recreation enterprise. The enterprise would close and benefits would drop to very low.

Bird Refuge Effects

The bird refuges and private marshlands on the shore of the Great Salt Lake provide areas for rest and food for migratory fowl on the intermountain flyway as well as for a number of species of local birds. Fresh water from the rivers flowing into the lake is spread and maintained at shallow depths in ponded areas in the bird refuges so that food grains will grow and waterfowl can rest in their preferred habitat. Christiansen and Low (1970) estimated annual consumptive use in these areas at 41 inches. System design includes distribution canals to deliver the water to the various ponds and dikes to protect the food grasses growing in the habitat areas from salt water intrusion from the lake. The feeding ponds require large flat areas such as those available near the lake and thus cannot be moved away from the lake to rougher topography.

Determination of the theoretical management economic optimum, the point minimizing the sum of damages and remedial costs is made more difficult for bird refuge areas by the problems in assigning economic measures to the values received from bird refuge areas and of the lack of work done in this area. In the one study that could be found, Hammack and Brown (1974) employed multiple linear regression analysis to estimate consumers surplus for duck hunters and thereby the marginal value of the bagged waterfowl at $3.29. This figure when multiplied by changes in average annual waterfowl bagged (e.g., reductions caused by salt water flooding of feeding areas) provides an order of magnitude estimate of the lower limit to the economic value of a feeding area. Using the Canadian averages quoted by Hammack and Brown (1974) of 2.7 waterfowl that can feed on an acre, that 24 percent of the waterfowl need to be saved for breeder stock and that 80 percent of the birds shot are bagged, one gets an annual value per acre of waterfowl feeding area of $5.40 (2.7 x 0.76 x 0.80 x 3.29) or about $7.00 at 1978 prices.

If one determines that preserving a wildlife area is justified, one can optimize the protection strategy on the basis of minimizing the cost of preserving the area. This approach, however, has an upper limit because high lake levels can be kept from the feeding areas only by high levees, and a pumping system to prevent flooding from freshwater coming from the landward side would be extremely expensive.

Two questions have to be addressed in evaluating the feasibility of protecting bird refuge areas. One is the value of the saved habitat as determined by the number of waterfowl that can be supported, the frequency and duration of periods when waterfowl use the area to capacity, the distribution of use among various species, the length of time it takes the areas to recover when salt water recedes, and importance attached to the protected species. The second is the financial capacity of the refuge managers to obtain the funds required for expensive protective measures. This second factor is probably the more limiting and certainly the easier to use to estimate economic loss. Taking it as dominating reduces a very complex set of issues on environmental effects and values to a relatively simple question of determining when bird refuge operators on fixed budgets would abandon some of their ponds.

The options open to refuge managers in responding to rising lake levels are basically to 1) abandon the facility, or 2) protect it. Movement to an alternate nearby location is not generally viable. When waters recede, the manager must decide how far and how long to let the water drop before going to the expense of reclaiming an area.

For developed marsh areas, a manager would want to know the probability distribution for expecting high water during the coming season. He would want to get as much food value as possible from the lower ponds before they were inundated and, if available fresh water supplies were limited, concentrate irrigation in areas not likely to be drowned out by salt water before the food grains ripened. For marsh areas recently exposed by receding lake levels, a manager would want a probability distribution of the expected time to the next inundation to help in deciding whether or not reclamation is worthwhile.

Helpful empirical information would include the cost of reclaiming exposed salt marsh, the uses made by waterfowl of different species of various pond areas so as to be better able to identify good ecological sites, the seasonal variation in plant growth and waterfowl use at the site, and the sensitivity of various food grasses to salt water inundation. Published references can be consulted for information on the role of given marshland types in supporting waterfowl along flyways and on how use of an area by migratory waterfowl varies with size (Chura, 1962; Rawley, 1976; and Sanderson, 1977).

Mineral Extraction Industry

The mineral extraction industry withdraws brine from the lake, evaporates the water in controlled basins, and removes individual residues as they precipitate for sale as various salt products, fertilizers, metal ores, etc. (Cohenour, 1966). The owners of individual plants invest considerable fixed cost in facilites to remove the brine from the lake at an advantageous point, transport it to evaporation ponds (located at low elevations to minimize pumping cost), and precipitate and separate the salt products for sale. The large fixed cost makes moving the plant impractical except for some adjustments in evaporation pond location. Thus the management alternatives are among ways for making the best possible situation in spite of the losses caused by changing lake levels. The losses include:

1. Damage from storm waves.

2. Rises in lake surface elevation that require diking and other works to protect the physical plant from the water.

3. Losses in salinity as a fixed salt content dissolved in a greater volume of water means that more evaporation will be required to reduce the brine to a salable product. Since the brines tend to concentrate in denser layers within the lake, an industry is advantaged by being able to locate its intake at such locations and particularly so if the locations with more concentrated brines remain relatively stable with changing lake elevations.

4. Drops in lake surface elevation that require longer lines and more pumping.

5. Changes in patterns of brine concentration within the lake that bring less concentrated or more polluted brines into the intake area.

Economic analysis of this situation suggests that a company should seek the least expensive way of protecting itself against rising water until the lake level rises to the point where the minimum cost of protection is too much for the company to bear and still remain profitable. The elevation of that point would vary according to whether the high lake level is believed temporary, in which case the business could stand a short term loss if it knew that the situation would correct itself soon, or likely to continue for a long time. Once the elevation of profitable operation is passed, a company can be expected to salvage movable equipment and abandon the site. If the water should stay up, a separate analysis is needed to decide whether development of a new site would be profitable, with justification normally quite difficult because the high lake level means a more dilute brine. When the lake level is falling, the company needs to decide whether it should revise its intake to abstract brine from a more advantageous location. Here again the decision would depend on the expected duration before the lake rises again to near the elevation best served by the current design.

Valuable information on lake level probabilities would thus include:

1. Given a lake level high enough to threaten the plant with further rises, a) the probability distribution of how high the lake can be expected to rise during the next year so that an immediate program for protection can be planned, and b) the probability distribution of duration until the lake will rise to a level at which continued operation is no longer profitable in the short run so that the company will have to evaluate its long term operation.

2. Given a lake level that is already high enough to make operation unprofitable but not so high as to have yet flooded the plant, the probability distribution of how long the lake can be expected to stay above that level.

3. Given a lake level that is receding after having risen so high as to flood out the industry, a) the distribution of lake levels during the payoff period required by the industry to make restoring the operation profitable, and b) the information in "1" for tentative site locations.

4. Given a lake level low enough to suggest an economic advantage to modifying the intake system, a) the probability distribution of how low the lake can be expected to drop during the next year or two so that needs for immediate extension can be evaluated, and b) the probability distribution of duration until the lake will return to a

level at which the extended intakes will no longer be profitable.

Analysis of the effects of lake level fluctuations on the mineral extraction industry is needed at two levels. Each company needs to evaluate its own situation in reaching its own decisions, and state and local planning agencies need to assess the effects on the industry as a whole from the public interest viewpoint. The companies use information on their costs and revenues to make their own calculations and evaluations based on the above probabilities. The agencies need information on how industry will react to lake level changes for its analysis of benefits and costs.

Relevant empirical information includes costs of self protection, wave damage, and process modification for companies making adjustments. Literature can be used to explore some relevant factors in industrial site location (Smith, 1971), the effects of the industry on the economy of nearby communities and the state as a whole, and the tax revenues accruing from industry. Effects range from the direct consequences of industrial purchasing, hiring, and selling to indirect effects that have to be traced through multiple linkages (e.g., by input-output models) as other industries buy from or sell to the mineral industries (Miernyk, 1966).

Others

Other groups affected by lake level changes on the Great Salt Lake include 1) the brine shrimp industry, 2) communities discharging drainage or treated sanitary wastes into the lake, 3) agriculture near the lake, 4) owners of buildings near the lake, and 5) the management of the Salt Lake Airport. Expected damages to each of these entities are much smaller than those to the entities described above. Each property owner or facility manager near the lake has probably already felt some concern over the consequences of rising lake levels for his operation, but few if any have in these five groups actually suffered losses. Consequently, one would not expect the managers to have the degree of interest in lake level information described above for the other groups. Each knows the lake elevation at which he expects to begin to suffer ill effects and would be interested in the probability of the lake rising to that elevation or higher during the coming planning horizon. The length of the applicable horizon would depend on the industry. The airport requires a fairly long time lag to adjust by building protective measures and a very long time lag for moving. Some agricultural operations do not look much beyond the coming growing season. If the probability of the lake rising to a problem elevation within the planning horizon is high enough, more detailed information on the expected length of time before the problem develops would be of concern.

Each of these entities would have a long lead time to respond to the threat of waters rising from present levels considerably below their damage thresholds. Each loss would largely be the cost of making the necessary adjustments: protective measures, moving, or abandoning. The principles used to estimate these losses are the same as those for the other sectors already discussed.

Specific Problems

13. Behavior Forecast. Since damages to transportation routes, recreation areas, wildlife refuges, and the mineral extraction industry all depend on how the respective managements respond to threatened inundation, some method for forecasting management behavior is required. One cannot reasonably assume that managers will do nothing in response to the slowly rising lake level until all is lost. Damage simulation is better advised to make reasonable predictions of probable response.

14. Viewpoint. The generally accepted viewpoint for the economic analysis of public works is that both benefits and costs should be counted to whomsoever they may accrue (Grant and Ireson, 1970). For purposes of financial analysis (James and Lee, 1971), state and local governments need information on effects on their revenues and expenditures. Analysis from the viewpoints of specific property managers is needed to forecast rational behavior for them.

15. Projected Futures. In requesting this study, the Utah Department of Development Services wanted damage estimates to be based on existing facilities and did not want to justify lake level control on the basis of providing for future growth in the areas of hazard.

16. Environmental and Social Effects. Some changes in the value of the Great Salt Lake as an environmental resource occur with lake level. Other sections of this report discuss the harm rising water does to marshlands and bird refuge areas along the outer shore of the lake and to migratory waterfowl that have been stopping there. Rising water also inundates sandbar areas on the nine islands in the lake used by pelicans for nesting and other birds and mammals. The steeper higher elevations on these islands provide much less suitable habitat (Knoph, 1974). Also according to Knoph (1974), falling lake levels could cause environmental loss to the pelicans and other birds that nest on the islands (particularly Gunnison) protruding from the western part of the lake (Knoph, 1974). Were levels to drop too low, predators and humans would gain access to these nesting areas and drive them away. Without good nesting areas, populations can be expected to decline considerably.

The major potential social loss from rising lake levels would be that associated with the jobs eliminated in damaged industries. Since such losses would be at least partially compensated by new jobs created in lake level control efforts, the net social effect may be rather small. An additional factor to consider is that the lake has an important place in Utah culture (Morgan, 1947) which would lead to a widespread sense of loss were it to go completely dry.

17. Scheduling Control Measures. The economic criterion of maximizing economic benefit can be applied to scheduling as well as to other alternatives (James and Lee, 1971). The probability estimations made possible by this study provide useful information for such analyses.

CHAPTER 3

PREPARATION OF THE DATA BASE

Introduction

Since stochastic models can represent real flows no better than do the statistics from which they are generated, it is important to start with statistics that represent the real data sequences as well as possible. Data collection requires searching out time series of recorded data that pertain to needed inflows and outflows, eliminating series that are unreliable or too short, compiling acceptable data time series for indexing each inflow and outflow, selecting combinations and computational methods for aggregating various flows (e.g., combining precipitation or evaporation measurements from points near the lake to estimate average values over the lake), and compiling series that are as long as possible (supplemented as necessary by techniques for estimating missing hydrologic data) for the selected combinations. This chapter describes how these tasks were completed in preparing data time series for precipitation, evaporation, surface inflows and subsurface inflows for the Great Salt Lake, presents the time series of data used, and concludes with some advice for collecting such series for other modeling efforts.

Recorded Lake Stages

Great Salt Lake stage data have been recorded at several sites and estimated by indirect methods for years when direct measurements were not made. For the period 1848-1875, the surface level was computed from traditional data; during 1875-1938, the level was measured periodically at staff gages; and since 1938, the level of the lake has been measured continuously.

The traditional data for computing lake levels were compiled by LaRue and Gilbert and reported by Gilbert (1890) for the period 1848-1875 by questioning residents at the southern end of the lake. For example, a stockman or farmer may have recalled that at a certain time the depth of water over the sand bars between the mainland and Antelope or Stansbury Island was to a certain height on his cow's legs when they were herded to the islands for pasture. Gilbert related the oral reports to soundings at the Antelope Island bar and correlated these soundings to the Black Rock and Farmington Bay gage readings. From 1875 to 1877, the lake level was measured at Black Rock staff gage; from 1877 to 1879 it was measured at Farmington Bay gage; from 1879 to 1881 measurements were taken near Black Rock; from 1881 to 1899, at Garfield Landing; from 1902 to 1903 at Midlake on the Southern Pacific Railroad Causeway; and 1903 to 1938 at Saltair (USGS, 1940). The lake level has been recorded continuously since 1938 at Salt Lake County Boat Harbor on the southeast shore of the lake 17 miles west of Salt Lake City. A recording gage station has been located at Saline on Promontory Point since 1966.

The maximum observed lake elevation was at 4210.9 feet in 1876 while the maximum elevation since the 1848 beginning of the reconstructed series was 4211.6 feet in 1873. The historic all time low was in 1963 at 4191.4 feet. Since then, the lake rose to 4202.2 in 1976 and fell back to 4199.4 in November 1978.

In order to compensate for wind-caused seiches, the reported lake elevations are taken from a line defined by readings over a period of several days. Thus, the short-term fluctuations associated with seiches are not reflected in published elevation tables.

The entire reconstructed and measured lake stage sequence is shown in Table 4. The end-of-the-year values are as of each October 1, and the peaks are the maximum stages occurring during the previous 12 months. The lake-stage sequences are particularly noteworthy for their very high lag-one serial correlation (0.979) and Hurst coefficients (1.079).

Precipitation on the Lake

Eight precipitation gages have been located near enough to the Great Salt Lake and operated for a long enough period to be potentially useful for this study. The sites are at Corinne (1871-1977), Farmington (1890-1977), Kelton (1879-1929), Lakepoint (1920-1930), Midlake (1912-1920), Ogden (1871-1977), Salt Lake City (1857-1868, 1875-1977), and Tooele (1897-1977) and are plotted by location on Figure 5. Annual precipitation totals for each water year are in Table 4 except for the 1920-1929 records for Midlake and Lakepoint in Table 5.

Table 4. Actual historic data by water year.

YEAR	LAKE STAGE PEAK	LAKE STAGE END OF YEAR	PAN EVAP BEAR RIV BIRD REF MAY-SEP	PRECIPITATION CORINNE	PRECIPITATION OGDEN	PRECIPITATION SLC DOWN-TOWN	PRECIPITATION KELTON	PRECIPITATION FARMIN-GTON	PRECIPITATION TOOELE	STREAMFLOW BEAR RIVER CORINNE	STREAMFLOW BEAR RIVER COLLINSTON	STREAMFLOW WEBER RIVER PLAIN CITY	STREAMFLOW JORDAN RT SURPLUS + 21 SOUTH
1848		4200.00											
1849		4200.00											
1850		4200.40											
1851	4202.10	4200.40											
1852	4203.00	4201.00											
1853	4204.10	4202.00											
1854	4204.60	4203.40											
1855	4204.70	4203.80											
1856	4204.50	4203.40											
1857	4204.00	4203.40				19.26							
1858	4203.10	4202.10				18.69							
1859	4201.80	4201.10				19.17							
1860	4201.60	4200.40				12.07							
1861	4201.00	4199.80				16.36							
1862	4203.00	4200.00				15.89							
1863	4204.00	4202.00				8.95							
1864	4204.70	4203.00				13.57							
1865	4205.50	4204.00				18.62							
1866	4207.00	4205.00				29.17							
1867	4209.70	4206.70				23.93							
1868	4210.00	4207.80				26.12							
1869	4211.20	4209.50											
1870	4210.70	4210.30											
1871	4210.70	4209.50		7.74	6.83								
1872	4211.70	4209.80		14.95	7.85								
1873	4211.80	4210.70		16.15	16.29								
1874	4211.70	4211.00		9.82	12.00								
1875	4211.00	4210.50		14.18	15.18	19.10							
1876	4210.90	4208.70		16.61	20.01	24.60							
1877	4210.40	4209.90		5.81	14.72	17.69							
1878	4209.40	4210.30		9.74	16.49	22.16							
1879	4208.20	4209.00		4.65	8.54	10.22	2.21						
1880	4206.50	4207.00		8.02	12.87	12.49	3.27						
1881	4206.50	4205.10		13.79	11.21	15.48	4.94						
1882	4206.00	4205.20		9.77	8.88	16.50	3.80						
1883	4205.30	4204.60		7.73	10.30	13.37	2.99						
1884	4205.90	4204.10		18.20	20.36	19.76	9.37						
1885	4207.30	4205.50		16.56	17.90	18.06	10.31						
1886	4207.70	4206.50		13.36	14.24	18.46	6.03						
1887	4207.20	4206.70		9.18	12.47	14.60	6.27						
1888	4206.00	4205.80		9.83	9.34	10.71	5.94						
1889	4204.40	4204.40		9.15	10.99	14.21	5.94						
1890	4204.10	4202.10		18.61	23.61	17.73	9.40	23.63			2070000.		
1891	4203.50	4203.40		15.44	22.21	13.43	11.51	23.63			1370000.		

Table 4. Continued.

YEAR	LAKE STAGE PEAK	LAKE STAGE END OF YEAR	PAN EVAP BEAR RIV BIRD REF MAY-SEP	PRECIPITATION CORINNE	PRECIPITATION OGDEN	PRECIPITATION SLC DOWN-TOWN	PRECIPITATION KELTON	PRECIPITATION FARMIN-GTON	PRECIPITATION TOOELE	STREAMFLOW BEAR RIVER CORINNE	STREAMFLOW BEAR RIVER COLLINSTON	STREAMFLOW WEBER RIVER PLAIN CITY	STREAMFLOW JORDAN RIVER SURPLUS + 21 SOUTH
1892	4203.00	4202.40		14.30	14.38	13.78	9.24	18.35			1530000.		
1893	4203.00	4202.00		13.39	17.98	17.43	3.91	16.37			1420000.		
1894	4203.00	4201.00		10.70	15.10	17.27	8.46	13.10			1950000.		
1895	4202.30	4201.90		7.95	12.00	10.95	2.54	14.08			1370000.		
1896	4201.80	4201.00		9.78	13.58	17.30	3.89	17.89			1550000.		
1897	4202.30	4200.70		11.31	14.70	16.86	3.44	17.01	11.09		2050000.		
1898	4201.90	4200.70		8.92	15.98	15.86	4.51	18.33	19.94		1520000.		
1899	4201.20	4200.30		9.60	11.92	17.39	3.80	17.67	16.36		1910000.		
1900	4201.20	4200.20		10.96	11.27	12.96	4.50	17.30	12.40		1350000.		
1901	4197.70	4200.00		14.79	16.55	16.57	3.30	19.04	13.74		1180000.		
1902	4198.30	4199.00		13.12	12.17	11.40	3.38	17.34	10.56		885000.		
1903	4197.60	4196.90		13.93	12.04	14.16	4.78	16.62	12.09		784000.		
1904	4198.30	4196.20		15.52	15.10	17.30	9.30	23.87	20.09		1590000.		
1905	4197.60	4197.20		11.54	16.53	14.51	10.91	21.03	13.41		729000.		
1906	4198.30	4196.90		20.12	22.00	19.53	8.56	25.12	20.11		1358000.	632900.	
1907	4200.50	4197.30		16.16	19.86	18.90	10.19	22.28	16.31		2556000.	1250000.	
1908	4201.00	4199.90		18.84	18.09	20.26	6.33	23.49	22.14		1410000.	451393.	
1909	4202.60	4199.90		19.26	23.90	20.05	10.50	21.71	24.25		2480000.	1257710.	
1910	4203.90	4202.00		14.71	12.63	10.55	6.59	15.80	12.43		1720000.	794447.	
1911	4203.20	4202.10		11.89	17.06	15.65	6.05	18.36	13.57		1410000.	575203.	
1912	4202.70	4201.60		12.43	20.61	17.99	5.07	21.19	17.09		1630000.	756204.	
1913	4202.80	4201.80		12.38	14.12	18.29	10.20	18.34	22.95		1340000.	512893.	
1914	4203.50	4201.90		14.59	22.27	17.19	9.29	22.48	19.09		1780000.	899452.	
1915	4203.10	4202.40		14.05	18.19	14.53	5.97	18.70	17.94		877000.	330539.	
1916	4202.80	4201.60		10.89	15.59	13.38	7.19	21.83	16.82		1240000.	794859.	
1917	4203.30	4201.30		21.17	19.39	18.46	8.04	26.92	20.28		1990000.	999914.	
1918	4203.40	4202.50		10.33	11.90	14.41	6.73	21.03	13.68		1210000.	433156.	
1919	4202.70	4202.10		10.27	14.61	12.13	5.25	17.16	11.73		984000.	341529.	
1920	4202.10	4200.80		11.54	20.42	19.42	6.86	22.68	23.05		1270000.	739270.	
1921	4203.30	4200.70		13.95	20.78	16.68	8.50	25.15	23.83		1750000.	1093625.	
1922	4204.30	4201.90		15.43	19.02	19.40	9.03	23.23	20.68		2020000.	939909.	
1923	4204.80	4203.10		11.86	23.56	21.72	4.20	22.79	20.95		1820000.	845631.	
1924	4205.00	4203.70		8.27	14.37	11.25	3.64	15.49	13.31		1200000.	420962.	
1925	4204.20	4203.10		20.34	26.68	20.97	12.37	24.60	18.38		1080000.	468610.	
1926	4204.20	4203.30		13.67	20.54	14.54	9.23	21.74	17.27		874000.	409815.	
1927	4203.60	4202.50		11.47	19.52	18.90	5.98	19.61	16.69		1080000.	571851.	
1928	4202.50	4201.90		7.05	13.86	13.69	4.89	16.68	12.63		878000.	529537.	
1929	4202.00	4200.70		13.44	22.97	17.17	8.99	20.75	19.69		923000.	613197.	
1930	4201.15	4200.70		15.67	20.85	14.23		20.81	16.19		684000.	272671.	
1931	4200.45	4199.70		10.19	11.72	10.49		13.56	11.83		454000.	141479.	
1932	4199.35	4198.10		19.22	17.82	15.16		20.08	15.47		780000.	559405.	
1933	4198.90	4198.00		9.76	15.15	13.41		15.55	14.92		625000.	383251.	
1934	4197.25	4197.10		8.87	10.94	9.41		11.22	10.55		319000.	61430.	
1935	4196.00	4195.00		14.33	19.90	16.73		12.90	13.95		451300.	223334.	

Table 4. Continued.

YEAR	LAKE STAGE PEAK	LAKE STAGE END OF YEAR	PAN EVAP BEAR RIV BIRD REF MAY-SEP	PRECIPITATION CORINNE	PRECIPITATION OGDEN	PRECIPITATION SLC DOWN-TOWN	PRECIPITATION KELTON	PRECIPITATION FARMIN-GTON	PRECIPITATION TOOELE	STREAMFLOW BEAR RIVER CORINNE	STREAMFLOW BEAR RIVER COLLINSTON	STREAMFLOW WEBER RIVER PLAIN CITY	STREAMFLOW JORDAN RI SURPLUS + 21 SOUTH
1936	4195.85	4194.20		15.58	19.67	15.19		19.79	14.71		826600.	506058.	
1937	4196.45	4194.40	50.4	16.99	22.38	14.82		19.96	18.09		762800.	470753.	
1938	4196.50	4195.00	47.8	17.48	20.60	15.87		19.39	17.37		807000.	471794.	
1939	4196.50	4194.90	50.6	14.55	22.00	13.89		18.74	12.87		659000.	254777.	
1940	4195.75	4194.80	53.8	11.39	18.93	14.39		18.37	13.23		448000.	150390.	
1941	4195.60	4193.80	42.7	22.58	27.09	20.25		25.59	19.70		506000.	210177.	
1942	4196.60	4194.10	45.9	17.38	23.39	19.29		23.07	19.66		702100.	429942.	
1943	4196.25	4194.90	47.4	13.99	16.00	13.42		16.37	14.54		911200.	426160.	132810.
1944	4196.50	4194.80	45.0	14.02	21.24	19.47		23.09	18.89		694200.	347535.	197800.
1945	4196.35	4195.00	41.2	16.11	23.91	17.16		21.25	19.00		872300.	345104.	180690.
1946	4197.15	4195.20	42.9	19.72	17.00	12.69		16.60	14.01		1090000.	433523.	180100.
1947	4197.25	4195.40	41.1	18.01	26.74	21.09		25.35	22.40		1036000.	306911.	202500.
1948	4197.75	4196.30	45.2	14.18	19.00	15.14		18.67	16.41		1100000.	509243.	220500.
1949	4198.25	4196.30	41.1	14.45	22.90	16.62		21.11	16.70		1045000.	495878.	235000.
1950	4198.85	4196.70	40.8	17.80	19.25	14.76		19.51	13.81	1796000.	1647000.	727472.	226500.
1951	4199.90	4197.60	43.8	18.92	22.75	14.99		20.30	15.97	1911000.	1682000.	550227.	215800.
1952	4200.95	4198.50	43.8	13.66	21.74	20.18		24.00	15.66	1775000.	1608000.	932907.	476900.
1953	4200.55	4199.60	42.8	14.14	18.42	14.21		21.05	19.11	1077000.	975200.	395547.	499700.
1954	4199.35	4199.00	46.9	10.77	11.78	10.74		13.28	19.64	609800.	510200.	176924.	264300.
1955	4198.05	4197.40	42.5	16.21	17.55	11.39		19.83	23.06	627800.	583800.	157413.	191100.
1956	4197.85	4196.60	42.8	14.12	19.50	11.25		16.13	18.28	969500.	968900.	327172.	204500.
1957	4197.45	4196.00	41.0	17.72	21.17	15.91		23.99	26.61	1064000.	969500.	370405.	223900.
1958	4197.40	4196.00	47.2	13.65	17.84	12.70		18.26	24.66		883300.	357670.	252000.
1959	4196.05	4195.50	42.1	12.44	18.07	13.96		19.31	20.42		536300.	101783.	220800.
1960	4195.30	4194.50	49.4	10.56	12.83	10.20		12.46	16.65		530100.	123726.	180900.
1961	4193.80	4193.40	47.9	12.90	15.72	9.87		14.90	14.61		363700.	60554.	132097.
1962	4193.85	4191.70	44.6	17.96	23.33	14.45		21.14	17.17		808400.	210203.	169094.
1963	4192.95	4192.20	42.5	12.61	18.08	12.46		19.34	12.75		576400.	145926.	157865.
1964	4194.15	4191.50	41.8	14.00	22.27	13.78		21.56	17.46	936154.	832500.	710327.	199348.
1965	4194.25	4192.60	39.0	14.05	24.90	18.32		25.00	20.96	1132281.	1074000.	737512.	239909.
1966	4195.60	4193.80	46.5	10.55	13.72	9.66		12.65	9.53	1154339.	1018000.	115917.	271165.
1967	4195.20	4193.40	38.5	17.36	23.68	19.00		18.93	18.13	1054183.	942000.	175557.	240210.
1968	4195.50	4193.90	42.5	18.68	23.11	19.53		25.42	20.72	1059290.	874500.	211194.	278071.
1969	4197.15	4194.40	47.1	17.00	19.06	16.55		17.62	18.99	1715445.	1046000.	493345.	373447.
1970	4196.45	4195.30	45.1	15.52	20.78	19.75		22.58	18.02	875699.	728600.	237420.	389038.
1971	4198.15	4194.90	41.9	19.49	24.92	20.94		25.60	21.49	2067709.	1922000.	495794.	379828.
1972	4199.70	4196.90	43.4	16.33	20.86	14.36		19.50	15.72	2070703.	1848000.	522197.	374298.
1973	4200.55	4197.90	44.7	21.48	28.61	23.09		29.28	23.03	1485069.	1309000.	450911.	360067.
1974	4201.30	4199.20	49.6	12.37	19.95	12.10		18.80	12.80	1505411.	1402000.	529953.	470390.
1975	4201.55	4199.30	39.6	18.44	31.01	20.50		27.69	18.69	1456563.	1300000.	550162.	388207.
1976	4202.25	4200.00	42.2	18.40	22.55	16.90		20.27	17.63	1619298.	1433000.	353540.	496411.
1977	4200.75	4200.40	41.5	16.01	17.44	15.29		17.40	15.14	689300.	593500.	77580.	219500.
MEAN	4201.77	4200.45	44.3	13.89	17.83	15.91	6.60 (1)	19.88	17.18	1312252 (2)	1156003	461839	267193
STD. DEV.	4.54	4.68	3.49	3.73	4.87	3.36	2.67	3.76	3.78	414187	497848	274396	103890
SKEW	0.322	0.311	0.605	-0.028	0.039	0.037	0.268	-0.020	0.166	0.554	0.583	0.891	0.888
HURST	1.079	1.079	0.752	0.584	0.612	0.538	0.659	0.517	0.570	1.397	0.828	0.885	0.459
LAG ONE CORR.	0.979	0.978	0.200	0.249	0.347	0.088	0.347	0.139	0.152	0.264	0.593	0.482	0.652

(1) Statistics based on period 1875-1977 (2) Statistics based on period 1964-1977

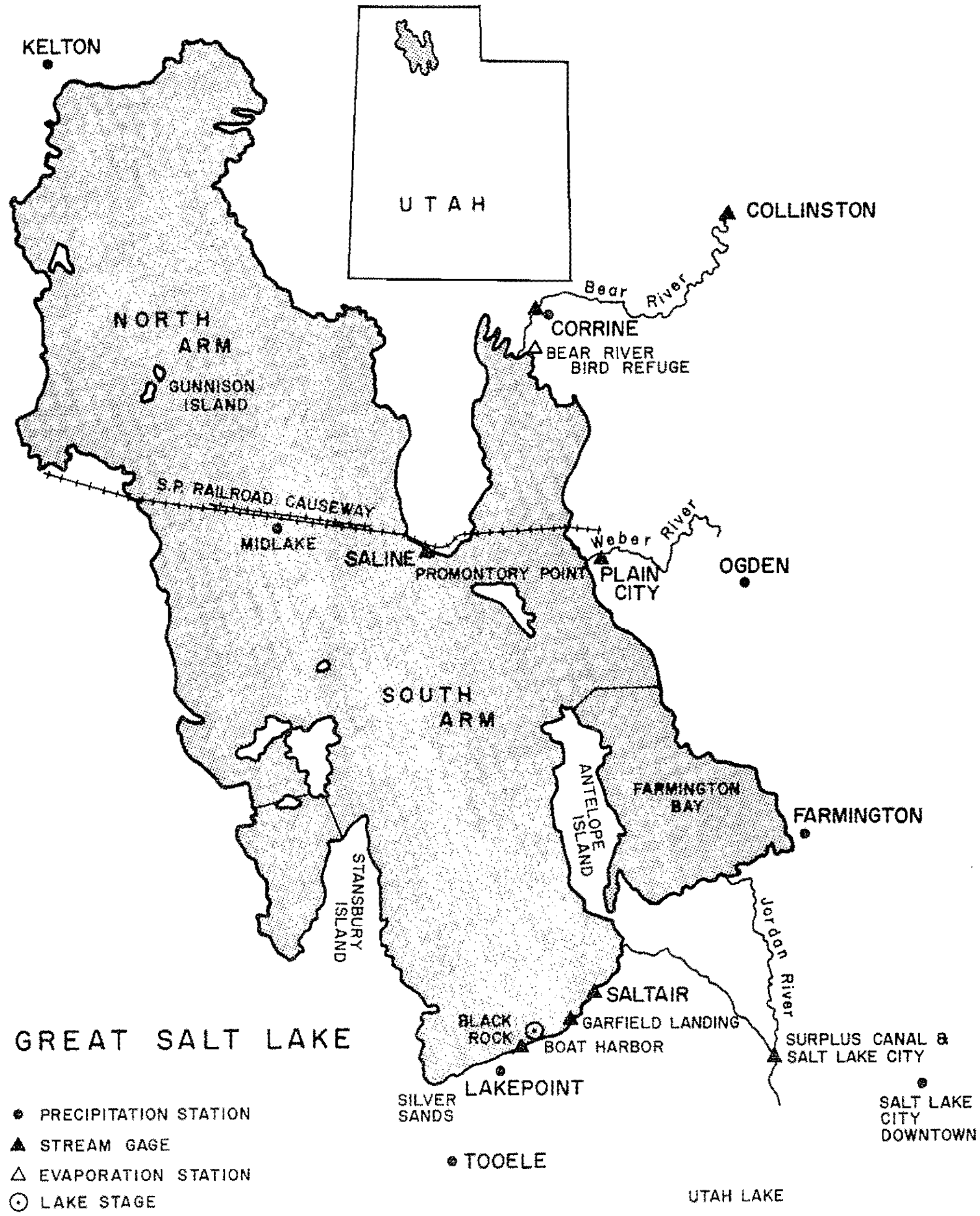


Figure 5. Locations of hydrologic and meteorologic recording stations near the Great Salt Lake.

Table 5. Annual precipitation totals for Midlake and Lakepoint for water years 1920-1929.

Year	Precipitation Stations	
	Midlake	Lakepoint
1920	3.38	14.79
1921	4.67	12.21
1922	7.41	10.52
1923	9.13	16.89
1924	2.43	6.96
1925	10.98	16.69
1926	12.36	13.04
1927	7.18	13.29
1928	4.65	8.28
1929	9.39	14.57
Mean	7.16	12.72
Std. Dev.	3.33	3.32

In order to develop a time series of annual precipitation on the lake, it was necessary to spatially integrate these point measurements to estimate average precipitation over the entire lake. In selecting the group of precipitation stations to use for this purpose, it was necessary to strike a balance between more accurate areal averages by using more and closer stations for a short period of record and better representation of time patterns by using a small group of stations with a long period of record. Both extremes have been used in past studies of the Great Salt Lake. Steed (1972) used a group of six (only five (group 4 in Table 6) of which had a Thiessen polygon area on the lake) precipitation stations to estimate lake precipitation over the time period 1920-1929. At the other extreme, the Utah Division of Water Resources (1974) and Glenne et al. (1977) used the precipitation record for Salt Lake City (beginning in 1875).

Table 6. Six precipitation networks considered for estimating average precipitation on the Great Salt Lake.

No.	Stations	Period of Record (Number of Years)	Selection Criteria: Correlation With Group 4 Estimate	Representativeness of Period of Record	Correlation With Salt Lake City Precipitation
1	Corinne Kelton Ogden Salt Lake City	1879-1929 (51)	r = 0.854[a]	μ = 13.2[b] σ = 3.1[b]	r = 0.782[a]
2	Corinne Farmington Kelton Ogden Salt Lake City	1890-1929 (40)	r = 0.844[a]	μ = 14.3[b] σ = 2.8[b]	r = 0.707[a]
3	Corinne Farmington Kelton Ogden Salt Lake City Tooele	1897-1929 (33)	r = 0.805[a]	μ = 14.4[b] σ = 2.9[b]	r = 0.771[a]
4	Corinne Kelton Lakepoint Farmington Midlake	1920-1929 (10)	r = 1.000	μ = 10.0[b] σ = 2.8[b]	r = 0.597
5	Corinne Ogden Salt Lake City	1875-1976 (102)	r = 0.862[a]	μ = 16.0 σ = 3.6	r = 0.710[a]
6	Corinne Farmington Ogden Salt Lake City Tooele	1897-1976 (80)	r = 0.805[a]	μ = 17.3[b] σ = 3.3[b]	r = 0.754[a]

[a]Correlation proved significant at the 1.0 percent level.

[b]Mean or standard deviation proved different than that at Salt Lake City for corresponding period at one percent significance level.

In order to obtain reasonably representative estimates of average lake precipitation over a long period, estimates of precipitation on the lake made by the Thiessen polygon method from the six groups of precipitation stations listed in Table 6 were evaluated. The criteria used in the evaluation were:

1. How well are the stations geographically distributed around the lake? Equal Thiessen polygon areas represent a better distribution.

2. How well correlated during the period of common record is the lake precipitation estimate from the group with the estimate from group 4 which has the best geographical distribution but the shortest period of record?

3. How representative is the time period covered by the group of stations of the total period of the longest record, the 102-year record of group 5? Precipitation statistics for the time period are more representative as they approach the values of the statistics for the maximum record length.

4. How well correlated is the lake precipitation estimate with the precipitation measured at Salt Lake City? A good correlation would make extension of the time series of lake precipitation through regression on the Salt Lake City data more reliable.

A Thiessen weighting procedure was used for spatial integration of the point precipitation values. The fraction of the lake area (Thiessen weight) assigned to each gage in a group was scaled from a USGS (1973) 1:125,000 contour map of the Great Salt Lake. The Thiessen weights vary with lake elevation as areas under water change more with elevation along some shores than along others. Weights were calculated at the high, mean, and low stage recorded during the period of record for each group (Tables 7-12). Weights for other lake stages were interpolated between the measured values. Before the Thiessen procedure was applied, each precipitation record on Table 4 was checked for consistency by double-mass plotting against a base network of at least three other stations in the area. No significant inconsistencies were identified that would affect the period since 1937 used in the stochastic modeling for this study.

Table 7. Thiessen weighting coefficients for group 1 (1879-1929).

Precipitation Station	Lake Stage		
	High (4208 ft)	Mean (4202 ft)	Low (4196 ft)
Corinne	0.134	0.134	0.103
Kelton	0.268	0.267	0.274
Ogden	0.359	0.374	0.437
Salt Lake City	0.239	0.225	0.186

Table 8. Thiessen weighting coefficients for group 2 (1890-1929).

Precipitation Station	Lake Stage		
	High (4205 ft)	Mean (4201 ft)	Low (4196 ft)
Corinne	0.168	0.140	0.105
Farmington	0.150	0.160	0.133
Kelton	0.256	0.260	0.273
Ogden	0.291	0.310	0.360
Salt Lake City	0.135	0.130	0.129

Table 9. Thiessen weighting coefficients for group 3 (1897-1919).

Precipitation Station	Lake Stage		
	High (4205 ft)	Mean (4201 ft)	Low (4196 ft)
Corinne	0.158	0.139	0.105
Farmington	0.110	0.122	0.106
Kelton	0.240	0.257	0.271
Ogden	0.261	0.287	0.351
Salt Lake City	0.049	0.038	0.039
Tooele	0.182	0.157	0.128

Table 10. Thiessen weighting coefficients for group 4 (1920-1929).

Precipitation Station	Lake Stage		
	High (4205 ft)	Mean (4203 ft)	Low (4201 ft)
Kelton	0.118	0.109	0.110
Corinne	0.055	0.048	0.037
Farmington	0.120	0.116	0.114
Lakepoint	0.163	0.162	0.163
Midlake	0.544	0.565	0.576

Table 11. Thiessen weighting coefficients for group 5 (1875-1976).

Precipitation Station	Lake Stage		
	High (4211 ft)	Mean (4200 ft)	Low (4191 ft)
Corinne	0.420	0.402	0.352
Ogden	0.335	0.379	0.437
Salt Lake City	0.245	0.219	0.211

Table 12. Thiessen weighting coefficients for group 6 (1897-1976).

Precipitation Station	Lake Stage		
	High (4205 ft)	Mean (4198 ft)	Low (4191 ft)
Corinne	0.397	0.337	0.326
Farmington	0.110	0.219	0.175
Ogden	0.262	0.279	0.317
Salt Lake City	0.049	0.035	0.044
Tooele	0.182	0.130	0.138

The six groups were evaluated with respect to the four criteria in Table 6. Group 5 (Corinne, Ogden, and Salt Lake City) was selected because of its high correlation with group 4 and relatively equal Thiessen weights while covering the entire historical period since 1875.

While the group 5 record was taken as the most representative of the annual precipitation time pattern, the regression relationship between group 5 and group 4 data showed the group 5 gages to be recording considerably more precipitation because all the stations are located in a relatively wetter area at the base of the Wasatch Mountains on the leeward side of the lake. The regression for the 10 years of common record for the two groups showed

$$R_4 = -1.67 + 0.705 R_5 \quad . . . . (43)$$

where R_5 is the average precipitation on the lake in a given year as estimated from the data for group 5 and R_4 is the average estimated for group 4. The correlation coefficient (R^2) was 0.74, and the standard error was 1.51.

The time series of lake precipitation used for this study was computed by weighting the annual totals measured at each group 5 station in each year (1875-1977) according to the Thiessen factors for the lake stage during that year. These computations are shown in Table 13. Each R_5 was then converted to R_4 by Equation 43 with the results shown as the lake precipitation in the right hand column of Table 13.

As Table 11 shows, the group 5 weighting factor for Ogden increases while the weighting factors for Salt Lake City and Corinne decrease as the lake stage drops. Since Table 4 shows Ogden to have somewhat greater mean annual precipitation than do the other two stations, the lake precipitations computed in Table 13 are biased toward a higher value when the lake stage is low. For precipitations generated by a multivariate model, one does not know the corresponding stage until executing the water balance model. Based on weighted average precipitation (R_5) computed by combining information in Tables 4 (1875-1977) and 11 of 15.83 for elevation 4211, 15.96 for 4200, and 16.19 for 4191, and using Equation 43 to convert each of these to an average precipitation on the lake (R_4), one would remove this bias by multiplying precipitations simulated at stage 4191 by 0.990, at 4200 by 1.000, at 4211 by 1.017, and by interpolating multipliers for intermediate elevations. These factors are small but they eliminate a bias that would otherwise damp lake level fluctuation probabilities.

Lake Evaporation

The information available for estimating a time series of annual lake evaporation totals from the Great Salt Lake were 1) a determination by the Utah Division of Water Resources (1974) from their lake water balance model that the long-term average annual freshwater equivalent lake evaporation is 52 inches, 2) 41 years of pan evaporation data at the Bear River Bird Refuge near Corinne (1937-1977), 3) 21 years of pan evaporation data at Saltair on the lake near Salt Lake City (1923-1977), 4) 55 years of pan evaporation data at Utah Lake 35 miles to the south, and 5) a few very short records of evaporation from salt water pans on the lake. The evaporation pans are not operated during the winter months when freshwater would freeze. These dates when records begin in the spring vary from April 1 to June 1. Records end in the fall between September 30 and November 30.

In order to represent the effect of variability in evaporation totals from year to year on lake levels, the evaporation time series need to reflect mean annual lake evaporation amounts (52 inches) and yet display the variability from year to year found in the pan measurements. The Corinne data were selected for providing the needed variability. That station had a longer record and was nearer to the lake than the Saltair station, which also has the disadvantage of being located at a site where unrepresentative wind and radiation conditions are probably biasing the data.

Before using the Corinne data, it was necessary to standardize the records to a common time period in each year (otherwise variation in measured totals from year to year would be in large part caused by variation in measurement beginning and ending dates rather than by variation in true annual evaporation totals) and to decide what to do about winter data being missing. The common period selected was May through September because these months were covered in most years. When missing months occurred in this period in the Corinne data, a monthly evaporation was estimated from the Utah Lake data by assuming that the ratio to mean monthly evaporation would be the same at Corinne as measured at Utah Lake (Table 14). Since winter evaporation is difficult to estimate from meteorological data and is a

Table 13. Average water year precipitation on the Great Salt Lake computed by Thiessen method.

YEAR	LAKE STAGE AVE ANNUAL	CORINNE PRECIP ACTUAL	CORINNE PRECIP T.C.[a]	OGDEN PRECIP ACTUAL	OGDEN PRECIP T.C.[a]	SALT LAKE CITY ACTUAL	SALT LAKE CITY T.C.[a]	SUM T.C.[a] PRECIP R5	LAKE PRECIP R4 (EQ. 43)
1875	4210.00	14.18	5.71	15.12	5.75	19.10	4.18	15.65	9.40
1876	4209.50	16.61	6.69	20.01	7.58	24.60	5.39	19.67	12.20
1877	4209.80	5.81	2.34	14.72	5.58	17.69	3.87	11.79	6.60
1878	4208.80	9.74	3.93	16.49	6.25	22.16	4.85	15.03	8.90
1879	4207.40	4.65	1.87	8.54	3.24	10.22	2.24	7.35	3.50
1880	4205.70	8.02	3.23	12.87	4.88	12.49	2.74	10.85	5.90
1881	4205.60	13.79	5.56	11.21	4.25	15.48	3.39	13.20	7.60
1882	4205.40	9.77	3.94	8.88	3.37	16.50	3.61	10.92	6.00
1883	4204.70	7.73	3.12	10.30	3.90	13.37	2.93	9.95	5.30
1884	4204.50	18.20	7.33	20.36	7.72	19.76	4.33	19.38	12.00
1885	4206.20	16.56	6.67	17.90	6.78	18.06	3.96	17.41	10.60
1886	4207.00	13.36	5.38	14.24	5.40	18.46	4.04	14.82	8.80
1887	4206.50	9.18	3.70	12.47	4.73	14.60	3.20	11.62	6.50
1888	4205.10	9.83	3.96	9.34	3.54	10.71	2.35	9.85	5.20
1889	4204.00	9.15	3.69	10.99	4.17	14.21	3.11	10.96	6.10
1890	4203.30	18.61	7.50	23.61	8.95	17.73	3.88	20.33	12.60
1891	4202.80	15.44	6.22	22.21	8.42	13.43	2.94	17.58	10.70
1892	4202.40	14.30	5.76	14.36	5.45	13.78	3.02	14.23	8.30
1893	4201.90	13.39	5.40	17.66	6.78	17.43	3.82	15.99	9.60
1894	4202.10	10.70	4.31	15.10	5.72	17.27	3.78	13.82	8.10
1895	4201.70	7.95	3.20	12.00	4.55	10.95	2.40	10.15	5.40
1896	4201.10	8.78	3.54	13.58	5.15	17.30	3.79	12.47	7.10
1897	4201.30	11.31	4.56	14.70	5.57	16.86	3.69	13.82	8.10
1898	4201.10	8.92	3.59	15.98	6.06	15.66	3.47	13.12	7.60
1899	4200.40	9.60	3.87	11.92	4.52	17.39	3.81	12.19	6.90
1900	4200.20	10.96	4.42	11.27	4.27	12.96	2.84	11.53	6.40
1901	4199.40	14.79	5.90	16.55	6.35	16.57	3.62	15.87	9.50
1902	4197.80	13.12	5.10	12.17	4.81	11.40	2.47	12.38	7.10
1903	4197.10	13.93	5.35	12.04	4.82	14.16	3.06	13.23	7.60
1904	4197.10	15.52	5.96	15.10	6.05	17.30	3.74	15.75	9.40
1905	4197.10	11.54	4.43	16.56	6.62	14.51	3.13	14.19	8.30
1906	4196.80	20.12	7.69	22.00	8.86	19.53	4.21	20.76	13.00
1907	4198.70	16.16	6.38	19.86	7.72	15.90	4.11	18.21	11.20
1908	4200.40	18.84	7.59	18.03	6.86	20.26	4.44	18.89	11.70
1909	4201.20	19.26	7.76	23.90	9.06	20.05	4.39	21.21	13.30
1910	4202.90	14.71	5.93	12.63	4.79	10.55	2.31	13.03	7.50
1911	4202.50	11.88	4.79	17.06	6.47	15.65	3.43	14.68	8.70
1912	4202.10	12.43	5.01	20.61	7.81	17.99	3.94	16.76	10.20
1913	4202.23	12.38	4.99	14.12	5.35	18.29	4.01	14.35	8.40
1914	4202.50	14.59	5.88	12.27	6.44	17.19	3.76	18.08	11.10
1915	4202.55	14.05	5.66	18.19	6.89	14.53	3.18	15.74	9.40
1916	4201.90	10.89	4.39	15.59	5.91	13.39	2.93	13.23	7.60
1917	4202.15	21.17	8.53	19.35	7.35	18.46	4.04	19.92	12.40
1918	4202.80	10.33	4.15	11.90	4.51	14.41	3.16	11.83	6.60
1919	4202.01	10.27	4.14	14.61	5.54	12.13	2.66	12.33	7.00
1920	4201.14	11.54	4.65	20.42	7.74	19.42	4.25	16.64	10.06
1921	4201.90	13.95	5.62	20.78	7.88	16.68	3.65	17.15	10.42
1922	4202.98	15.43	6.22	18.02	6.85	19.40	4.25	17.30	10.52
1923	4203.60	11.86	4.78	23.56	8.95	21.72	4.76	18.47	11.35
1924	4204.21	8.27	3.33	14.37	5.45	11.25	2.46	11.24	6.25
1925	4203.59	20.34	8.20	26.68	10.11	20.97	4.59	22.90	14.47
1926	4203.54	15.67	6.31	20.54	7.78	14.54	3.18	16.48	9.95
1927	4202.69	11.47	4.62	18.52	7.02	18.90	4.14	15.78	9.45
1928	4201.93	7.05	2.84	13.66	5.25	13.69	3.00	11.05	6.15
1929	4201.10	13.44	5.42	22.97	8.71	17.17	3.76	17.88	10.93
1930	4200.58	15.67	6.32	20.85	7.90	14.23	3.12	17.33	10.50
1931	4199.75	10.19	4.09	11.72	4.46	10.49	2.29	10.85	5.90
1932	4198.45	19.22	7.75	17.82	6.96	15.16	3.30	17.41	10.90
1933	4198.00	9.76	3.81	15.15	5.97	13.41	2.91	12.68	7.30
1934	4196.54	8.67	3.37	10.94	4.45	9.41	2.03	9.53	5.20
1935	4195.24	14.33	5.32	19.90	8.25	15.73	3.58	17.16	10.50
1936	4194.74	15.50	5.74	19.67	6.22	15.19	3.24	17.21	10.50
1937	4195.33	16.99	6.33	22.30	9.26	14.82	3.17	18.76	11.60

Table 13. Continued.

YEAR	LAKE STAGE AVE ANNUAL	CORINNE PRECIP ACTUAL	CORINNE PRECIP THEIS	OGDEN PRECIP ACTUAL	OGDEN PRECIP THEIS	SALTLAKECITY ACTUAL	SALTLAKECITY THEIS	SUM THEIS PRECIP	[illegible]
1938	4195.51	17.48	6.53	20.60	[illegible]	15.87	3.40	18.43	[illegible]
1939	4195.80	14.55	5.45	22.00	9.06	15.89	2.98	17.46	[illegible]
1940	4194.89	11.69	4.21	16.96	[illegible]	14.39	3.08	15.18	[illegible]
1941	4194.54	22.56	8.31	27.09	[illegible]	20.25	4.32	23.96	[illegible]
1942	4193.52	17.38	6.47	23.39	[illegible]	19.29	4.13	20.28	[illegible]
1943	4195.40	13.99	5.22	16.00	6.41	13.42	2.68	14.70	[illegible]
1944	4195.44	14.02	5.23	21.24	8.77	15.47	4.17	16.18	[illegible]
1945	4195.49	16.11	5.02	23.91	[illegible]	17.16	3.68	19.56	12.10
1946	4196.13	19.72	7.45	17.00	[illegible]	12.68	2.73	17.11	[illegible]
1947	4196.46	18.01	6.64	26.71	[illegible]	21.09	4.54	22.22	14.00
1948	4196.94	14.16	5.43	19.00	[illegible]	15.14	3.27	16.33	[illegible]
1949	4197.13	14.45	5.55	22.90	[illegible]	15.62	3.59	16.31	11.20
1950	4197.77	17.60	6.91	19.25	[illegible]	14.76	3.20	17.73	[illegible]
1951	4198.74	16.62	7.43	22.75	[illegible]	14.99	3.26	19.53	12.10
1952	4199.63	13.66	5.47	21.74	[illegible]	20.18	4.41	16.18	11.20
1953	4199.95	14.14	5.69	18.42	[illegible]	14.21	3.11	15.79	[illegible]
1954	4198.84	10.77	4.26	11.78	[illegible]	10.74	2.34	11.16	[illegible]
1955	4197.50	16.21	6.27	17.55	[illegible]	11.39	2.47	15.73	9.40
1956	4197.10	14.12	5.42	18.50	[illegible]	11.25	2.43	15.26	[illegible]
1957	4196.55	17.72	6.74	21.17	[illegible]	15.91	3.64	18.95	11.70
1958	4196.50	13.65	5.19	[illegible]	[illegible]	12.70	2.74	15.15	[illegible]
1959	4195.90	12.44	4.56	[illegible]	[illegible]	15.86	2.97	15.07	[illegible]
1960	4194.63	10.56	3.38	12.65	[illegible]	10.20	2.18	11.44	6.40
1961	4193.17	12.90	4.62	15.72	6.76	9.87	2.09	13.47	7.30
1962	4192.68	17.96	6.38	23.35	10.11	14.45	3.06	19.55	12.10
1963	4192.22	12.61	4.44	16.08	[illegible]	12.46	2.63	14.97	[illegible]
1964	4192.53	14.00	4.96	22.27	[illegible]	15.78	2.91	17.55	10.70
1965	4193.44	14.05	5.06	24.90	10.67	15.32	3.69	19.60	12.10
1966	4194.62	10.55	3.88	13.72	5.75	6.66	1.85	11.48	6.40
1967	4194.01	17.36	6.32	23.68	10.03	19.00	4.04	20.39	12.70
1968	4194.71	18.68	6.88	23.11	9.67	19.53	4.17	20.72	12.90
1969	4195.81	17.00	6.39	19.00	7.82	15.55	3.55	17.76	10.90
1970	4195.90	15.52	5.84	20.76	8.51	19.75	4.24	18.59	11.40
1971	4196.70	19.49	7.43	24.92	[illegible]	23.94	4.51	22.01	13.60
1972	4198.47	16.33	6.42	20.86	8.14	14.36	3.12	17.68	10.60
1973	4199.39	21.48	5.57	28.61	10.97	23.09	5.04	24.59	15.70
1974	4200.11	12.37	4.99	18.95	7.16	16.10	3.96	16.13	9.70
1975	4200.23	18.44	7.43	31.01	11.75	20.50	4.49	23.67	15.00
1976	4201.07	18.40	7.42	22.55	[illegible]	15.90	3.70	19.66	12.20
1977	4200.60	16.01	6.45	17.44	[illegible]	15.29	3.35	16.41	9.90

[a]Thiessen contribution taken as the actual precipitation multiplied by the value of the Thiessen weighting factor for the average annual lake stage for that year.

relatively small part of the annual total, its influence on the variability in evaporation from year to year was neglected.

Based on these principles, a time series of freshwater equivalent lake evaporations was established from the relationship:

$$E_{SL,t} = \frac{\overline{E}_{SL}}{\overline{E}_{BR}} E_{BR,t} \quad . . . . (44)$$

in which

$E_{BR,t}$ = pan evaporation at the Bear River Bird Refuge near Corinne in the t^{th} year (ins)

$\overline{E}_{BR}$ = mean annual (May-September) pan evaporation at the Bear River Bird Refuge (44.3 ins)

$\overline{E}_{SL}$ = mean annual freshwater equivalent lake evapotranspiration (52 ins)

The measured Corinne pan evaporations listed in Table 4 were thus transformed by means of Equation 44 into the estimated Salt Lake freshwater equivalent evaporations in Table 15.

Surface Inflows

Of the total drainage basin tributary to the Great Salt Lake of 21,540 sq mi, 1686 sq mi is lake surface at elevation 4200. Most of the inflow comes from the Bear River (7029 sq mi), Weber River (2060 sq mi), and Jordan River (3420 sq mi). These three

Table 14. Monthly evaporations estimated at Corinne from Utah Lake data.

Station	Inches		
	May	June	July
Monthly Means (as of 1975)			
Bear River Bird Refuge	7.70	9.31	11.37
Utah Lake	8.40	10.00	10.93
Monthly Evap.			
Utah Lake			
1937	10.6	10.3	9.4
1938	7.3	*	*
1941	8.8	*	*
1942	7.5	10.5	10.9
1944	8.2	8.1	*
1946	8.2	*	*
1947	8.1	*	*
1952	8.7	*	*
1964	6.5	*	*
Bear River Bird Refuge			
1937	9.7	9.6	9.8
1938	6.7	*	*
1941	8.1	*	*
1942	6.9	9.8	11.3
1944	7.5	*	*
1946	7.5	7.5	*
1947	7.4	*	*
1952	8.0	*	*
1964	6.0	*	*

*Months not missing data. There were no missing data in the years not tabulated above.

rivers drain high mountain areas where runoff is much greater than it is from the low-lying desert covering most of the remaining tributary area.

All three principal tributaries are gaged near their mouths, but changes in all three catchments have considerably altered runoff conditions during the period of record. Two efforts were made to convert the series to a homogeneous basis. One used previous work by the Utah Division of Water Resources that transformed the historical time sequence to a present watershed basis. The second transformed the historical time sequence to a natural watershed basis.

Historical Streamflows

Flows at the mouths of these rivers into the Great Salt Lake have been measured on the Bear River at Corinne since 1950 (with a gap from 1958-1963), on the Weber River near Plain City since 1906 and on the Jordan River at 2100 South, Salt Lake City, and the Surplus Canal since 1943. The data are recorded on Table 4.

The record of flows at Corinne was extended from the measured years of 1950-57 and 1964-77 by regressing these measurements on the flows recorded since 1890 at Collinston 18 miles upstream. The resulting relationship was

$$Q_{R,t} = 81,393 + 1.0484\, Q_{L,t} \quad . \; . \; . \; . \; . \; (45)$$

in which

$Q_{R,t}$ = annual streamflow in the Bear River at Corinne (ac ft)

$Q_{L,t}$ = annual streamflow in the Bear River at Collinston (ac ft)

The coefficient of determination (R^2) was 0.995, and the standard error was 31,700. Equation 45 was then used to reconstruct the annual flow series at Corinne shown as the historical flows and used to compute the natural flows in Table 19. In Table 19, historical flows for 1890-1949 and 1958-1963 are estimated from Equation 45, and the flows for 1950-1957 and 1964-1977 are gaged (Table 4).

Average historical flows measured from six other streams with shorter gage records are shown in Table 16. The gage locations are shown in Figure 5. Waddell and Fields (1977) estimated inflow to the lake from seven small streams entering the lake between the Weber River and Farmington Bay to average 5089 acre-feet annually.

The average annual inflow to the lake from the three principal rivers has totaled 2,038,000 acre feet. Based on their drainage areas (totaling 7345 sq mi) and the total inflows implied from the lake water balance model, inflow from ungaged streams totals about 163,000 acre feet annually. Thus the total average historical stream inflow to the Great Salt Lake has been about 2,201,000 acre feet of which about 93 percent is gaged, or

$$Q_t = 1.07\,(Q_B + Q_W + Q_J) \quad . \; . \; . \; . \; . \; . \; . \; . \; (46)$$

Estimates of average annual subsurface discharge into the Great Salt Lake have been made from the principal groundwater basins near the lake as shown in Table 17 and total about 190,000 acre feet annually. Waddell and Fields (1977) estimated a total of 75,000 acre feet annually. The referenced studies have found that very little groundwater is entering the lake from the Weber and Jordan Basins, and hence further groundwater development in these areas would have little effect on the lake water balance. One can also see that whereas most of the runoff into the lake from the mountains to the east is surface flow, most of the much smaller total amount of runoff from the western desert is subsurface.

Present Modified Streamflows

The terminology "present modified streamflow" was adopted for this study from previous work by the Utah Division of Water Resources (1974, 1977). They used this term for the results when they adjusted historic flows to a homogeneous series of what the flows would have been had present (1965) practices of land and water use existed continuously over the period of historical record. They estimated separate series

Table 15. Water year input data for the lake water balance model.

YEAR	LAKE EVAP	LAKE PRECIP	PRESENT MODIFIED INFLOWS BEAR R	WEBER R	JORDAN R	NATURAL INFLOWS BEAR R	WEBER R	JORDAN R
1890		12.60	2056200.	855710.	394032.	2413742.		
1891		10.70	1371700.	567037.	311944.	1684309.		
1892		8.30	1528200.	633019.	332069.	1855611.		
1893		9.60	1420600.	587657.	318338.	1745324.		
1894		8.10	1938900.	806223.	380936.	2305320.		
1895		5.40	1371700.	567037.	311944.	1702159.		
1896		7.10	1547700.	641267.	334519.	1893933.		
1897		8.10	2036700.	847462.	391873.	2420336.		
1898		7.60	1518400.	628896.	330839.	1868159.		
1899		6.90	1899800.	789728.	376494.	2283384.		
1900		6.40	1352100.	558789.	309358.	1707894.		
1901		9.50	1204800.	408000.	263300.	1541262.		
1902		7.10	883300.	274000.	227900.	1247159.		
1903		7.60	773100.	286000.	210300.	1152489.		
1904		9.40	1595900.	814000.	282300.	2008419.		
1905		8.30	764900.	287000.	214300.	1115226.		
1906		13.00	1224700.	556000.	253700.	1779886.		
1907		11.20	2293500.	1100000.	340700.	3041008.		
1908		11.70	1366300.	397000.	298000.	1844406.	876136.	
1909		13.30	2233400.	1100000.	343800.	2971051.	1680072.	
1910		7.50	1960000.	698000.	363500.	2177623.	1223070.	
1911		8.70	1487500.	506000.	301700.	1858664.	1005751.	
1912		10.20	1414200.	673000.	278600.	2095181.	1197986.	
1913		8.40	1416900.	450000.	279800.	1794123.	945184.	
1914		11.10	1770700.	782000.	307100.	2260658.	1322187.	
1915		9.40	921500.	291000.	247700.	1319742.	764468.	
1916		7.60	1270500.	699000.	284900.	1702369.	1225962.	
1917		12.40	1771100.	879000.	303600.	2493487.	1432646.	
1918		6.60	1249400.	346000.	288100.	1682220.	864152.	
1919		7.00	1052900.	301000.	262100.	1454058.	771529.	
1920		10.06	1306900.	650000.	270600.	1761644.	1173147.	
1921		10.42	1696300.	959000.	312100.	2276289.	1530036.	
1922		10.52	2112400.	828000.	333900.	2557358.	1380141.	
1923		11.35	1808900.	745000.	322000.	2313373.	1285507.	
1924		6.25	1297200.	370000.	292700.	1485258.	865119.	
1925		14.47	1113900.	411000.	269000.	1474322.	913551.	
1926		9.95	904600.	360000.	243200.	1050843.	856446.	
1927		9.45	784800.	503000.	266700.	1489503.	1018490.	
1928		6.15	780800.	466000.	240100.	1492538.	977504.	
1929		10.93	880600.	540000.	246000.	1600771.	1081213.	
1930		10.50	776200.	233000.	217000.	1155936.	740781.	
1931		5.90	466600.	114500.	230100.	672450.	610110.	
1932		10.90	781800.	412400.	212000.	1488978.	1050981.	
1933		7.30	646800.	367300.	229200.	1119262.	854509.	
1934		5.20	343200.	89900.	166500.	501862.	510730.	
1935		10.50	470800.	188400.	140000.	866237.	724638.	
1936		10.50	860800.	429900.	177900.	1681742.	1124318.	
1937	59.2	11.60	767800.	412200.	219200.	1489477.	936243.	
1938	56.1	11.30	811800.	438400.	236200.	1598311.	925879.	
1939	59.4	10.70	600200.	283100.	239100.	1149745.	664630.	
1940	63.2	9.00	468600.	166900.	225500.	755986.	561887.	
1941	50.1	15.20	524800.	180100.	235200.	1034351.	693538.	
1942	53.9	12.60	707800.	411500.	280000.	1308664.	885705.	
1943	55.7	8.70	875400.	436100.	264000.	1726225.	911622.	436470.
1944	52.8	11.20	697400.	344600.	263800.	1393739.	840498.	619106.
1945	48.4	12.10	812000.	370400.	235100.	1574532.	879209.	612788.
1946	50.4	10.40	1041400.	483600.	282100.	2006662.	921232.	425585.
1947	48.3	14.00	1070600.	322900.	236500.	1828312.	865102.	631171.
1948	53.1	9.80	1167800.	447200.	284000.	1742175.	966186.	443492.
1949	48.3	11.20	1020000.	512600.	270300.	1577535.	1011710.	587912.
1950	47.9	10.80	1741000.	633400.	258100.	2567502.	1232177.	579653.
1951	51.4	12.10	1630200.	602000.	252600.	2210311.	1140197.	541699.
1952	51.4	11.20	1686400.	659100.	235200.	2314573.	1419904.	1217989.
1953	50.3	9.50	1043800.	444300.	280000.	1352947.	868112.	456186.
1954	55.1	6.20	539200.	151600.	264500.	980382.	605228.	309270.

Table 15. Continued.

YEAR	LAKE EVAP	LAKE PRECIP	PRESENT MODIFIED INFLOWS BEAR R	PRESENT MODIFIED INFLOWS WEBER R	PRESENT MODIFIED INFLOWS JORDAN R	NATURAL INFLOWS BEAR R	NATURAL INFLOWS WEBER R	NATURAL INFLOWS JORDAN R
1955	49.9	9.40	611200.	119200.	191400.	1150293.	691814.	385400.
1956	50.3	9.10	879800.	301300.	211700.	1709003.	884431.	375108.
1957	48.2	11.70	954400.	327100.	224000.	1826894.	921050.	628941.
1958	55.4	9.00	1058800.	425600.	252200.	1559644.	835945.	549267.
1959	49.4	9.00	602200.	112500.	220800.	1150754.	577042.	384828.
1960	58.0	6.40	569800.	112100.	180900.	1088201.	647008.	293555.
1961	56.3	7.80	405200.	60500.	131900.	761400.	550835.	401814.
1962	52.4	12.10	874800.	210400.	168100.	1768388.	902695.	568387.
1963	49.9	8.90	629400.	145900.	157900.	1263446.	700258.	401306.
1964	49.1	10.70	916400.	312300.	199400.	1700612.	892530.	646647.
1965	44.6	12.10	1091000.	337700.	239700.	2268558.	984211.	694403.
1966	54.6	6.40	1154400.	116000.	231200.	1506500.	626950.	477211.
1967	45.2	12.70	1054200.	175100.	240200.	1857784.	851037.	632409.
1968	49.9	12.90	1059200.	211100.	278100.	1694596.	792492.	722886.
1969	55.3	10.90	1215400.	492400.	373400.	1819022.	958507.	717528.
1970	53.0	11.40	875800.	233500.	389200.	1465112.	773839.	592725.
1971	49.1	13.80	2067800.	496800.	378900.	2821548.	1051521.	661813.
1972	51.0	10.80	2070600.	522400.	374400.	2682658.	1019141.	531668.
1973	52.5	15.70	1485000.	451000.	360000.	2046410.	990740.	876093.
1974	58.3	9.70	1505000.	529900.	430400.	2069439.	972390.	575922.
1975	46.5	15.00	1457000.	560000.	395000.	2198857.	1118689.	895256.
1976	49.6	12.20	1827000.	353546.	496411.	2168149.	760320.	562656.
1977	48.7	9.90	689300.	77580.	218600.	917957.	427131.	354756.
Mean	52.00	9.96	1181693	454331	275204	1710389	932657	565483
Std. Dev.	4.10	2.38	483941	235873	67197	524542	247196	183330
Skew	0.605	0.092	0.414	0.531	0.529	0.189	0.174	1.324
Hurst	0.753	0.574	0.830	0.748	0.736	0.766	0.587	0.594
Lag One Coeff.	0.197	0.162	0.621	0.421	0.720	0.429	0.402	0.077

At the time the parameters and cross correlation matrices for present modified (Table 20) and natural (Table 21) were computed, the 1977 Weber present modified flow was incorrectly entered at 770,580 instead of the correct 77,580, the Bear natural flow was incorrectly entered at 1305437 instead of the correct 917957, and the Weber natural flow was incorrectly entered at 1221016 instead of the correct 427131. Correction of these errors would not have a significant effect on the results reported subsequently in this study, but they will be corrected for subsequent use of the model.

of "present modified flows" for the Bear, Weber, and Jordan Rivers from water year 1901 to present and total combined flows for the three rivers from 1851 to 1900. In this study, their method was used to construct three separate present modified flow series beginning in 1890.

For the Bear River, the 1966-1975 historic flows at Corinne were taken as present modified inflows. For the 1927-1965 period, the present modified flows were taken from the U.S. Bureau of Reclamation hydrologic studies of the Bear River (USBR, 1967), with minor adjustments, to account for specific known local conditions by the Bear River Tri-State Negotiating Committee. The present modified flows for the 1901-1926 period were determined by a log-log correlation of the 1927-1965 present modified flows at Corinne with the historic flows at Collinston. The least squares line was established by an orthogonal regression procedure minimizing the sum of the errors measured perpendicular to the line of best fit, and annual correlation coefficient (R) was 0.99.

For the Weber River, the 1961-1975 historic flows were taken as present modified flows. For 1931-1960, the present modified flows were determined by a simulation model of the Weber Basin developed at the Utah Water Research Laboratory (Wang, 1971). The best regression between historic and present modified flows for the first 10 years (1931-1940) turned out to be to estimate the latter

Table 16. Small stream inflows to the Great Salt Lake.

Stream	Period of Record	Mean Annual Discharge (Acre-feet)	Mean Annual Discharge mi^2
Centerville Creek	1951-1976	2165	3.15
Farmington Creek	1951-1971	9099	10.00
South Willow Creek	1963-1969	4523	4.19
Goggin Drain	1963-1968 1971-1976	179000	-
Kennecott Drain	1963-1967 1971-1976	86026	-
Lee Creek	1971-1976	3610	-

Note: Goggin Drain, Kennecott Drain, and Lee Creek are distributaries of the Jordan River. Ungaged creeks flow into the lake from Tooele and Skull Valleys on the south, and from Blue, Hansen, and Curlew Valleys on the north. South Willow Creek is gaged some distance upstream from the lake.

Table 17. Estimate of groundwater inflow to the Great Salt Lake.

Aquifer	Source	Mean Annual Discharge (Acre-feet)
Bear River Basin	Hill et al. (1970)	3%-10% Bear River Surface Flow 39368-131225
Weber River Basin	Haws et al. (1970)	67 ≈ Negligible
Jordan River Basin	Kely et al. (1971)	4000
Great Salt Lake Desert	Foote et al. (1971) Steed (1972)	99,900

Table 18. Present modified water year streamflow and precipitation estimates (1851-1889).

Year	Sum of Streamflows (Ac-Ft) (Bear, Weber, Jordan)	Salt Lake City Precipitation* (inches)
1851	2000000	16.00
1852	2260000	15.72
1853	2840000	17.52
1854	2210000	15.60
1855	1620000	13.80
1856	1610000	13.63
1857	1220000	12.60
1858	770000	11.16
1859	1060000	12.12
1860	1010000	12.50
1861	1363000	13.80
1862	3353000	19.80
1863	2760000	18.80
1864	2870000	19.20
1865	2920000	19.40
1866	3730000	22.20
1867	3900000	23.00
1868	4700000	26.40
1869	3990000	23.60
1870	1930000	15.80
1871	2890000	19.40
1872	3600000	22.20
1873	2880000	19.40
1874	2440000	17.60
1875	2480000	17.80
1876	2530000	18.00
1877	3240000	17.40
1878	2530000	18.90
1879	1970000	14.60
1880	860000	11.50
1881	1250000	15.40
1882	1970000	16.10
1883	1580000	14.80
1884	1840000	16.80
1885	2700000	19.20
1886	3000000	19.00
1887	1600000	13.30
1888	910000	12.70
1889	1780000	17.00

*The Utah Division of Water Resources used 72 percent of this amount as their estimate of precipitation on the Great Salt Lake. The percentage found in this study was 63 (Tables 4 and 15).

as 88 percent of the historic flows, and the 1906-1930 present modified flows were computed as 88 percent of the historic streamflows on the Weber during the same period. The present modified flows for 1901-1905 were computed by estimating historic Weber flows from a log-log orthogonal regression on flows in the Bear River at Collinston (1931-1972) and computing the present modified flows as 88 percent of the historic flows estimated from the regression. The correlation coefficient (R) was 0.89.

For the Jordan River, the 1961-1975 historic flows were taken as present modified flows. For 1931-1960, the present modified flows were taken from the Great Basin Region Comprehensive Framework Study (Water Resources Council, 1971). The present modified flows for 1901-1930 were determined from a log-log orthogonal regression of 1931-1972 present modified flows on flows in the Bear River at Collinston. The correlation coefficient (R) was 0.79.

The Utah Division of Water Resources present modified flow sequences (1901-1977) for the three rivers are reproduced in Table 15. Their methodology was used to complete tabulation of present modified streamflows beginning in 1890 since all necessary data and equations were available for using the

Table 19. Computation of natural streamflows for Bear, Weber, and Jordan Rivers 1880-1977 water years.

BEAR RIVER

Year	Historical Flows Q_b	Consumptive Use U_c	Carry-over Storage $C_e - C_b$	Diversion $D_o - D_i$	Natural Flows* Q_n
1890	2251538	162204			2413742
1891	1517673	166636			1684309
1892	1685413	170198			1855611
1893	1570091	175233			1745324
1894	2125733	179587			2305320
1895	1517673	184486			1702159
1896	1706381	187552			1893933
1897	2230571	189765			2420336
1898	1674929	193230			1868159
1899	2083797	199587			2283384
1900	1496705	211189			1707894
1901	1318480	222782			1541262
1902	1009208	237951			1247159
1903	903322	249167			1152489
1904	1748316	260103			2008419
1905	845661	269565			1115226
1906	1505092	274794			1779886
1907	2761051	279957			3041008
1908	1559608	284798			1844406
1909	2681374	289677			2971051
1910	1884605	293018			2177623
1911	1559608	299056			1858664
1912	1790251	304930			2095181
1913	1486221	307902			1794123
1914	1947508	313150			2260658
1915	1000821	318921			1319742
1916	1381383	320986			1702369
1917	2167668	325819			2493487
1918	1349932	332288			1682220
1919	1112998	341060			1454058
1920	1412835	348809			1761644
1921	1916057	360232			2276289
1922	2199119	370239	-12000		2557358
1923	1989443	372930	-49000		2313373
1924	1339448	380810	-235000		1485258
1925	1213642	384180	-123500		1474322
1926	997676	388267	-335100		1050843
1927	1213642	388761	-112900		1489503
1928	1001870	390068	100600		1492538
1929	1049047	421224	130500		1600771
1930	798484	421352	-63900		1155936
1931	557357	421699	-306606		672450
1932	899129	421049	168800		1488978
1933	736630	421632	-39000		1119262
1934	415826	421836	-335800		501862
1935	554526	425161	-113450		866237
1936	947983	425609	308150		1681742
1937	881097	428880	179500		1489477
1938	927435	429176	241700		1598311
1939	773218	473147	-96620		1149745
1940	551067	479719	-274800		755986
1941	611873	487898	-65420		1034351
1942	817460	497134	-5930		1308664
1943	1036676	503709	185840		1726225
1944	809178	513571	70990		1393739
1945	943475	512577	118480		1574532
1946	1224126	511286	271250		2006662
1947	1167514	512458	148340		1828312
1948	1234610	511735	-4170		1742175
1949	1176949	510666	-110080		1577535
1950	1796000	514762	256740		2567502

Table 19. Continued.

BEAR RIVER

Year	Historical Flows Q_b	Consumptive Use U_c	Carry-over Storage $C_e - C_b$	Diversion $D_o - D_i$	Natural Flows* Q_n
1951	1811000	518611	-119300		2210311
1952	1775000	524413	15160		2314573
1953	1077000	531487	-255540		1352947
1954	609800	536312	-165730		980382
1955	687800	543583	-81090		1150293
1956	969500	552573	186930		1709003
1957	1064000	564554	198340		1826894
1958	1007426	573728	-21510		1559644
1959	643639	582695	-75580		1150754
1960	637139	589372	-138310		1088201
1961	462688	593592	-294880		761400
1962	928903	598025	241460		1768388
1963	685679	606817	-29050		1263446
1964	936154	611378	153080		1700612
1965	1182281	621947	464330		2268558
1966	1154339	631441	-279280		1506500
1967	1054183	641441	162160		1857784
1968	1059280	653316	-18000		1694596
1969	1215445	631527	-27950		1819022
1970	875699	629503	-40090		1465112
1971	2067709	627579	126260		2821548
1972	2070703	625655	-13700		2682658
1973	1485068	623732	-62390		2046410
1974	1505411	621808	-57780		2069439
1975	1456663	619884	122310		2198857
1976	1619298	618061	-69210		2168149
1977	689300	616137	-387480		917957

*Statistics for natural and present modified flows for the period from 1901 to 1977 are given below for comparison:

	Bear PMF	Bear Natural
Mean	1116196	1670572
Std. Dev.	475293	538674
Skew	0.649	0.329
Hurst	0.787	0.683
Lag one	0.615	0.441

WEBER RIVER

Year	Historical Flows Q_b	Consumptive Use U_c	Carry-over Storage $C_e - C_b$	Diversion $D_o - D_i$	Natural Flows* Q_n
1908	451383	424753			876136
1909	1252710	427362			1680072
1910	794447	428623			1223070
1911	575203	430548			1005751
1912	766204	431782			1197986
1913	512883	432301			945184
1914	889462	432725			1322187
1915	330539	433929			764468
1916	794859	431103			1225962
1917	999914	432732			1432646
1918	433166	430986			864152
1919	341629	429900			771529
1920	739270	433877			1173147
1921	1093625	436411			1530036

Table 19. Continued.

WEBER RIVER

Year	Historical Flows Q_b	Consumptive Use U_c	Carry-over Storage C_e-C_b	Diversion D_o-D_i	Natural Flows* Q_n
1922	939909	440232			1380141
1923	845631	439876			1285507
1924	420962	444157			865119
1925	468610	444941			913551
1926	409815	446631			856446
1927	571851	446639			1018490
1928	529537	447967			977504
1929	613197	468016			1081213
1930	272671	468110			740781
1931	141479	468631			610110
1932	559405	467526	17100	6950	1050981
1933	383251	468498	-8540	11300	854509
1934	61430	468700	-21870	2470	510730
1935	223334	470334	19700	11270	724638
1936	606058	470900	30300	17060	1124318
1937	470753	472300	-18410	11600	936243
1938	431704	472635	15870	5670	925879
1939	254777	421343	-23660	12170	664630
1940	150390	426257	-18650	3890	561887
1941	212137	433681	38710	9010	693538
1942	429942	441853	-3380	17290	885705
1943	426160	448462	1730	35270	911622
1944	342595	456553	-16880	58230	840498
1945	345104	459985	34060	40060	879209
1946	438523	463489	-41870	61090	921232
1947	306911	466821	26300	65070	865102
1948	509243	471153	-19780	5570	966186
1949	495828	474722	9530	31630	1011710
1950	723472	477475	25760	5470	1232177
1951	660027	479630	-4750	5290	1140197
1952	932907	483087	280	3630	1419904
1953	395547	488095	-33790	38260	888112
1954	126924	492158	-26444	12590	605228
1955	157413	486197	10844	37360	691814
1956	322132	482659	9950	69690	884431
1957	336405	479695	30830	74120	921050
1958	367630	475905	-57530	49940	835945
1959	101283	470988	-28229	33000	577042
1960	123726	480363	6979	35940	647008
1961	60564	487181	-18460	21550	550835
1962	210203	495132	108930	88430	902695
1963	145926	505172	1330	47830	700258
1964	312327	513203	9100	57900	892530
1965	337512	514939	60130	71630	984211
1966	115817	515033	-42760	38860	626950
1967	175057	515030	93030	67920	851037
1968	211194	515908	42420	22970	792492
1969	492345	485032	-56480	37610	958507
1970	233480	479399	8240	52720	773839
1971	496784	473367	29770	51600	1051521
1972	522187	467434	-17200	46720	1019141
1973	450911	460802	35056	43970	990740
1974	529953	456669	-42682	28450	972390
1975	560162	451837	43690	63000	1118689
1976	353546	447004	-76180	35950	760320
1977	77580	442171	-100885	8265	427131

Table 19. Continued.

*The statistics for natural flows and present modified flow for the period from 1908 to 1977 are given below:

	Weber PMF	Weber Natural
Mean	411048	932657
Std. Dev.	220611	247196
Skew	0.697	0.174
Hurst	0.783	0.587
Lag one	0.454	0.402

JORDAN RIVER

Year	Historical Flows Q_b	Consumptive Use U_c	Carry-over Storage C_e-C_b	Diversion D_o-D_i	Natural Flows* Q_n
1943	132810	395830	1240	-93410	436470
1944	197800	385976	150580	-115250	619106
1945	180600	387438	133990	-89240	612788
1946	180100	391225	-15310	-130430	425585
1947	202500	392621	160900	-124850	631171
1948	220500	397012	-96100	-77920	443492
1949	235000	398512	49300	-94900	587912
1950	226600	396163	31500	-74610	579653
1951	215800	394059	5300	-73460	541699
1952	476900	394899	395600	-49410	1217989
1953	489700	396816	-311100	-119230	456186
1954	264300	399930	-235190	-119770	309270
1955	191100	402620	-67450	-140870	385400
1956	204500	409068	-62820	-175640	375108
1957	223900	420251	146660	-161870	628941
1958	252000	426767	10020	-139520	549267
1959	220800	430818	-130290	-136500	384828
1960	180900	430565	-169110	-148800	293555
1961	132097	427727	-63240	-94770	401814
1962	168094	427243	164220	-191170	568387
1963	157865	428411	-56490	-128480	401306
1964	199348	427819	175090	-155610	646647
1965	239809	431514	175540	-152460	694403
1966	231165	433926	52470	-135410	477211
1967	240210	436929	112170	-156900	632409
1968	278071	440175	99400	-94760	722886
1969	373447	417931	43400	-117250	717528
1970	389038	416297	-66300	-146310	592725
1971	378829	416064	400	-133480	661813
1972	374298	415730	-106900	-151460	531668
1973	360067	415496	219500	-118970	876093
1974	430390	414162	-155000	-113630	575922
1975	388207	412829	236200	-141980	895256
1976	496411	411395	-214600	-130550	562656
1977	218600	410061	-183700	-90205	354756

*The statistics for natiral flows and present modified flows for the period from 1943 to 1977 are:

	Jordan PMF	Jordan Natural
Mean	270572	565483
Std. Dev.	80764	183330
Skew	0.858	1.324
Hurst	0.675	0.594
Lag one	0.710	0.077

same procedure that they started to apply for 1901.

For 1851-1889, no streamflow records are available. The Utah Division of Water Resources (1970) has, however, reconstructed series of the combined Bear, Weber, and Jordan River inflows (QBWJ) to the lake for this period and of precipitation at Salt Lake City from 1851-1876. To estimate QBWJ for the 1851-1889 period, they used lake elevations in adjusting inflow and precipitation values as necessary to match the lake levels. Subsurface inflow and flow in other rivers were estimated internally within the model through relationships described later in this report. These estimates of inflow and precipitation were also compared with data from the 1877-1900 output from a Markov model (Glenne et al., 1977) of the lake stages. Adjustments were made to the input inflow and precipitation data until the 1851-1900 water balance fit the present modified lake levels taken from the UDWR report. The present modified flow sequences and corresponding estimates of the lake precipitation for 1851-1889 are shown in Table 18.

Problems in Using Present Modified Flows

The present modified flows in Table 15 have both advantages and disadvantages for use in this study. Their advantage comes from their previous use in lake level control studies by the Utah Division of Water Resources. A new data base would complicate coordination of this study with their work and, more important, be more difficult to communicate to potential users. Furthermore, their preference is reinforced by the difficulty in transforming flows simulated on any other basis to the present basis required to predict lake stage probabilities under present conditions with the water balance model.

The disadvantage of using present modified flows is that the greater serial correlation and persistence (shown at the end of Table 15) caused by water resources and land development in the basins mean correlation matrices that are more difficult to match through stochastic generation. This is because storage reservoirs:

1. Even out flows from year to year as runoff during wet years is stored and used during dry years.

2. Reduce cross correlation as streams with more storage have their annual runoff values more evened out over time than do streams with less storage.

In addition, as one can see from the above description of how the present modified flows were obtained, the shifts from one estimating method to another at various points in time may have created discontinuities that bias the serial correlation and cross correlation statistics.

Since, as discussed in a later chapter, considerable difficulty was encountered in preserving the correlation matrices computed from present modified flows in a multivariate stochastic generation model, it was decided to establish a natural flow series to see if this would improve the situation.

Natural Streamflows

Natural streamflows are defined as those that would have been recorded had the watershed remained in its natural or pre-1848 state until the present day. The available data base for estimating a time series of natural flows is:

1. Estimated flows at the mouth of the Bear River, 1890-1977.

2. Estimated flows at the mouth of the Weber River, 1906-1977.

3. Estimated flows at the mouth of the Jordan River, 1943-1977.

4. Estimated consumptive use of water in the Great Salt Lake Basin, 1850-1968, divided among irrigation, municipal, bird refuges, artificial wetlands, and reservoir evaporation (Utah Division of Water Resources, 1970).

5. Irrigated acreage data for selected years beginning about 1943.

6. Population data from the U.S. Census every 10 years for counties and cities.

7. Measured or estimated diversions of Colorado River Basin water into the Jordan River Basin and among the basins tributary to the Great Salt Lake. Diversions into the Jordan River Basin from the Colorado River come through the Strawberry Tunnel, Duchesne Tunnel, and Daniels conduit. In addition, water is diverted from the Weber to the Jordan River in the Weber-Provo Diversion.

8. Measured or estimated end-of-the-year storages by year in the reservoirs in the basin with carryover storage. Year end storage records were obtained for reservoirs in the basin with carryover storage, namely Bear Lake and Woodruff Narrows Reservoirs in the Bear River Basin (Cutler Dam has no carryover storage); Willard Bay and Causey, Pineview, Rockport, Echo, Lost Creek, and East Canyon Reservoirs in the Weber Basin; and Deer Creek Reservoir and Utah Lake in the Jordan Basin.

Natural flows vary from measured historical flows because:

1. Water development projects have been constructed to divert water from the rivers for beneficial uses. The consumptive use (diversions net of return flows) should be

added to the historical flows to estimate the natural flows that would have occurred. The principal consumptive use in Utah is for irrigation. Other consumptive uses include urban (principally for yard watering since uses inside buildings are largely not consumptive), waters that have been diverted into open lands near the lake to provide bird habitat, and evaporation from reservoir surfaces. An increase in consumptive use in headwater areas, however, may not be entirely a net depletion because the water might have gone to some other consumptive use anyway between the use area and the river month, the higher soil moisture caused by irrigation may increase runoff from storms, and evapotranspiration losses may contribute atmospheric moisture that augments downwind precipitation.

2. Reservoirs large enough to hold water from one year to the next store water during wet years for use during dry years. Some of this carryover water will be used consumptively (including that which adds to reservoir evaporation losses), and the rest will eventually discharge into the lake. One can adjust historical flows for this carryover-storage effect by adding recorded annual gains in storage, subtracting annual losses, and assuming that the effect of the storage in increasing consumptive use is adequately handled by adjustments for that effect.

3. Men divert water from one basin to another. In the Great Salt Lake Basin, diversions carry substantial amounts of water into the Jordan Basin from the Colorado Basin and from the Weber Basin. Flows diverted out of a basin can be added to the historical to estimate natural flows. Flows brought into a basin can be subtracted from the sum of the historical flow and consumptive use because the water largely leaves the basin in one of those two ways.

4. Land management practices change runoff amounts. Likely effects include vegetation management (including fire control) that preserve and hence increase evapotranspiration from range and forest areas, soil conservation practices that hold the water on the land, and paving and channelization in urban areas that increase runoff and speed it downstream before losses can occur. The first two are upland effects that reduce runoff (would be a cause to add to historical to estimate natural flows) while the third effect acts in the opposite direction. The first two effects are probably larger in the Great Salt Lake Basin where urban areas cover only a small fraction of the land.

5. Cloud seeding increases winter snowfall by amounts estimated as high as 15 to 20 percent.

6. Groundwater development may pump water recharged many years before. Consumptive-use adjustments to historical to estimate natural stream flows will be too large for years in which groundwater supplies the consumptive use. The pumping will in fact add to streamflow the amount of return flow from the areas served (less consumptive use by those who take the return flow downstream) during the same year and deplete base flow and groundwater discharge directly into the lake for a number of years thereafter. During periods when pumping is lowering the water table (mining groundwater), or holding it down (moving recharge through aquifers more rapidly), the net effect is probably to add to streamflow. If pumping should be reduced, one would expect a net depletion to streamflow as aquifers are recharged.

In considering how one might adjust for these six effects to convert recorded to natural flows, it was concluded that: 1) the consumptive use effect was largest but rather difficult to quantify because of the lack of direct recorded time series of annual consumptive use amounts, 2) the annual additions and depletions to storage and diversions were significant and mostly well documented by recorded data series, and 3) land use management reduces runoff while cloud seeding and groundwater development increase runoff, and all three effects are probably relatively small (though becoming larger in recent years) in the Great Salt Lake Basin. Since these last three effects are relatively smaller, not backed by time series data, and partially compensate by acting in opposite directions, it was decided to adjust only for consumptive use, carryover storage, and interbasin diversions in estimating natural from recorded flows.

The adjustment was executed through the following steps:

1. Read from the curves plotted by Palmer of the Utah Division of Water Resources (1970) the total consumptive (man-induced increase in evapotranspiration) use in the basin for the years 1890 through 1968 and his division of this total among a) irrigation, b) municipal, and c) wetlands.[1] Other sources of evapotranspiration (principally from reservoir surfaces) were indicated by Palmer to be relatively very small and were combined into consumptive use for irrigation.

2. Divide Palmer's irrigation consumptive use in the Great Salt Lake Basin between the three subbasins (Bear, Weber, Jordan) proportional to the irrigated acreage in each

---

[1]Stauffer (1979) of the Utah Division of Water Resources indicated that these values are now believed to be up to 50 percent too high because they underestimated evapotranspiration rates under natural conditions. If this is true, the natural flows estimated in this study are considerably too high.

one. This assumes that Great Salt Lake Basin total estimated by Palmer does not include large amounts for irrigation in other subbasins draining into the lake. U.S. census data give total irrigated acreage by county in 1919, 1929, and 1939. The Great Salt Lake Basin irrigation consumptive use totals for these three years were then distributed into river basin totals proportional to these acreages. The proportionality fractions were interpolated for intermediate years and extrapolated for years before 1919. For years since 1939 irrigated acreage was divided among the three basins proportional to irrigated acreage totals reported in the agricultural census. Summed county totals vary from basin totals as county boundaries do not coincide with basin boundaries and because of differences in the census and USDA reporting systems.

3. Divide Palmer's total municipal consumptive use in the Great Salt Lake Basin between the three subbasins proportional to population in communities of over 2000 people. Proportionality fractions for years between census were interpolated.

4. Divide Palmer's wetlands consumptive use in the Great Salt Lake Basin between the three subbasins proportional to the current wetlands acreage in the three basins as reported by Hughes et al. (1974). The same proportional division among the basins was used in every year; specifically 0.70 for the Bear, 0.16 for the Weber, and 0.14 for the Jordan.

5. Sum the irrigation, municipal, and wetlands river basin consumptive uses for each river basin for each year from 1890 through 1977 for the Bear; 1908 through 1977 for the Weber; and 1943 through 1977 for the Jordan.

6. Sum from the USGS records the diversions into and out of each river basin for each year.

7. Sum from USGS or other records of end-of-the-water-year storage in each reservoir total carryover storages for each basin for each year.

8. Estimate the natural flow for a river in a given year as

$$Q_n = Q_h + U_c + D_o - D_i + C_e - C_b \quad . \quad . \quad . \quad . \quad (47)$$

where Q_n is the natural flow, Q_h is the historical flow, U_c is the consumptive use, D_o is the diversion out of the basin, and D_i is the diversion into the basin, C_e is the end-of-the-year reservoir storage, and C_b is the beginning-of-the-year reservoir storage.

The adjustments converting historical to natural flows by means of Equation 47 are summarized in Table 19. The natural flows used in the stochastic modeling are in Table 15. The stochastic modeling based on natural flows used series beginning in 1943, the date that the record began on the Jordan River.

Scaling of Data Series

The input data series available for use in the stochastic modeling are listed in Table 15. Each series was then expressed in common units of feet over the surface area of the lake. Precipitation and evaporation are in inches over the lake area and are converted by dividing by 12 inches per foot, and streamflows are converted to feet by dividing streamflow in acre-feet by the lake area of 1,079,000 acres (corresponding to a water surface elevation of 4200 feet).

Two sets of scaled data were developed. One combined precipitation, evaporation, and the present modified flows for the three rivers for the years 1937-1977. The other combined precipitation, evaporation, and the natural flows for the three rivers for the years 1943-1977. The beginning of the evaporation record controlled the length of the "present modified" set, and the beginning of the historical record on the Jordan River controlled the length of the "natural" set.

For both sets, the mean, standard deviation, and skewness coefficients were calculated for the five time series. If the absolute value of the skewness coefficient exceeded 0.1, the time series was assumed to be better represented by a three parameter log normal distribution (3PLN) than by a normal distribution. Because it was the only series with a skew less than 0.1 (Table 15), precipitation was represented by a normal distribution, and evaporation and streamflow were represented by 3PLNs. Burges and Hoshi (1978) suggest that better matrices could probably be achieved in this case by using a 3PLN for all five series.

The mean and standard deviation were computed by standard formula for the normally distributed precipitation series, but the latter was adjusted for the serial correlation effect using Equation 16. For the four series for which a 3PLN was used, the third parameters, a, was estimated by assuming a lower bound for each streamflow series equal to one half the minimum in the period of record and a lower bound for evaporation equal to 90 percent of the recorded minimum, and the mean and standard deviations were estimated from Equations 14 and 13 respectively. Equation 11 was not used to estimate a because large negative values resulted. These transformed statistics are shown on Table 20 for the present and modified flows and on Table 21 for the natural flows.

Relationships Among Data Series

Cross-correlation matrices M_0, M_1, and M_2 were calculated for the series using

Equations 35-37 to transform elements in which mixed normal and log normal or two log normal series were correlated. The results are in Table 20 for the data sets with present modified flows and in Table 21 for the data sets with natural flows.

One can see by comparing these two tables that the natural flow series when compared with the present modified series have much less serial correlation but have greater cross correlation for two out of the three combinations. Also, as one might expect, natural flows are much more highly correlated with precipitation than are the present modified flows. One can see from these comparisons that for stochastic generation combining precipitation and evaporation with streamflow data the more highly correlated M_0 matrix for natural flows has disadvantages that tend to counteract the advantages gained by reducing the coefficients in the M_1 and M_2 matrices.

Elements in the M_0, M_1, and M_2 matrices of Table 20 smaller than 0.320 are not significantly different than zero at the 5 percent significance level. The corresponding figure for Table 21, with six fewer years of data, is 0.345. Setting these values equal to zero was tried but did not help in solving for the multivariate generating matrices (Equations 24, 28, 31, and 32). The possibility, however, may still prove worthwhile in future model development.

The values on Tables 20 and 21 are computed over a common time period to avoid aggravating the difficulties with poorly ordered matrices. Much longer records, however, are available for estimating some of the statistics. The effect of going to longer series can be observed by comparing the raw data statistics and M_1 matrix diagonal on Table 20 with the statistics on the bottom of Table 15. Values of 1890 to 1977 series divided by the 1937-1977 series values actually used are shown in Table 22 for easy reference. Some of these ratios are significantly different than unity, and the differences are largely of the sort that would increase the risk of high lake stages.

In order to assess how representative the recorded series are of longer term climatic patterns, tree ring data going back to 1698 were used to reconstruct a 1700-1977 sequence of annual flows on the Bear River (Appendix A). The results suggest that the 278-year period had on the average slightly lower flows and somewhat less flow variance than did the period of record. The flows estimated from tree ring data do, however, contain one prolonged period of high flows in the middle 1700s when the lake might well have risen to quite high levels. Overall the comparisons of 1937-1977 with the 1890-1977 and 1700-1977 periods suggest no strong reason to believe that simulation based on 1937-1977 would not be reasonably representative of long term lake stage probabilities (Tables 22 and 23).

Table 20. Parameters and correlation matrices for present modified flows (1937-1977).

Variable	Raw Data Statistics: Mean $\hat{\mu}$	Standard Deviation $\hat{\sigma}$	Lag-One Auto-correlation $\hat{\rho}(1)$	Hurst h
Evap.	52	4.05	0.197	0.753
Precip.	10.86	2.2	0.036	0.729
Bear	1,030,729.3	427,926.3	0.627	0.503
Weber	357,973.8	171,393.8	0.551	0.699
Jordan	265,980.8	75,807.5	0.712	0.557

	Transformed Statistics for Stochastic Generation: a	$\hat{\mu}'_y$	$\hat{\sigma}'_y$
Evap.	3.33	-0.05	0.33
Bear	0.19	-0.38	0.51
Weber	0.03	-1.31	0.51
Jordan	0.06	-1.75	0.39

M_0 Correlation Matrix	Evap.	Precip.	Bear	Weber	Jordan
Evap.	1.0	-0.462	-0.359	-0.205	-0.065
Precip.		1.0	0.403	0.348	0.385
Bear			1.0	0.639	0.692
Weber				1.0	0.443
Jordan					1.0

M_1 Correlation Matrix	Evap.	Precip.	Bear	Weber	Jordan
Evap.	0.205	0.219	-0.227	-0.057	-0.136
Precip.	0.210	0.036	0.221	0.144	0.291
Bear	-0.490	0.481	0.653	0.504	0.497
Weber	-0.293	0.518	0.611	0.580	0.554
Jordan	-0.195	0.608	0.566	0.512	0.725

M_2 Correlation Matrix	Evap.	Precip.	Bear	Weber	Jordan
Evap.	0.223	-0.017	-0.011	-0.090	-0.056
Precip.	0.140	0.165	0.111	-0.023	0.296
Bear	-0.168	0.131	0.483	0.308	0.604
Weber	-0.245	0.429	0.427	0.417	0.548
Jordan	0.009	0.336	0.568	0.322	0.735

See footnote to Table 15.

Summary Comments on Data Collection

The dominating problem in compiling long term data series as basic data for stochastic modeling is obviously one of combining information collected at diverse points over different time periods by different instrumentation into a consistent set of series.

Table 21. Parameters and correlation matrices for natural flows (1943-1977).

Variable	Raw Data Statistics: Mean $\hat{\mu}$	Standard Deviation $\hat{\sigma}$	Lag-One Auto-correlation $\hat{\rho}(1)$	Hurst h
Evap.	51.15	3.34	-0.067	0.754
Precip.	10.71	2.22	0.062	0.728
Bear	1,744,300.1	474,290.4	0.420	0.622
Weber	897,303.9	189,888.7	0.360	0.636
Jordan	565,482.9	180,691.8	0.077	0.594

Variable	Transformed Statistics for Stochastic Generation: a	$\hat{\mu}_y'$	$\hat{\sigma}_y'$
Evap.	3.33	-0.12	0.29
Bear	0.35	0.18	0.34
Weber	0.26	-0.60	0.30
Jordan	0.14	-1.03	0.41

M_0 Correlation Matrix	Evap.	Precip.	Bear	Weber	Jordan
Evap.	1.0	-0.588	-0.381	-0.345	-0.298
Precip.		1.0	0.637	0.515	0.722
Bear			1.0	0.719	0.585
Weber				1.0	0.618
Jordan					1.0

M_1 Correlation Matrix	Evap.	Precip.	Bear	Weber	Jordan
Evap.	-0.070	0.188	-0.044	-0.063	0.058
Precip.	0.168	0.062	0.308	0.176	0.048
Bear	-0.275	0.446	0.435	0.358	0.269
Weber	-0.119	0.323	0.422	0.370	0.153
Jordan	0.086	0.154	0.367	0.317	0.084

M_2 Correlation Matrix	Evap.	Precip.	Bear	Weber	Jordan
Evap.	0.020	-0.147	0.147	0.066	0.006
Precip.	-0.005	0.271	0.201	-0.017	0.000
Bear	0.130	0.110	0.188	0.092	-0.054
Weber	-0.185	0.323	0.351	0.322	0.046
Jordan	-0.195	0.237	0.412	0.185	0.016

See footnote to Table 15.

One further suspects that data discontinuities that are unimportant for other types of hydrologic analysis may have an important effect on the serial correlation and persistence statistics used in multivariate stochastic models. In this data-collection effort, the series based on present conditions had significant discontinuities as the method of estimation was changed on different dates. The series based on natural conditions suffered from the difficulties in developing a good transform for converting recent measurements to a natural basis of long ago. The overall conclusion at this point, however, would have to be that one should not force use of a natural basis if more reliable series can be established on another basis.

A second problem is in determining how long a period to attempt to cover in the data series in light of the facts that long series provide better estimates of important parameters but increase the danger of introducing unreliable information. One also has a trade off between using series of different lengths to estimate different parameters in order to maximize the value obtained from the recorded information and the statistical problems caused by introducing this sort of data heterogeneity. This problem was not examined empirically in this study and deserves further consideration.

Table 22. Ratios of long (1890-1977) to short (1937-1977) series statistics, present modified flows.

Variable	Mean $\hat{\mu}$	Std. Dev. $\hat{\sigma}$
Precipitation	0.89	1.17
Bear	1.15	1.14
Weber	1.33	1.42
Jordan	1.03	0.89

Table 23. Ratios of very long (1700-1977) to long (1890-1977) series statistics, present modified flow as estimated from tree-ring data.

	Mean $\hat{\mu}$	Std. Dev. $\hat{\sigma}$	Range $Q_{max}-Q_{min}$
Bear	0.93	0.78	1.17

CHAPTER 4

STOCHASTIC FLOW GENERATION MODELS

Available Models

Two multivariate stochastic models were tried in generating annual sets of simultaneous data for the three rivers, precipitation and evaporation for the Great Salt Lake. Both are special cases of the ARIMA (p,d,q) class. The parameter d refers to representation of variables in a summed (or integrated) form. Since Watts (1972) has shown analytic estimation of the ARIMA model parameters to be unmanageable, no integrated variables were tried.

The parameter p denotes the number of autoregressive terms. Thus a multivariate ARIMA (p,0,0) has the form:

$$\underline{X}(t) = A_1\underline{X}(t-1) + A_2\underline{X}(t-2) + \ldots + A_p X(t-p) + B\underline{\varepsilon}(t) \quad \ldots \ldots \ldots \ldots (48)$$

where $\underline{X}(t)$ is the vector of values of the random variable in time t. The parameter q denotes the number of moving average terms in the model. Thus, an ARIMA (p,0,q) model has the form:

$$\underline{X}(t) = C_1\underline{X}(t-1) + C_2\underline{X}(t-2) + \ldots + \underline{C}_p\underline{X}(t-2) + D\underline{\varepsilon}(t) - E_1\underline{\varepsilon}(t-1) - \ldots - E_q\underline{\varepsilon}(t-q) \quad \ldots \ldots (49)$$

where the $\underline{\varepsilon}(t)$ are independent vector random variables.

The two models tried were the ARIMA (1,0,0) and the ARIMA (1,0,1), alternately designated the ARMA (1,0) and ARMA (1,1). The (1,0,1) model is the simplest model which possesses autocorrelations suitable for modeling long term persistence (values of h >> 0.5) in finite records. The subsequent failure of this model to generate acceptable synthetic sequences forced simplification to the (1,0,0) case, the simplest workable stochastic simulation model.

The multivariate ARMA (1,0) model can be represented by the mathematical expression

$$\underline{X}(t) = A\underline{X}(t-1) + B\underline{\varepsilon}(t) \quad \ldots \ldots \ldots (50)$$

where $\underline{X}(t)$ and $\underline{X}(t-1)$ are standardized vectors whose elements are random variables relating process values at times t and t-1. For convenience, the error vector $\underline{\varepsilon}(t)$ is assumed to have independent standard normal elements. The parameter B may be chosen to provide any variance-covariance matrix. The parameters A and B are chosen so that the sets of simultaneous data generated by the model have the same correlation properties as the simultaneous sets of recorded data by use of Equations 23 and 24. The procedures are illustrated in Appendix B.

The multivariate ARMA (1,1) model can be represented by the expression:

$$\underline{X}(t) = C\underline{X}(t-1) + D\underline{\varepsilon}(t) - E\underline{\varepsilon}(t-1) \quad \ldots \ldots (51)$$

with vectors $\underline{X}(\cdot)$ and $\underline{\varepsilon}(\cdot)$ defined as above and with three parameter matrices C, D, and E. C, D, and E can be written as functions of the lag zero (M_0), lag-one (M_1), and lag-two (M_2) correlation matrices and solved for by use of Equations 30, 31, and 32. The procedure is detailed in Appendix C. The ARMA (1,1) model has been developed specifically to approximate persistence characteristics observed in long term geophysical records. Since the ARMA (1,1) model contains the Markov model as a special case, it is more general and more powerful. Theoretically, it has the capability of preserving more of the characteristics of an observed data series.

This theoretical advantage, however, cannot be realized unless one can solve the functions defining the parameter matrices. Matalas and Wallis (1971a) encountered difficulty in solving Equations 23 and 24 and subsequently characterized the properties of M_0 and M_1 that prevent solution. Equations 30, 31, and 32 are more complex, and one would consequently expect to have to meet even more restrictive constraints on the properties of M_0, M_1, and M_2 in order to obtain a solution. While the properties of these constraints have not been characterized, the values computed for the matrices from the Great Salt Lake data (Tables 20 and 21) did not permit solution.

In an effort to overcome this problem, principal component techniques found to be useful in multivariate analysis were tried. The strategy in using principal components is to simplify mathematical specification of the multidimensional system by reducing the number of components without loss of useful information. By reducing the number of elements in M_0, M_1, and M_2, one increases the probability that Equations 30, 31, and 32 can be solved.

The principal components of a multivariate system are linear transformations of the system random vector $\underline{X}$ which satisfy the following properties:

(a) The first principal component is the scalar random variable[1] $Y_1 = T_1{}^T X$ where the transformation vector T_1 satisfies $\underline{T}_1{}^T \underline{T}_1 = I$ and maximizes the variance of Y.

(b) The ith principal component is the scalar random variable $Y_i = \underline{T}_i{}^T \underline{X}$ where the vector $\underline{T}_i$ satisfies $\underline{T}_i{}^T \underline{T}_j = 0$ for $j \neq i$ and $\underline{T}_i{}^T \underline{T}_i = I$ and maximizes the variance of Y_i. If the dimension of X is n, there are n principal components.

Thus the matrix transformation $\underline{T} = (\underline{T}_1, \underline{T}_2, \ldots, \underline{T}_n)$ transforms the multivariate system of random variables X into a new system $Y = T^T \underline{X}$ where $\underline{Y}$ is a multivariate random variable with independent element $\underline{Y}^T = (Y_1, Y_2, \ldots, Y_n)$. Also var $(Y_i) \geq$ var (Y_j) for $i > j$. Furthermore, $T^T T = T T^T = I$ where I is the identity matrix. As i decreases, the variance of each added principal component becomes less. When the added variance becomes small enough, the remaining components may effectively be considered as constants, thus reducing the number of dimensions used to describe the system.

The computational process used to model with principal components requires several steps. Observed values need to be scaled in converting measurements to the time series $\underline{X}(t)$ so that all the variables are measured in the same units. Then the variance-covariance matrix

$$\Psi = \frac{1}{n-1} \sum_t (\underline{X}(t) - \bar{\underline{X}}(t))(\underline{X}(t) - \bar{\underline{X}}(t))^T \quad . \quad . \quad . \ (52)$$

is computed. Principal component vectors $\underline{T}_i$, with variances λ_i associated with the random variables $\underline{Y}_i = \underline{T}_i{}^T \underline{X}$ are obtained as solutions to the matrix equations (Morrison, 1976)

$$(\Psi - \lambda_i I) T_i = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \ (53)$$

where i = 1, 2, etc. Standard computer programs are available to obtain this solution (IMSL, 1976). By examining the values of λ_i (i.e., the variances of the principal components), the variances of some of the components may be found so small that they may be treated as constant and need not be generated. For example, if estimated principal components variances are $\lambda_1 = 25$, $\lambda_2 = 5$, $\lambda_3 = 0.1$, the third component $Y_3 = \underline{T}_3{}^T \underline{T}$ represents only 0.1/(25 + 5 + 0.1) or 0.3 percent of the total variation in the system. Only that percentage of the information is lost when the system is regarded as two dimensional with a third constant component assigned an average value over the data. For this case, the T matrix is $T = (\underline{T}_1, \underline{T}_2)$ transforming both sides of Equation 51 yields

$$T^T \underline{X}(t) = \underline{Y}(t) = T^T C T T^T \underline{X}(t) = T^T D T T^T \underline{\varepsilon}(t) - T^T E T T^T \underline{\varepsilon}(t-1) = C^* Y(t) + D^* \underline{\varepsilon}^*(t) - E^* \underline{\varepsilon}^*(t-1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \ (54)$$

The transformed error vector $\underline{\varepsilon}^*(t)$ is seen to have the same mean variance as $\underline{\varepsilon}(t)$.

Application of Equation 54 requires scaling the observed data to common units, computing principal components for the data set, noting the variance for each component, making a judgment as to the percentage of the variation not to preserve in the model, using constant components where the variation is not to be preserved, and solving for the ARMA model parameters from the relationships shown in Equation 53 and Appendix C. If Equation 54 cannot be solved because of ill-conditioned matrices, one has the option of accepting preservation of less variation, using constants for the term whose variation is dropped, and trying for solution with matrices of one less dimension.

Since each principal component tends to load most heavily on one or two data series of observed measurements, treating a principal component as a constant comes close to neglecting the observed variability in the associated data series. The reasonableness of this decision needs to be considered in model formulation.

From the parameters computed for a selected principal components model, synthetic sequences can be generated and expressed in vectors $\underline{Y}(1)$, $\underline{Y}(2)$, ..., $\underline{Y}(n)$. Each vector then needs to be augmented by the constant components. For the example of a case with two principal components and a third constant component, one augments each vector $\underline{Y}(i)$ with the constant third component to form the new sequence

$$\left(\frac{\underline{Y}(t_1)}{y_3}\right) \quad \left(\frac{\underline{Y}(t_2)}{y_3}\right) \quad \ldots\ldots\ldots \left(\frac{\underline{Y}(t_n)}{y_3}\right),$$

The natural sequence is generated via the transformation

[1]The symbol T is used to represent a matrix inverse.

$$\underline{X}(t_i) = (\underline{T}_1\underline{T}_2\underline{T}_3) \left(\frac{\underline{Y}(t_i)}{y_3}\right) \quad . . . . . (55)$$

Problems Encountered with the Multivariate ARMA (1,1) Model

In the process of implementing O'Connell's (1974) procedures presented in Chapter 2 for parameter estimation for the multivariate ARMA (1,1) model, difficulty was experienced in obtaining iterative solutions for the S and DD^T matrices. To provide the setting for a discussion of these difficulties and the attempts that were made to resolve them, the estimation and generation procedures for the multivariate ARMA (1,1) model are summarized below.

Overview of ARMA (1,1) Procedures

Figure 6 is a schematic of the procedures for parameter estimation and hydrologic sequence generation as divided into five steps:

1. Data transformations and estimations of statistics.

2. Solution for S and T matrices.

3. Estimation of coefficient (parameter) matrices.

4. Generation and untransformation.

5. Comparison of synthetic and original time series.

Sets of time series of evaporation, precipitation, and lake inflows are available for five different-length time periods as shown in Table 2. In the series, X_1 denotes Great Salt Lake evaporation, X_2 denotes precipitation on the lake, and X_3, X_4, and X_5 denote annual inflow to the lake from the Bear, Weber, and Jordan Rivers respectively as shown in Table 24. To have all five time series in common units of feet over the lake area, the inflow series, which are in acre feet, are divided by the surface area of the lake when the water level is at elevation 4200 (1,079,000 acres). Next, the computer program written to process the data for this study computes the $\hat{\mu}$, $\hat{\sigma}$, $\hat{\gamma}$ of each time series in a set, and the cross-correlation matrices for each set at lag 0, 1, and 2 (M_0, M_1, and M_2, respectively). If the absolute value of the skewness coefficient (γ_x) of any time series exceeds 0.1, that series is assumed to be distributed 3PLN and $\hat{\mu}_x$ and $\hat{\sigma}_x$ are transformed using Equations 13 and 14. A 3PLN was selected to provide a minimum value or a for the respective series greater than zero. In addition elements of M_0, M_1, and M_2 which represent a mixture of 3PLN and normal variables or two 3PLN variables are transformed using Equations 35 through 37. Values for the lower bounds a in the 3PLN distributions are estimated as a

Table 24. Great Salt Lake time series.

	Time Series
X_1	Great Salt Lake Evaporation
X_2	Great Salt Lake Precipitation
X_3	Bear River Inflow
X_4	Weber River Inflow
X_5	Jordan River Inflow

fraction of the minimum values in each time series. For flows and precipitation, the fraction used was 0.5; and for evaporation, it was 0.90. The computerized procedure as outlined in Figure 6 then provides the option to perform a principal components analysis on the lag-zero covariance matrix in order to try to reduce the order of the stochastic model (number of time series) for reasons described above.

In the second stage, Equations C-9 and C-11 from Appendix C are solved for the S and T matrices which are used to calculate DD^T and hence the coefficient matrices D and E in the third stage. The coefficient matrix C is calculated directly from M_1 and M_2 using Equation C-8.

Synthetic time series are generated in stage 4 using C, D, and E coefficient matrices estimated for the multivariate ARMA (1,1) model. These synthetic series are then transformed back to offset any earlier 3PLN and principal components transformations, and the flow series are scaled back from a depth over the lake area to a flow volume basis. Finally, the statistics (μ, σ, h), and matrices (M_0, M_1, and M_2) of the synthetic series are compared with the corresponding statistics of the original time series. Since each synthetic trace generated has different values for these parameters, a number of traces are generated and the results averaged before making the comparison.

Attempts to Resolve Difficulties with ARMA (1,1) Application

The results of the seven approaches tried in applying the multivariate ARMA (1,1) model are summarized in Table 25. These approaches were all tried using the present modified flow sequences, and the results are discussed below.

The initial approach was to use the five time series for the period 1937-1977. Unfortunately, it was not possible to obtain a solution to DD^T. Up to 500 iterations were used with a convergence criterion of 0.006 for the largest difference between elements of DD^T in successive iterations. For each of the time series sets necessary and sufficient conditions that DD^T and EE^T be positive semidefinite were checked. These conditions are that $(S + T + T^T)$ and

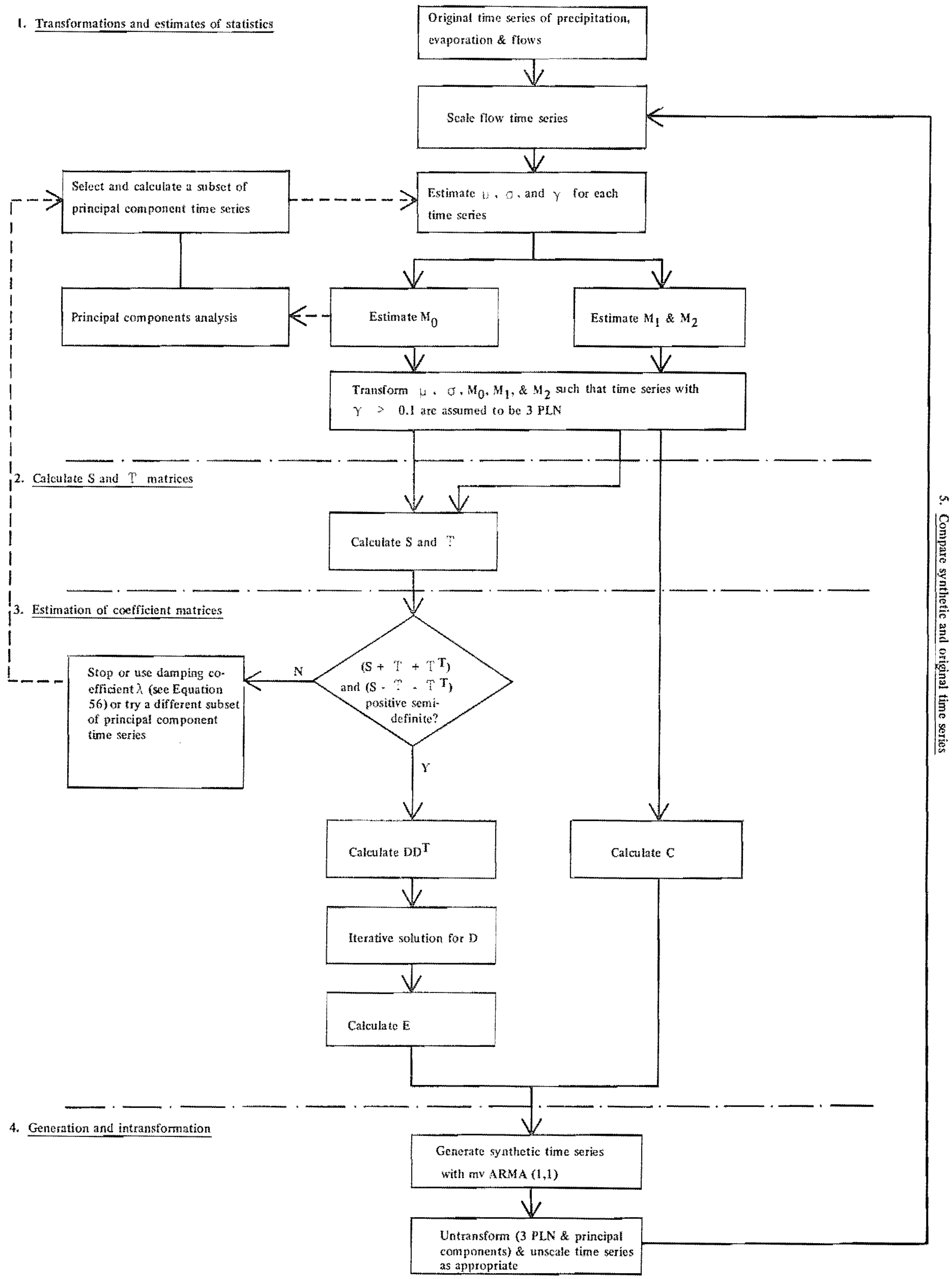


Figure 6. Generalized procedure for estimating coefficient matrices, generating synthetic time series, and analyzing for the quality of the preservation of statistics with the multivariate ARMA (1,1) model (including the principal components option).

Table 25. Summary of the results of the attempts to apply the multivariate ARMA (1,1) model.

No.	Description[a]	Results
1.	5 original time series	DD^T did not converge
2.	Set elements in M_0, M_1, and M_2 matrices not significantly different than zero equal to zero.	DD^T did not converge
3.	Subsets of principal component time series	DD^T converged only for some pairs of principal components[b]
4.	Combinations of subsets of principal components time series	Poor resemblance of original statistics
5.	Set negative diagonal elements of DD^T to zero in 3 and 4 above	Poor resemblance of original statistics
6.	Select univariate ϕ values from O'Connell (1974) and insert on diagonal of C matrix in 1 above	DD^T did not converge
7.	Least squares solution of DD^T for D with a full D matrix	Very poor resemblance of original statistics

[a]Present modified flow series were used in each case.

[b]See Table 26 for list of subsets which converged. The bivariate subsets which converged provided the best replication of the statistics of any ARMA (1,1) model.

$(S - T - T^T)$ be positive semidefinite (O'Connell, 1974). To be positive semidefinite all the eigenvalues of these matrices must be greater than, or equal to zero. This condition is conceptually analogous to requiring that the computed variance be positive to a two dimensional model. The conditions were satisfied for the 1937-1977 series with present modified flows. In an attempt to control oscillations in the iteration process and to obtain convergence, a damping coefficient λ was introduced in the iterative procedure:

$$U_j = S - \lambda T U_{j-1}^{-1} T^T \quad . . . . (56)$$

$$DD^T + \lambda EE^T = S \quad . . . . (57)$$

$$E\, D^T = T \quad . . . . (58)$$

in which U is defined as DD^T and λ is a damping coefficient in the range $0.0 < \lambda < 1.0$. While the ideal would be for solution to require minimal damping (i.e., λ close to 1.0) solutions for DD^T could only be obtained for low values of λ, which did not serve the cross-correlations in generation.

A second attempt to obtain positive semidefinite $(S - T - T^T)$ and $(S + T + T^T)$ matrices was to set elements of the cross-correlation matrices equal to zero if they were not found to be different than zero at the 95 percent level of significance. The effect of small elements in M_0, M_1, and M_2 did not prove to be the obstacle to obtaining a solution for DD^T, and convergence was still not obtained.

The next approach was to transform the five original time series through principal component analysis to principal component variables independent at lag zero, i.e. M_0 is diagonal. By this means it was possible to experiment with various subsets of the principal components to determine whether the coefficient matrices for any of these lower order models could be obtained successfully. For the 1937-1977 series with present modified flows, it was found that about 88 percent of the total variance was explained by only two of the principal component variables (see Table 26). For each subset, $(S + T + T^T)$ and $(S - T - T^T)$ were tested to determine whether they were positive semidefinite, and if not no attempt was made to solve for the coefficient matrices.

The only cases for which the necessary coefficient matrices could be successfully defined were for the bivariate subsets listed in Table 27. As shown in Table 27, the percentage of the total variance explained by these bivariate subsets was small, and therefore they could not be expected to adequately preserve the cross-correlations in the original time series. Nevertheless, flows were generated using the mean values of the principal components not included in a bivariate subset in lieu of synthetic values of the excluded principal components to transform the bivariate synthetic principal component time series back to synthetic time series with the form of the original time series. Use of a constant mean value omits from the model variance associated with these principal components but is justified because that variance is small and most of the total variance is contained in the bivariate subset. The mean values were calculated using the linear equations given in Table 26 and for P_i but with mean values substituted in the following way:

$$\bar{P}_i = \sum_{j=1}^{n} K_{ij}\, \bar{X}_j \quad . . . . (59)$$

Comparison of synthetic and original time series showed that cross-correlations were well preserved between the original variables that were "well represented" by principal components (i.e. large coefficients in the linear equations in Table 26). However, cross-correlation between original variables one or both of which was not so "well represented" by the principal components were correspondingly not well preserved.

Table 26. Principal components and total variance explained for the 1937-1977 series with present modified flows.

Principal Component[a]	Percent Total Variance Explained by P_i
$P_i = \sum_{j=1}^{n} K_{ij} X_j$ (n = number of original time series, X_j)	
$P_1 = +0.486 X_1 - 0.227 X_2 - 0.811 X_3 - 0.217 X_4 - 0.091 X_5$	60.6%
$P_2 = +0.841 X_1 - 0.138 X_2 + 0.493 X_3 + 0.148 X_4 + 0.093 X_5$	27.3%
$P_3 = +0.221 X_1 + 0.932 X_2 - 0.191 X_3 + 0.200 X_4 + 0.081 X_5$	7.1%
$P_4 = -0.065 X_1 - 0.225 X_2 - 0.220 X_3 + 0.944 X_4 - 0.074 X_5$	4.3%
$P_5 = -0.057 X_1 - 0.101 X_2 - 0.122 X_3 + 0.021 X_4 - 0.986 X_5$	0.7%

[a]See Table 24 for definition of the time series X_j.

The fourth approach attempted was to combine bivariate and univariate ARMA (1,1) models of the principal component variables. The two combinations tried were: 1) two bivariate subsets and one univariate, and 2) one bivariate subset and three univariate. It was hoped that the these combinations would improve the preservation of the cross-correlations and the standard deviations because this approach treats all five principal components as stochastic variables whereas the previous approach treated three principal components as constants. However, when generation was attempted, both combinations gave very large values beginning with five years after the initial conditions. This instability was traced to large elements in C which led to rapidly increasing synthetic values.

Following a recommendation by Mejia (personal communication, May 1978) a modification was incorporated into the solution procedure for D from DD^T such that negative diagonal elements of DD^T were set equal to zero. The occurrence of negative diagonal elements in DD^T prohibits a solution for D because the solution procedure involves taking the square root of these elements. Approaches two and three were repeated for subsets in which negative diagonal elements

Table 27. Bivariate subsets of principal components which resulted in a solution for DD^T using time series set 3.

Bivariate Subsets[a]	Percent Total Variance Explained By Subset
P_1 & P_2	67.7[b]
P_2 & P_3	34.4[c]
P_2 & P_4	11.4
P_2 & P_5	7.8
P_4 & P_5	5.0

[a]See Table 24 for definition of the principal component variables.

[b]Unstable generation containing both large positive and large negative values.

[c]Used for ARMA (1,1) generation.

had prohibited solution for D. The result was that a solution for D was obtained but some of the diagonal elements of D were zero. Therefore D could not be inverted to calculate E (see Equation 32). Since the preservation of statistics was poor for cases where D was obtained without setting negative diagonal elements to zero it was decided not to calculate E using a pseudo inverse because it was not expected to yield improved results.

The sixth approach listed in Table 25 was suggested by O'Connell (1974) as a simplification of the first approach. At the expense of not being able to preserve the off-diagonal elements of M_2, the coefficient matrix C can be treated as a diagonal matrix with elements c_i defined by Equation 34. In this way, the c_i are actually moment estimates of the ϕ_i parameter in the univariate ARMA (1,1) model. O'Connell (1974) recommends that his empirically derived values of ϕ_i, which are tabulated for different ρ_i (1) and h_i values, should be used for c_i since these correct for bias in the method of moments estimate of ϕ_i given by Equation 34. Sample estimates of ρ_i (1), ρ_i (2), and h_i for the 1937-1977 series with present modified flows are given in Table 28. This table also contains the values of c_i values obtained from Equation 34 and from O'Connell's tables. Large differences between the two estimates of c_i are readily apparent and are caused at least in part by estimation bias in the method of moments to estimate $\rho_i(1)$ and ρ_i (2). It should be noted that three of the estimates of c_i from Equation 34 exceed the maximum reasonable value of 1.0. Also, for all three rivers, the combination of estimated values for $\hat{\rho}_i$ (1) and h_i values are outside the range of O'Connell's tables for ϕ_i and thus outside the range in which the ARMA (1,1) model can be used (Lettenmaier

Table 28. Diagonal elements of the C matrix for the 1937-1977 series with present modified flows.

X_i	Time Series	$\hat{\rho}_i(1)$	$\hat{\rho}_i(2)$	h_i	$c_i = \frac{\hat{\rho}_i(2)}{\hat{\rho}_i(1)}$	$c_i = \phi$ (O'Connell, 1974)
X_1	Great Salt Lake Evaporation	0.21	0.22	0.75	1.09	0.96
X_2	Great Salt Lake Precipitation	0.04	0.17	0.73	4.55	0.75
X_3	Bear River Inflow	0.65	0.48	0.50	0.74	-[a]
X_4	Weber River Inflow	0.58	0.42	0.70	0.72	-[a]
X_5	Jordan River Inflow	0.73	0.74	0.56	1.01	-[a]

[a]The combination of $\hat{\rho}_i(1)$ and h_i values is outside the range for which the ARMA (1,1) model is suitable (Burges and Lettenmaier, 1975).

and Burges, 1977). In these cases, ϕ_i values obtained for X_1 and X_2 were used (i.e. 0.75 and 0.96); but in both cases, the iterative solution for DD^T did not converge. A copy of O'Connell's Fortran program for estimating the coefficient matrices was obtained, and the results were compared with those from the programs developed in this study. The coefficient matrices from the two programs agreed for the 1937-1977 series with present modified flows and for a precipitation data set of order 3 obtained from Armbruster (personal communication, June 1978).

The final attempt to overcome problems with parameter estimation and improve matching of the original statistics used an alternative solution procedure for DD^T. A least squares procedure was used in which a full D matrix was assumed in contrast to the lower triangular form for D which must be assumed in O'Connell's (1974) solution procedure. The least squares procedure was applied to the five original time series which were run in the first approach and did yield a solution for D, but preservation of the statistics was very poor.

Evaluation of Problems

Two basic causes appear to underlie the problems that were encountered with the multivariate ARMA (1,1) model. One is that the method of moments is a biased estimation procedure, and the bias may well be in the direction of increasing the probability of causing nonpositive definite matrices. For the univariate case, O'Connell (1974) provides empirically derived tables to correct for this estimation bias, but such corrections are not available for the multivariate case, nor was a way found in which generally applicable corrections could be obtained. Ledolter (1978) recommends use of maximum likelihood parameter estimates; however, this procedure would require 50 parameters for the five series of this study and was not attempted. The seventh approach in Table 25, using a least squares estimation procedure, was an attempt to overcome any difficulties caused by bias in the method of moments. Convergence of the DD^T matrix was achieved, but the resulting generated flows were quite poor.

These difficulties suggest that the underlying problem in this case may well be that the time-series data are incompatible with the ARMA (1,1) models. Evidence for this is seen on Table 28, where all five time series either have a serial correlation too high for the model according to the figure prepared by Burges and Lettenmaier (1975) or a C matrix element exceeding unity which violates the model according to O'Connell (1974). The C matrix problem is associated with random fluctuations of correlations too small to be statistically significant for the evaporation and precipitation series. This problem might well be handled by taking both c_i as unity. The C matrix problem with the Jordan River and the high serial correlations for all three rivers are probably caused by the use of present modified flows which are modified by large volumes of storage that increase serial correlation by damping flow fluctuations. This would suggest using natural flows rather than present modified flows in the ARMA (1,1) model versions. This possibility would have been explored in greater depth with additional time, but the results described below for use of natural flows in an ARMA (1,0) model suggest that the gained better matching of the natural flow data is lost by errors in the best available estimating procedure for transforming the generated natural flows into the present modified flows needed for lake stage forecasting.

Since the reservoir storage influence on the present modified flows obviously creates a memory longer than one year in the hydrologic system, an alternative approach to the problem would have been to go to values of p or q or both greater than 1 in the ARMA (p,q) model. The difficulties encountered in solving for functional parameters for the ARMA (1,1) case, however, suggested that it would be quite difficult to solve these more complex cases. Further effort, such as further development of a homogeneous ARMA model of the sort described later in this chapter, is needed to develop practical solutions for these models.

Comparison of Model Applications

The above analysis lead to application of three flow generating schemes so that their results could be compared and evaluated. These were:

1. A bivariate principal components ARMA (1,1) model of the 1937-1977 series with present modified flow using the two principal components shown on Table 27 to give the best results and holding the other three principal components constant.

2. An ARMA (1,0) or Markov model of the 1937-1977 series with present modified flows.

3. An ARMA (1,0) or Markov model of the natural flows followed by transformation of these flows to a present modified basis.

For the purpose of comparing these models only, in each case 21 125-year series were generated. The selection of 21 series was based on a criterion of estimating the mean stage for each year with an accuracy of one foot and formulas provided by Hahn and Shapiro (1967). Parameter values and correlation matrices were computed for each series. The means and standard deviations of each number in the resulting 21 parameter and correlation matrices for the first flow generating scheme are shown in Table 29. The results are compared with the statistics and correlation coefficients of the original data from Table 20 in Table 30.

In comparing the statistics for the generated data on Table 29 with those for the input data on Table 20, one can see that the means are quite close, the standard deviations of the generated data are about half those observed, and the lag-one autocorrelations are much too high. The average error in matching these statistics and the number of correlation matrix elements within various standard deviation fractions of the data values are shown in Table 30 for easier comparison with the results from the other methods. The two principal components used loaded most heavily on evaporation and precipitation respectively, and these were the two sequences that the generated flows matched best.

The ARMA (1,0) or Markov model was then applied. The means and standard deviations of the resulting parameter and correlation matrices from the 21 synthesized 125-year

Table 29. Parameters and correlation matrices generated by using two principal components is an ARMA (1,1) model, present modified flow inputs and 21 sequences of 125 years generated.

Variable	Mean $\hat{\mu}$	Standard Deviation $\hat{\sigma}$	Lag One Auto-correlation $\hat{\rho}(1)$	Hurst[a] h
Evap.	52.00	2.86	-0.459	
Precip.	10.92	1.72	0.178	
Bear	1028614	161138	-0.485	
Weber	358786	50140.3	-0.094	
Jordan	266239	29181	-0.271	

	M_0 Correlation Matrix				
	Evap.	Precip.	Bear	Weber	Jordan
Evap.	1.0	-0.337	0.956	0.880	0.961
Precip.		1.0	-0.611	0.168	-0.041
Bear			1.0	0.693	0.828
Weber				1.0	0.979
Jordan					1.0

	M_1 Correlation Matrix				
	Evap.	Precip.	Bear	Weber	Jordan
Evap.	-0.459	0.340	-0.497	-0.297	-0.373
Precip.	0.314	0.178	0.208	0.420	0.387
Bear	-0.487	0.230	-0.485	-0.385	-0.438
Weber	-0.311	0.444	-0.406	-0.094	-0.188
Jordan	-0.381	0.413	-0.455	-0.183	-0.271

	M_2 Correlation Matrix				
	Evap.	Precip.	Bear	Weber	Jordan
Evap.	0.237	-0.084	0.227	0.204	0.224
Precip.	-0.084	0.162	-0.123	-0.005	-0.039
Bear	0.226	-0.123	0.231	0.173	0.201
Weber	0.204	-0.004	0.173	0.211	0.214
Jordan	0.224	-0.038	0.201	0.214	0.224

[a]Not computed for this model.

sequences are shown in Table 31. In comparing the statistics for the generated data on Table 31 with those on Table 20, one can see that the means are a little low (and lower than those on Table 29 as well), but that a much better match of the standard deviations has been achieved (primarily by preserving the variation in the three series that were not closely associated with one of the two principal components of the ARMA (1,1) solution. The lag one autocorrelations are uniformly lower on Table 31 than they are on Table 29. The matching of the lag-one autocorrelations is much better for evaporation and precipitation and only slightly worse for the three stream flow series. The Hurst coefficients are also on the whole slightly

Table 30. Comparison of generated with original data correlation matrices for alternative generating schemes.

Scheme	1	2	3	4
Model	ARMA (1,1)	ARMA (1,0)		
Data Type	Pres. Mod. F.	Pres. Mod. F	Nat. Flows	Transformed P.M.F.
Historic Data in Table No.	20	20	21	20
Synthesizied Data in Table No.	29	31	32	34
Mean $\Delta\hat{\mu}/\hat{\mu}$[c]	0.00	0.02	0.00	0.24
Mean $\Delta\hat{\sigma}/\hat{\sigma}$[c]	0.50	0.05	0.02	0.21
Mean $\Delta\hat{\rho}(1)/\hat{\rho}(1)$[c]	2.07	0.34	0.22	0.58
Mean $\Delta\hat{h}/\hat{h}$[c]	-[b]	0.27	0.20	-[b]
M_0 Matrix[a]				
Within 0.5 σ	0	7	5	3
0.5 to 1.0 σ	1	3	5	2
1.0 to 2.0 σ	2	0	0	3
Over 2.0 σ	7	0	0	2
M_1 Matrix[a]				
Within 0.5 σ	3	24	25	14
0.5 to 1.0 σ	0	1	0	7
1.0 to 2.0 σ	4	0	0	2
Over 2.0 σ	18	0	0	2
M_2 Matrix[a]				
Within 0.5 σ	3	12	12	9
0.5 to 1.0 σ	1	9	11	7
1.0 to 2.0 σ	3	3	2	3
Over 2.0 σ	18	1	0	6

[a]Number of cases in which the value of the matrix element averaged from the 21 sequences when compared with the corresponding element estimated from the data matched within a range normalized by the standard deviation of the matrix element values generated from the 21 sequences. Total cases are 10 for the M_0, 25 for the M_1, and 25 for the M_2 matrix. More elements within fewer standard deviations suggests a better match.

[b]Values were not estimated for the Hurst coefficient on Tables 29 and 34.

[c]Difference between the data value and the mean of the 21 synthesized values divided by the data value and the resulting ratio averaged over the five flow sequences. A smaller average ratio suggests a better match of simulated to recorded values.

worse. The correlation matrices match quite well overall but exhibit the expected increase in difference for the longer time lags as one goes from M_0 to M_2. Overall the ARMA (1,0) has to be judged superior, largely on the strength of much better matching of $\hat{\sigma}$ and $\hat{\rho}$ for the evaporation and precipitation series and $\hat{\rho}$ for the Weber River flows. These better matches should greatly improve the estimated probabilities for high lake stages.

Finally, the ARMA (1,0) model was applied to the natural flow data. The means and standard deviations of the resulting parameter and correlation matrices from the 21 synthesized 125-year sequences are shown in Table 32. In terms of the matching of the means, standard deviations, and lag one autocorrelations of the original data, this method performed much better than either of the others. As one would expect theoretically, the model is not preserving values for persistence (h) much larger than 0.5. The matching of the correlation matrices is roughly equivalent to that achieved by the same model for the present modified flows. However, since the purpose of the flow generation is to examine lake stage probabilities under present rather than under natural conditions, how well generated natural flow sequences match reconstructed historical ones is not the critical test. One needs to transform these generated natural flows back to present conditions and compare those results with Table 20.

Conversion of Natural to Present Modified Flows

Equation 47 to estimate natural flows from historical data can be reoriented to estimate present flows from generated natural flows. The result is

$$Q_p = Q_n - U_c - D_o + D_i - C_e + C_b \quad . . . (60)$$

where Q_n is the generated natural flow, U_c is the present annual consumptive use estimated at the 1977 value from Table 19, D_i-D_o is the net diversion into the basin estimated as the average annual value over the ten year period 1968-1977, and C_b-C_e is an estimated value of net water withdrawn from reservoir storage during the year.

Regressions were run to estimate the change in basin wide reservoir storage ΔS_t during a year (C_e - C_b) from the storage S_{t-1} at the end of the previous year and N_t^T (C_e - U_c - C_o + D_i). The best regression relationships based on reservoirs existing in 1977 and using the last ten years of data are shown on Table 33. Both variables proved to be significant predictions in all three relationships, and all three show storage to increase in years when the reservoir is down at the beginning of the year and inflow levels are high.

The 21 synthesized 125-year sequences of natural flows were transformed to present modified flows by applying Equation 60 in which the parameters were estimated as shown in Table 33. The means and standard deviations of the 21 values for each parameter and element in the correlation matrices are shown on Table 34. The results are compared with those achieved by the other models for estimating present modified flows in Table 30. From that comparison, one can readily

Table 31. Means and standard deviations of the values for the parameters and correlation matrices computed for the 21 125-year present modified flow sequences generated using an ARMA (1,0) model.

Variable	Mean $\hat{\mu}$		Standard Deviation $\hat{\sigma}$		Lag One Autocorrelation $\hat{\rho}(1)$		Hurst h	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	51.83	0.63	3.83	0.36	0.17	0.10	0.51	
Precip.	10.91	0.30	2.13		0.09	0.10	0.52	
Bear	1054000	104000	441000		0.59	0.08	0.70	
Weber	374000	39000	182000		0.55	0.09	0.72	
Jordan	271000	20000	82000		0.71	0.06	0.72	

M_0 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	1.00	0.00	-0.42	0.11	-0.30	0.07	-0.20	0.11	0.00	0.11
Precip.			1.00	0.00	0.41	0.10	0.34	0.10	0.39	0.07
Bear					1.00	0.00	0.59	0.08	0.67	0.08
Weber							1.00	0.00	0.41	0.11
Jordan									1.00	0.00

M_1 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	0.17	0.10	0.23	0.08	-0.14	0.07	-0.02	0.13	-0.07	0.11
Precip.	0.22	0.10	0.09	0.10	0.19	0.11	0.12	0.12	0.27	0.10
Bear	-0.46	0.06	0.49	0.09	0.59	0.08	0.47	0.11	0.43	0.12
Weber	-0.27	0.09	0.53	0.07	0.58	0.09	0.55	0.09	0.52	0.09
Jordan	-0.14	0.11	0.64	0.05	0.54	0.11	0.49	0.12	0.71	0.06

M_2 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	0.27	0.10	-0.06	0.13	-0.11	0.08	-0.06	0.10	-0.07	0.10
Precip.	-0.03	0.11	0.26	0.10	0.14	0.10	0.11	0.14	0.16	0.12
Bear	-0.20	0.12	0.24	0.12	0.38	0.09	0.26	0.13	0.35	0.12
Weber	-0.12	0.12	0.35	0.09	0.43	0.11	0.35	0.11	0.44	0.10
Jordan	0.00	0.12	0.45	0.07	0.41	0.12	0.36	0.14	0.53	0.10

see that the matching achieved for present modified flows is definitely inferior than that achieved when the ARMA (1,0) model is applied to the recorded present modified flow series directly.

Possible Model and Estimation Procedure Revisions

The results presented in the previous section were disappointing in that the matrices had to be so reduced in solving for coefficient matrices for the ARMA (1,1) model that the results with that model were unacceptable. The Markov model did a better, but not an entirely satisfactory, job. As shown in Table 20, two of the five Hurst coefficients were less than 0.60 and thus in the range where use of an ARMA (1,1) model would not be necessary to preserve persistence. The significantly higher Hurst values for the other three variables, however, strongly recommends a moving average process for better replication. Before accepting the Markov results the best that could be obtained, it was decided to explore ways to revise combinations of ARMA (1,1) model and the parameter estimation procedures to overcome the difficulties that were preventing an acceptable solution.

Analysis of Model Deficiencies

ARMA models are plagued by matrices of observed information which produce unsolvable equations when substituted into the expressions used to estimate the model parameters. Various simplifications have been discovered which permit preservation of selected parameters of the observed sequence but not others

Table 32. Means and standard deviations of the values for the parameters and correlation matrices computed for the 21 125-year natural flow sequences generated using an ARMA (1,0) model.

Variable	Mean $\hat{\mu}$		Standard Deviation $\hat{\sigma}$		Lag One Autocorrelation $\hat{\rho}(1)$		Hurst h	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	51.11	0.30	3.29	0.24	-0.10	0.11	0.50	
Precip.	10.71	0.24	2.19		0.03	0.12	0.50	
Bear	1741000	46000	450000		0.42	0.06	0.57	
Weber	901000	20000	192000		0.34	0.09	0.53	
Jordan	569000	16000	185000		0.07	0.09	0.53	

M_0 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	1.00	0.00	-0.59	0.08	-0.34	0.08	-0.31	0.08	-0.25	0.08
Precip.			1.00	0.00	0.61	0.06	0.47	0.08	0.70	0.04
Bear					1.00	0.00	0.69	0.05	0.58	0.05
Weber							1.00	0.00	0.57	0.07
Jordan									1.00	0.00

M_1 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	-0.10	0.11	0.22	0.11	-0.04	0.09	-0.05	0.11	0.08	0.13
Precip.	0.20	0.11	0.03	0.12	0.28	0.08	0.12	0.08	0.02	0.10
Bear	-0.27	0.08	0.44	0.07	0.42	0.06	0.31	0.09	0.21	0.10
Weber	-0.09	0.08	0.30	0.08	0.39	0.07	0.34	0.09	0.10	0.11
Jordan	0.09	0.10	0.15	0.10	0.37	0.08	0.32	0.06	0.07	0.09

M_2 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	0.11	0.12	-0.08	0.10	0.01	0.08	-0.06	0.09	-0.04	0.09
Precip.	-0.13	0.11	0.22	0.11	0.12	0.09	0.06	0.08	0.10	0.09
Bear	-0.00	0.08	0.11	0.08	0.17	0.09	0.08	0.09	0.06	0.10
Weber	-0.07	0.09	0.18	0.09	0.16	0.11	0.08	0.10	0.07	0.09
Jordan	-0.12	0.11	0.25	0.09	0.17	0.08	0.10	0.08	0.11	0.08

Table 33. Factors for converting natural to present modified streamflows.

River	Consumptive Use U_c	Diversions $D_o - D_i$	Storage Regressions Based on 1968-1977 Data	R^2
Bear	616000	None	$\Delta S_t = 1355644 + 0.07729\ N_t' - 1.2294\ S_{t-1}$	0.88
Weber	442000	39130	$\Delta S_t = 400329 + 0.15518\ N_t' - 1.3481 S_{t-1}$	0.79
Jordan	410000	-123860	$\Delta S_t = 240492 + 0.78784\ N_t' - 0.7184 S_{t-1}$	0.98

Notes:

All units in acre-feet

ΔS_t = change in storage during year $(C_e - C_b)$

S_{t-1} = beginning of year storage (C_b)

N_t' = natural flow less consumptive use and diversions out of the basin $(Q_n - U_c - D_o + D_i)$

t = year

Table 34. Means and standard deviation of the values for the parameters and correlation matrices computed for the 21 125-year present modified flow sequences computed by equations shown on Table 33 from natural flow sequences generated using an ARMA (1,0) model.

Variable	Mean $\hat{\mu}$		Standard Deviation $\hat{\sigma}$		Lag One Autocorrelation $\hat{\rho}(1)$		Hurst h	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	51.14	0.39	3.27	0.25	-0.04			
Precip.	10.68	0.33	2.20		0.07			
Bear	1291000	241000	463000		0.49			
Weber	562000	170000	172000		0.45			
Jordan	362000	107000	135000		0.49			

M_0 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	1.00	0.00	-0.59	0.08	-0.37	0.09	-0.35	0.10	-0.09	0.12
Precip.			1.00	0.00	0.65	0.08	0.55	0.07	0.43	0.15
Bear					1.00	0.00	0.75	0.07	0.52	0.07
Weber							1.00	0.00	0.51	0.09
Jordan									1.00	0.00

M_1 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	-0.04	0.09	0.18	0.08	-0.03	0.10	-0.04	0.10	0.04	0.10
Precip.	0.14	0.08	0.07	0.12	0.32	0.08	0.18	0.10	0.09	0.09
Bear	-0.34	0.09	0.49	0.08	0.49	0.09	0.37	0.11	0.16	0.09
Weber	-0.19	0.11	0.40	0.12	0.50	0.11	0.45	0.12	0.15	0.13
Jordan	-0.15	0.16	0.57	0.21	0.63	0.14	0.63	0.17	0.49	0.23

M_2 Correlation Matrix

	Evap.		Precip.		Bear		Weber		Jordan	
	Mn	SD	Mn	SD	Mn	SD	Mn	SD	Mn	SD
Evap.	0.08	0.08	-0.02	0.09	0.01	0.09	-0.03	0.11	0.04	0.09
Precip.	-0.14	0.09	0.21	0.09	0.14	0.07	0.08	0.10	0.02	0.09
Bear	-0.04	0.08	0.11	0.08	0.18	0.08	0.09	0.09	0.02	0.12
Weber	-0.09	0.11	0.22	0.11	0.22	0.11	0.08	0.09	0.08	0.12
Jordan	-0.07	0.10	0.36	0.12	0.44	0.15	0.37	0.20	0.24	0.15

(O'Connell, 1974; Matalas and Wallis, 1971). Since model parameters are estimated from observed sequences that contain significant measurement error, the system parameters estimated from the observed data are also not without error. The following question therefore deserves attention. Is the failure of the models to preserve estimated parameters due to failure of the model to approximate nature or due to a sensitivity of parameter estimation for the model to errors in estimation that cannot be prevented because of limitations to the precision with which the data are measured.

A simulation experiment was tried to gain insight on this issue. For this experiment, 100 sets of two dimensional random sequences of length 20 were generated with the ARMA (1,0) model of Equation 50 with

$$A = \begin{pmatrix} .9 & 0 \\ 0 & -.9 \end{pmatrix}, \quad B = \begin{pmatrix} \sqrt{.19} & 0 \\ 0 & \sqrt{.19} \end{pmatrix}$$

and the $\varepsilon(t)$ vector being independent standard normals. For each of the 100 sequences, M_0 and M_1 were estimated. For 7 of the 100 sequences, the estimated M_0 and M_1 violated the constraints of the model. Since the data originated from Equation 50, violation of the constraints is at least an occasional result of using statistics from a short period of record (approximately 20 years).

An alternate method of estimation may reduce the problem, e.g., the method of maximum likelihood (ML). In addition to providing parameter estimates for the situation in which the method of moments as given by O'Connell (1974) fails, it has recently been shown (Ledolter, 1978) that the ML method is generally better in large samples. That is, the parameter estimates have greater asymptotic relative efficiency when compared with those by the method of moments. However, the ML method requires numerical optimization programs. In application to systems with many multivariate components, estimation can be very expensive if not impossible. For the data under consideration, optimization on 50 variables is required. In addition, the optimization follows an iterative scheme that must be repeated several times in the process of obtaining estimates.

Ledolter (1978) has also pointed out an inconsistency in multivariate autoregressive models. He has shown mathematically that in the general case, the order of individual series contained within a multivariate autoregressive model of order p may be of order greater than p. This generality does not seem necessary. Indeed, in most applications of multivariate analysis, it is more reasonable to generalize from the univariate to the multivariate while preserving the order of the univariate model.

There is a similar inconsistency in the multivariate moving average process. The univariate model (ARMA (0,q) may be represented by

$$X(t) = \varepsilon(t) - e_1\, \varepsilon(t-1) - e_2 \varepsilon(t-2) - \dots e_q \varepsilon(t-q) \quad \dots\dots\dots (61)$$

and in the multivariate case:

$$\underline{X(t)} = \underline{\varepsilon(t)} - E_1 \underline{\varepsilon(t-1)} - \dots - E_q \underline{\varepsilon(t-q)} \quad \dots\dots\dots (62)$$

It is easily observed that for arbitrary E_i's, vector subsets of $\underline{X}(t)$ are not ARMA (0,q). Consider for example the first element in $\underline{X}(t)$,

$$x_1(t) = \varepsilon_1(t) - e_1{}' \underline{\varepsilon(t-1)} - \underline{e}_2 \underline{\varepsilon(t-2)} - \dots - \underline{e}_q{}' \underline{\varepsilon}(t-q) \quad \dots\dots\dots (63)$$

where $\underline{\varepsilon}_1(t)$ is the first element of $\underline{\varepsilon}(t)$, and b_i's are the ith row of E_i. Equation 63 is not of the form of Equation 62 due to the complexity of the error structure at the t-1, t-2, ..., t-q times.

This difference in form suggests the possibility of restricting the multivariate ARMA (p,q) model in such a way that every univariate vector is ARMA (p^*,q^*) where $p^* \leq p$ and $q^* \leq q$ and of using this restriction as a means of establishing parameter matrices which can be solved. For example, one vector of an ARMA (1,1) model could be (1,0), but none could be (2,1). ARMA models which possess this characteristic are denoted homogeneous ARMA (p,q) models. The technique achieves considerable simplification of parameter estimation at little sacrifice of generality.

Homogeneous ARMA (p,q) Models

The following theorem states the conditions under which an ARMA (p,q) model is homogeneous. Note that the conditions are "if and only if," i.e., no further simplifications nor generalizations can be made and still preserve the homogeneous character of the model.

Theorem. The ARMA (p,q) model (Equation 49) is homogeneous if and only if the matrices C_i, i = 1, 2, ..., p and E_i, i = 1, 2, ..., q are diagonal.

Proof. The "if" portion of the proof is immediate. Every vector subset of the original variable has the model formed by taking the corresponding subset of the rows of the C_i and E_i matrices. Since these are diagonal, the subset matrix of the rows can be redefined to be diagonal and the $\underline{\varepsilon}$ vector shortened to include only those elements necessary.

The "only if" portion of the proof is most easily accomplished by assuming that one (or more) of the C_i and/or E_i have one or more off-diagonal elements that are non zero. If there is one off-diagonal element of an C_i that is non zero, then it follows directly from the proof of the inconsistency referred to in Ledolter (1978) that there exists a marginal univariate model with autoregressive order greater than p.

Suppose there is one non zero off-diagonal element of a E_i, i = 1, 2, ..., q. Without loss of generality, suppose it is the 1,2 element of E_i. Then Equation 63 represents the moving average portion of the first element of $\underline{X}(t)$ i.e., $x_1(t)$. Thus the vector $\underline{b}_1{}^T$ in Equation 63 results in the inclusion of the second element of $\underline{\varepsilon}(t-1)$ into the model for $x_1(t)$. Since this element cannot be incorporated in the "error" term at time t (i.e., $\varepsilon_1(t)$), the error structure does not have the univariate moving average form.

It has been shown that no off-diagonal elements of C_i, i = 1, 2, ..., p nor E_i, i = 1, 2, ..., q can be non zero or the ARMA (p,q) model will not preserve at least one univariate subset. The theorem is proved.

For the multivariate case, Ledolter (1978) has shown that maximum likelihood estimators are preferred over those obtained by the method of moments. Maximum likelihood estimation for the non-homogeneous model involves n^2 (p + q + 1) parameters, where n is the dimension of X(t) in the model. A numerical optimization is required which involves n^2(p + q) parameters. Thus for a system with five variables, the simplest ARMA model exhibiting long term persistence in finite sequences (i.e., ARMA (1,1)) requires numerical optimization for 50 parameters. By contrast the homogeneous model involves n (p + q + n) parameters and numerical optimization on n (p + q) of them. For the five variable case, this is 10 parameters as opposed to 50. Numerical optimization on 50 variables seems questionable while on 10 it is reasonable.

Although maximum likelihood estimation is more efficient than the method of moments for multivariate models, it is not necessarily best for the univariate case. The method of moments with the bias correction given by O'Connell (1974) has the distinct advantage of preserving observed long term persistence in synthetic sequences. This persistence is usually measured by the Hurst coefficient. In O'Connell's formulation, the Hurst coefficient is a parameter in the univariate case. Unfortunately, this parameterization and the bias correction is lost in the multivariate case. It is possible using the homogeneous models to take advantage of O'Connell's method to estimate the n (p + q) parameters which are the diagonal elements of the C_i, i = 1, 2, ..., p and E_i, i = 1, 2, ..., q. Then the conditional maximum likelihood method can be used to estimate the n^2 elements of the variance-covariance matrix of the $\varepsilon(t)$ random variable. This estimation technique has the advantage of preserving a measured persistence in the univariate series and of requiring no numerical optimization procedures. However, it requires information which may be difficult to obtain in many cases. O'Connell (1974) has prepared tables for the ARMA (1,1) case only; however, this case is important in applications.

In the absence of empirical validation of the homogeneous models (testing with natural data), it is important to investigate on intuitive grounds the effect of the restrictions as compared with the general ARMA models. The most notable effect due to the diagonal nature of the C_i and E_i matrices is that the historical contribution to the present value of a given element of the random vector $\underline{x}(t)$ is limited to the historic values of that same element. This does not at all imply independence because the present "error" (i.e., $\underline{\varepsilon}(t)$) can be a correlated random vector. As time progresses, e.g., as time t becomes t+1, the values in $\underline{\varepsilon}(t)$, as they contribute to the then present values of $\underline{x}(t)$, contribute to the new present value only as modified by a constant specific to each element in $\underline{\varepsilon}(t)$. For example, suppose the homogeneous model were used to model yearly volume of several streams in a large basin. The restrictions imply that for a given stream, the present flow volume is due to the present and past "errors" (precipitation) and past streamflow in that stream drainage area and no other areas. The "errors" may be correlated, but what actually happened in the past in the given area is what influences streamflow in that area. This implies that if, for example, one stream in the system receives considerable recharge from groundwater originating in the area of another stream in the system, the homogeneous model would not be applicable.

In conclusion, the restrictive assumptions in the homogeneous ARMA model seem rather small in comparison with the advantages the model has in making maximum likelihood parameter estimation computationally feasible. Since the method of moments produces biased parameter estimates that cause modeling problems and maximum likelihood techniques require too many parameters to be computationally feasible for complex multivariate or multilag models, the above homogenous approach provides a real possibility that deserves further exploration for such cases as occur when a number of variates need to be generated or multiple lags (p or q > 1) are required. Multiple lags are required to reproduce series where lag-two correlations exceed lag-one correlations because of long aquifer travel time or the long carryover storage periods in large reservoirs. Further development of this model and appropriate parameter estimation techniques was not possible within the scope of this study, but continued work is highly recommended. For immediate application, it was necessary to choose from among the other models.

Transformation of Generated Series to Flows, Precipitation, and Evaporations

Since M_0, M_1, and M_2 are cross-correlation rather than cross-covariance matrices, the sequences generated by Equations 50 and 51 are all in the form of standardized normal distributions of zero mean and unit variance. Up to three transformations thus must be performed to convert the generated data to present modified flows, and these transformations were used to produce the data summarized in the statistics on the top of Tables 29, 31, and 32. The three transformations are:

1. Destandardization to convert the distribution of synthetic flows from N(0,1) to N(μ,σ).

2. Transformation from N(μ,σ) to 3LPN (μ^T, σ^T, a) for those variables (all except precipitation) for which the original series have skewness coefficients exceeding 0.1.

3. Conversion of streamflow series to acre feet by an area of 1,079,259 acres.

Computer Programming

All of the computations required to input raw data provided in the form shown on Table 15 (i.e., all records complete for a uniform time period), perform the necessary analyses and transforms, and estimate the parameter matrices for the multivariate stochastic model are performed on a computer program documented in Appendix D. The documentation includes a program listing, a description of the required input, explanation of the generated output, and a dictionary of variables.

The programming to use the estimated parameter matrices in generation of the desired time series and transform those series from their generated standardized normal form to natural or present modified series are similarly documented in Appendix E.

Selection of a Model for Subsequent Damage Analysis

The Markov ARMA (1,0) model calibrated to match present modified flow relationships during the 41-year period from 1937 through 1977 was selected as the option in the computer program best meeting the needs of this study. Present conditions for initializing stage sequences generated with the model were established by the October 1, 1978, lake level of 4198.6 feet.

CHAPTER 5

HYDROLOGIC EVALUATION OF LAKE LEVEL CONTROL ALTERNATIVES

Introduction

The end product desired from this study was a model that could be used to estimate benefits for various lake control alternatives. Since the benefits amount to the reduction in expected damage from lake level fluctuation that a level control program achieves, the key step in the analysis is to develop a capability to model how lake level fluctuation patterns are altered by control alternatives. One needs to predict how each alternative affects inflows and outflows for the lake, the stage-area-volume relationship, or any other parameters changing the lake water balance. For this reason, it was necessary to identify the likely control alternatives, describe how they function to control lake levels, and represent them within the lake water balance model as options that the user can call as needed to evaluate the alternative.

Control Alternatives

The three concepts most frequently mentioned for lake level control or damage reduction on the Great Salt Lake are:

1. Develop upstream consumptive uses (such as irrigation) for Bear River water to reduce inflows to the Great Salt Lake (Riley, 1978).

2. Pump the water from the Great Salt Lake into the western desert for evaporation. (At the requestion of the Utah Division of the Great Salt Lake this alternative was studied by the U.S. Army Corps of Engineers, 1976.)

3. Construct dikes to protect vital areas from flooding as the lake rises (Utah Water Research Laboratory, Section V, 1977).

A fourth alternative is to do nothing and gamble that the lake will not rise to cause excessive damage. Should it begin to do so, one may presuppose that from a political standpoint alone some action would have to be taken and people would ask "was enough done soon enough?"

The fifth alternative would combine the three control concepts. One would theoretically expect there to be some mixture of diking, upstream consumptive use, and pumping that would be better than using any one of these options exclusively.

The expected damages associated with the fourth alternative would be estimated by the basic damage model. The need is to examine the first three alternatives to determine how they affect the lake water balance and how those effects can best be represented quantitatively in a model. It was also necessary to consider any special problems that might be caused by trying to model effects of using more than one measure simultaneously.

Increasing Consumptive Use Within the Bear River Basin

The second strategy for regulating the fluctuating water levels of the Great Salt Lake is to irrigate additional land to increase consumptive use only during high flow years. Permanent increases would have the adverse effect of aggravating the problems caused by low lake levels.

This strategy has considerable appeal in an arid climate since it uses "surplus" fresh waters before they become mixed with the lake brines and lose much of their economic value. It is also associated with considerable difficulty because implementation of a plan to use water for agriculture only during wet years would have to overcome many physical, economic, and social and institutional problems.

The only tributary stream to the Great Salt Lake which contains significant irrigable, but not yet irrigated, land is the Bear River. Fortunately, this river contributes an estimated 56 percent of the total gaged streamflow into the Great Salt Lake, enough water to provide the needed lake level regulation. There are approximately 1,000,000 acres of arable land within the Bear River Basin. An additional 600,000 acres to the west of the basin in the Blue Creek, Hansel, and Curlew Valleys could be irrigated from the Bear River. Of the 1,000,000 irrigable acres within the Bear River Basin, approximately half are already being irrigated.

Riley (1978) suggested that increasing consumptive use be explored by beginning with a plan for irrigating on a continuous basis all those lands to which irrigation water could be supplied at benefit/cost ratios of one or greater. The additional irrigation would increase water usage and both the high and low water levels in the lake. In addition, Riley proposed that as rising stages bring the lake level close to a point of causing major damage, additional lands be irrigated with those where B/C ratios were closest to one being brought under irrigation first. If lake levels continued to rise, still additional lands would be irrigated until the desired regulation was achieved. Under falling lake stages, irrigated areas would be reduced in reverse order.

Hydrologic modeling of the effect of this alternative on lake levels needs to represent how the irrigation changes the time series of inflows from the Bear River. The required computations are obviously much more complex than those required for the diking alternative. An exact representation would have to simulate a reservoir operating policy for adding and deleting marginal irrigated areas and the consequences of that policy on how much water would be stored in a given year, how much would be used for irrigation, and how much return flow would get back into the lake. Until it is established that this alternative is sufficiently promising to warrant analysis in this detail, the planned approximation was to make the liberal assumption that whatever increase in consumptive use is necessary to achieve a targeted degree of lake level control can be accomplished. If such an idealistic project does not produce enough benefits to justify new irrigation projects, there would be little hope for a more realistic one.

Pumping to the Western Desert

In 1976, the Corps of Engineers was requested by the Utah Division of the Great Salt Lake to evaluate "alternatives dealing with a possible contingency plan to pump water from the lake to the desert area west of the lake." The Corps (1976) provided a reconnaissance design with associated costs, hydrologic evaluations, and a cursory investigation of possible adverse effects to the west desert area including the Hill Air Force Bombing Range. The concept was to pump water from the Great Salt Lake during periods of high lake stages, spread the water over a confined area of the adjacent west desert, and return water saturated with salt to the lake to avoid losing the lake's valuable mineral resources to the desert salt deposits. The structural features included an intake channel from the south arm of Great Salt Lake to a pumping plant to lift the water about 30 feet, a conveyance canal, a holding area, and a drainage channel back to Great Salt Lake. Three alternatives were costed with the variable being the amount of water to be pumped from the lake. The most modest design would pump up to 1000 cfs to a holding area that could contain 137,000 acre feet between two dikes. During a year, 520,000 acre feet would be pumped from the lake, 210,000 would be returned through a 600 cfs capacity channel, and 310,000 acre feet would be evaporated.

Hydrologic representation of this process requires specification of lake elevations at which to begin and end pumping and of pumping rates. Within a year, the desert holding area may damp lake level fluctuation by being filled during spring highs and emptied during fall lows, and the relationship between end-of-the-year and annual peak lake level may need to be modified. If the return flow canal also returns salts dissolved from the western desert and increases the lake's salt content, evaporation may be slightly reduced.

Diking Alternative

The diking alternative employs levees to provide flood protection to specific properties. A levee section for reconnaissance design (Utah Water Research Laboratory, 1977) was patterned after the Willard Bay diking system designed by the U.S. Bureau of Reclamation. This design has on the lake side an embankment slope of 10:1 to the design level lake elevation. A 6-foot freeboard above this elevation has a slope of 2.5:1 and is protected from wave action by rip-rap. The top width of the dike is 25 feet, and the downstream or land side of the embankment is designed with a slope of 2:1.

Possible dike locations were plotted by Riley as shown on Figure 7. If the bird refuges at Bear River Bay and at the mouth of the Weber River are to be protected by levees, pumping plants will be required to lift the flows of the two rivers into the Great Salt Lake. Protection of all bird refuges, mineral companies, and highways requires construction of dikes 1, 2, 4.5, 5, 6, 7, 8, 9, 10, 11, 15, 17, 19, 20, 21, 22, 23, and 24. Dikes 15 and 19 would each require a pumping plant. In summary, Riley's reconnaissance found diking attractive in terms of its flexibility as to area protected and for building and then raising later if needed, its cost with a range of likely economic feasibility, lack of interference with other uses of the lake, and the fact that it can be designed and operated independently of upstream land and water uses.

Each dike would prevent flooding on its landward side, reduce the volume of water stored in the lake at a given stage, cause the lake as a whole to be a little higher, and consequently slightly increase damages to unprotected property. The principal information required to analyze the effect of diking alternatives on lake levels would be data on how much the dikes reduced the surface area and volume of water in the lake at various elevations. The result would be a revised stage-area-volume relationship.

A second need would be a planned course of action as water levels rise to overtop levees and programming of that plan in the water balance model. The pumping plants at the mouths of the rivers could not be economically designed to pump river flood peaks over the dikes and would thus require some upstream freshwater storage. When rising lake levels threaten to overtop the dikes, it may well be better to reduce pumping rates and add to upstream fresh water flooding rather than continue pumping until other dikes are overtopped and the areas behind flooded with salt water. In summary, a planned sequence of levee failure may increase benefits, and hydrologic modeling representation of alternative sequences may be helpful.

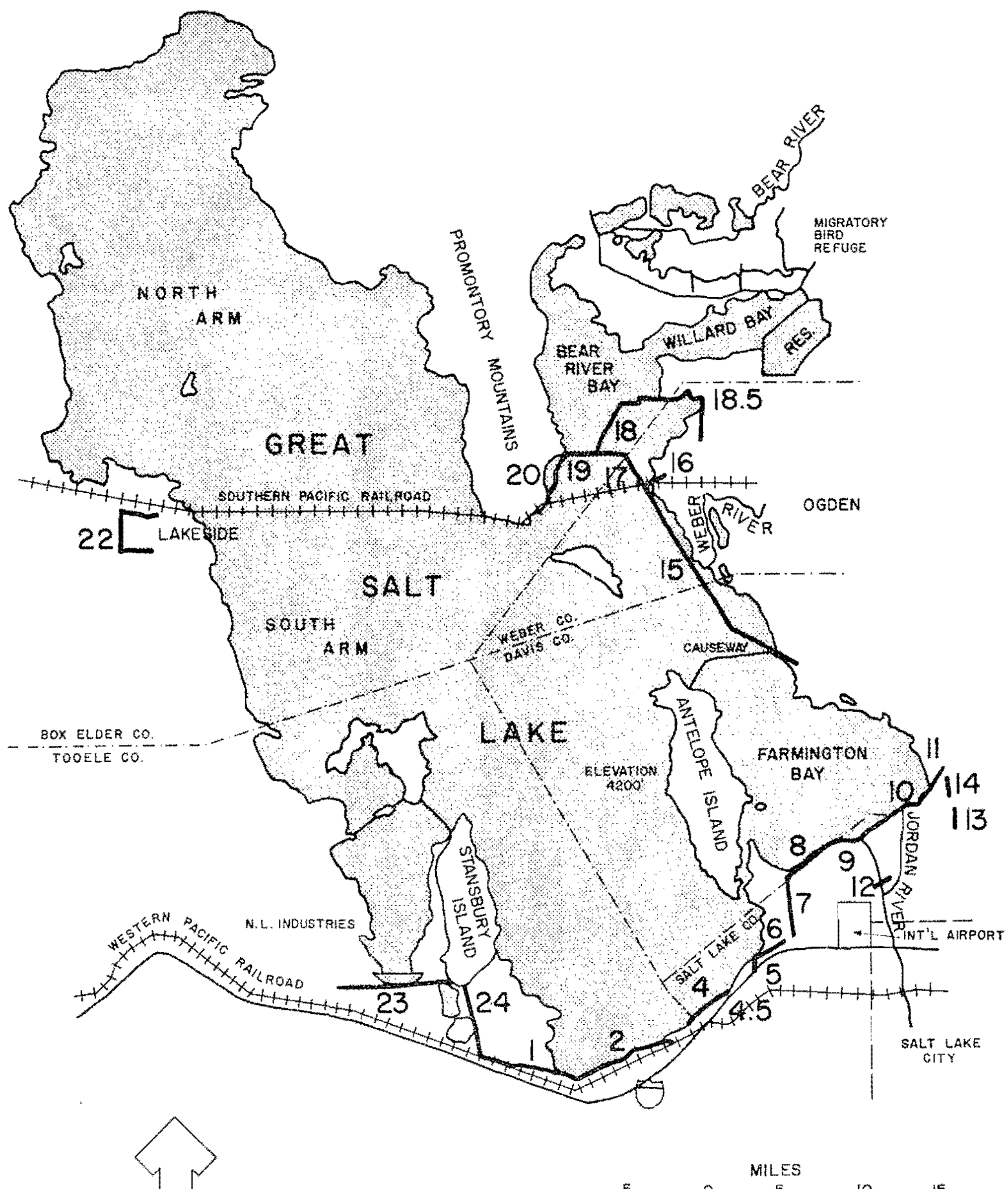


Figure 7. Alternative dike layout configurations indicating dike section numbers.

CHAPTER 6

LAKE WATER BALANCE MODEL

Purpose of the Model

For each year, a lake water balance model starts from the water volume at the beginning of the year and adds lake inflows and subtracts evaporation losses to estimate end of the water year volume, stage, and surface area. Historic sequences of lake stage can be simulated from an initial stage and historic sequences of inflows and evaporation. Alternatively, inflow sequences can be adjusted to represent, for example, natural flows, and the model can be used to estimate a sequence of lake stages that would have occurred under natural inflow conditions. The major role of the lake water balance model in this study is to convert stochastically generated sets of sequences of streamflow, precipitation, and evaporation to corresponding sequences of lake stages. The lake water balance model may also be used to study the effectiveness of various schemes for controlling lake stages by adjusting the changed inflows, outflows, or lake characteristics.

Lake Water Balance Algorithm

A lake water balance model developed by the Utah Division of Water Resources (1974) for application to the Great Salt Lake was adapted in this study. The form of the model is generally applicable to terminal lakes although some of the relationships (e.g., Equations 65 and 66) would need to be recalibrated before one could apply the model to another lake. The basic relationship for the model is the water balance equation:

$$V_t = V_{t-1} + Q_{B,t} + Q_{W,t} + Q_{J,t} + S_t + G_t + (p_t - e_t)A_{t-1} \quad . . . . (64)$$

in which

V_t = volume of lake at the end of the t^{th} water year (ac ft)

$Q_{B,t}$ = surface inflow from the Bear River in the t^{th} water year (ac ft)

$Q_{W,t}$ = surface inflow from the Weber River in the t^{th} water year (ac ft)

$Q_{J,t}$ = surface inflow from the Jordan River in the t^{th} water year (ac ft)

S_t = ungaged surface inflow from small streams during the t^{th} water year (ac ft)

G_t = subsurface inflow during the t^{th} water year (ac ft)

p_t = precipitation on the lake during the t^{th} water year (ft)

e_t = evaporation rate from the lake during the t^{th} water year (ft)

A_t = lake surface area at the beginning of the t^{th} year (ac)

In applying Equation 64, the initial stage can be translated into corresponding values for the lake surface area (A_{t-1}) and volume (V_{t-1}) from the surface areas and storage volumes for various Great Salt Lake stages given in Table 35. Annual totals for the flows represented by all the other terms on the right side of Equation 64 are then used to calculate V_t one year later. V_t becomes V_{t-1} for the next application, and the information in Table 35 can then be used to determine a corresponding A_{t-1}. The water balance computations can then proceed iteratively for as many years as flow information is available.

Of the seven flow variables on the right side of Equation 64, five ($Q_{B,t}$, $Q_{W,t}$, $Q_{J,t}$, P_t, and e_t) are generated by the multivariate model. Two (S_t and G_t) were not, primarily because the necessary data series were not available. For this study, these variables were estimated from the relationships:

$$S_t = 0.08\,Q_t = 0.08\,(Q_{B,t} + Q_{W,t} + Q_{J,t}) \quad . . . (65)$$

$$G_t = 0.07\,Q_t + 0.04\,Q_{t-1} + 0.02\,Q_{t-2} \quad . . . . (66)$$

The coefficients in Equations 65 and 66 were obtained by UDWR (1974) through a trial-and-error calibration by using historic inflow, evaporation, and lake stage data in Equation 64. The calibration was confirmed in this study (Figure 8).

Evaporation is input to the model as fresh water equivalent evaporation. The reduction in evaporation caused by salinity is estimated by approximating the relevant portion of Figure 10 with the linear equation:

$$e_t = e_t^T (1 - 0.00833\,C_t) \quad . . . . (67)$$

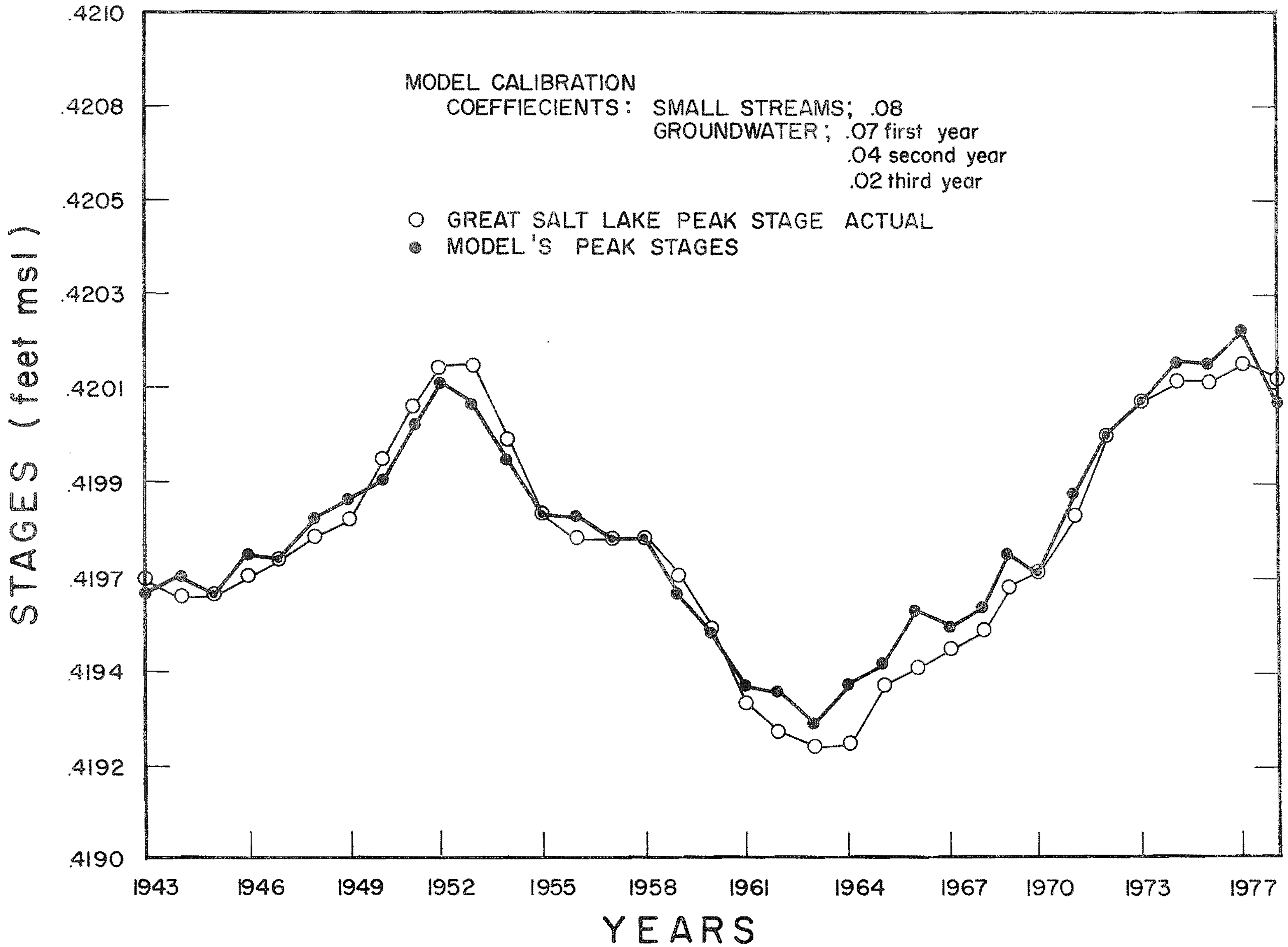


Figure 8. Results with the calibration of small streamflow and groundwater inflows selected for the water balance model.

Table 35. Stage-volume and stage-area data for the Great Salt Lake.

Water Surface Elev. ft (msl)	Surface Area acres	Volume acre-feet
4170	160000	161000
4180	2950500	407000
4184	4732990	482000
4186	5724620	509034
4188	6768670	535056
4189	7311200	550000
4190	7868300	564196
4191	8440400	580000
4192	9030560	601861
4193	9645950	632676
4194	10301090	677888
4195	11002040	719964
4196	11749730	772964
4197	12556430	839809
4198	13421890	890047
4199	14350140	969949
4200	15370180	1079259
4201	16481450	1140000
4202	17640700	1175000
4203	18828700	1201000
4204	20040700	1223000
4205	21276000	1250500
4206	22542000	1330000
4207	23808000	1375000
4208	25075000	1410000
4209	26341000	1450000
4210	27607000	1490000
4211	29800000	1530000
4212	30700000	1570000
4219	43200000	2000000

in which

e_t^T = fresh water equivalent lake evaporation in the t^{th} water year (ft)

C_t = mean lake salinity in percent up to a maximum value of 27.5 at saturation

C_t is calculated by the model by dividing the total weight of salt in the lake (4.7×10^9 tons) by the total weight of water ($62.4 \times 43560\ V_t/2000$), multiplying by 100, and truncating the value of C_t at its saturation value when lake levels are low.

The model applies Equation 64 in annual time steps from the end of one water year to the end of the next. However, the annual peak stage, which usually occurs between April and July on the Great Salt Lake, is of primary concern for a study of lake stage control measures. To account for the fact that the lake peaks after the spring runoff water rather than at the end of the water year, the peak stage is estimated by using the fractions of the annual lake inflows and evaporation that have occurred historically before the date of the recorded peak. By substituting these fractions in Equation 64, the water balance is written:

$$V_{p,t} = V_{t-1} + 0.75\,(Q_{B,t} + Q_{W,t} + Q_{J,t} + S_t + G_t) + 0.71\,p_t A_t - 0.30\,e_t\,A_t \quad . \; . \; . \; . \; (68)$$

in which

$V_{p,t}$ = estimated peak lake volume during the t^{th} water year

$V_{p,t}$ is used to establish lake stages for estimating damages from high water while V_t is used to establish stages for estimating damages from low water since the end-of-the-water-year lake level is usually near the minimum value.

The input data options available in the lake water balance model are shown in the flow diagram of Figure 9. The strategy used to evaluate the hydrologic effects of the three lake stage management options is also depicted. The computer programming is documented in Appendix E with a program listing, input and output descriptions, and a dictionary of variables.

Options in Model Application

Application Alternatives

The water balance model may be applied either with historical data for calibration or validation purposes or with generated flows to estimate probabilities for future lake stages. In historical applications, one can estimate unmeasured quantities (such as subsurface inflow and ungaged streamflow to the Great Salt Lake or flows during gaps in the historical record) as those giving the best match of historical stages. In probability applications, one begins from flows generated stochastically and representing homogeneous watershed conditions. If the homogeneous data are based on natural conditions, they must be transformed to reflect present conditions in order to calculate present probabilities. If future probabilities are desired, one either has to assume that present conditions will continue into the future or further transform the data to represent some selected scenario of future changes. For this study, the assumption was no change into the future other than the lake control alternatives explicitly considered. Provision is made in the model for the user to select from among the various options according to the desired application.

Methods for Specifying Input Data

Four options are provided for specifying the input time series (Figure 10). The first option reads time series of precipitation, evaporation, and streamflow data at three sites. This option was used with historical data to calibrate Equations 65 and 66. The second option uses a constant annual evaporation rate and can be used when evaporation time series data are not available.

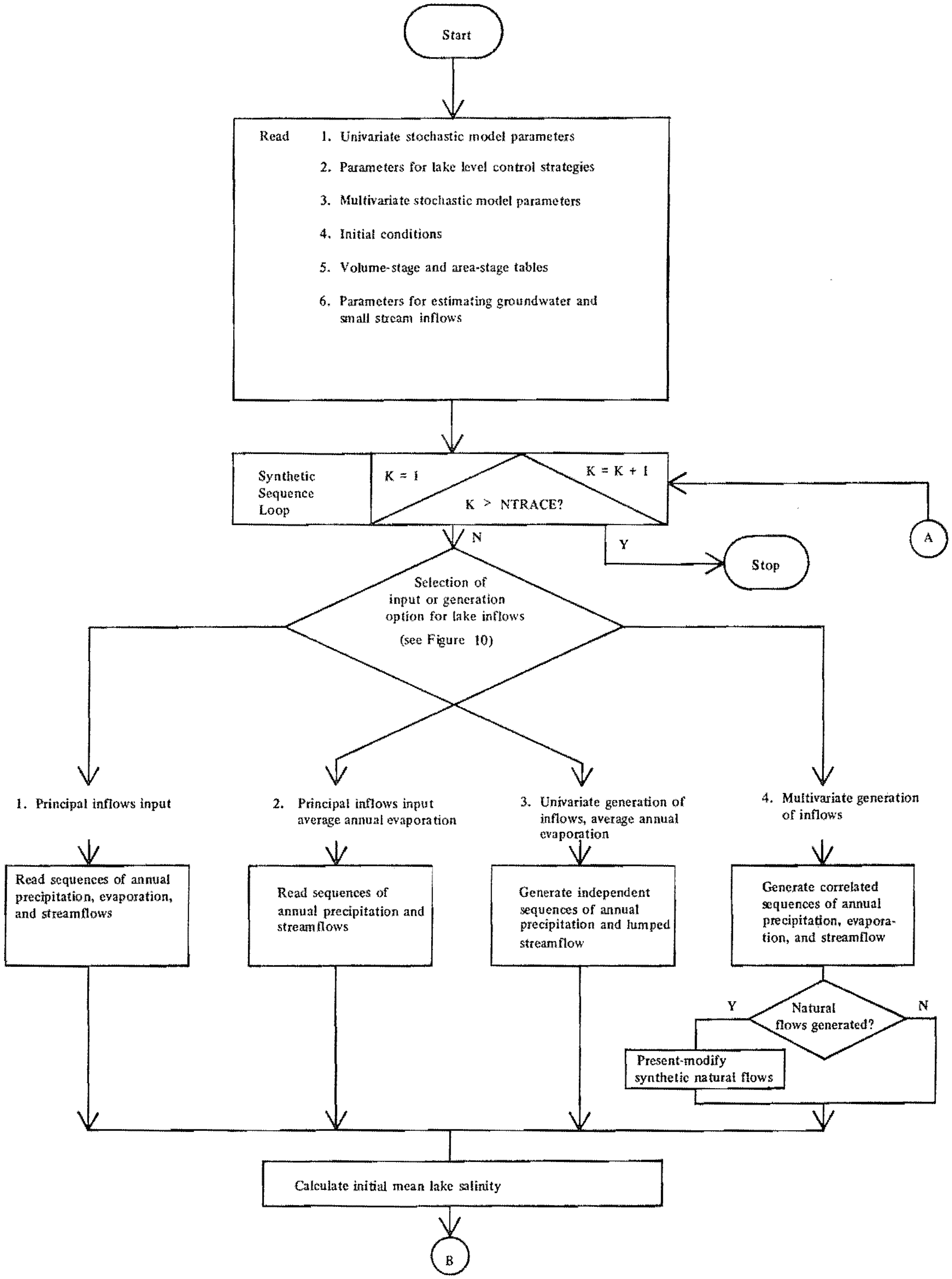
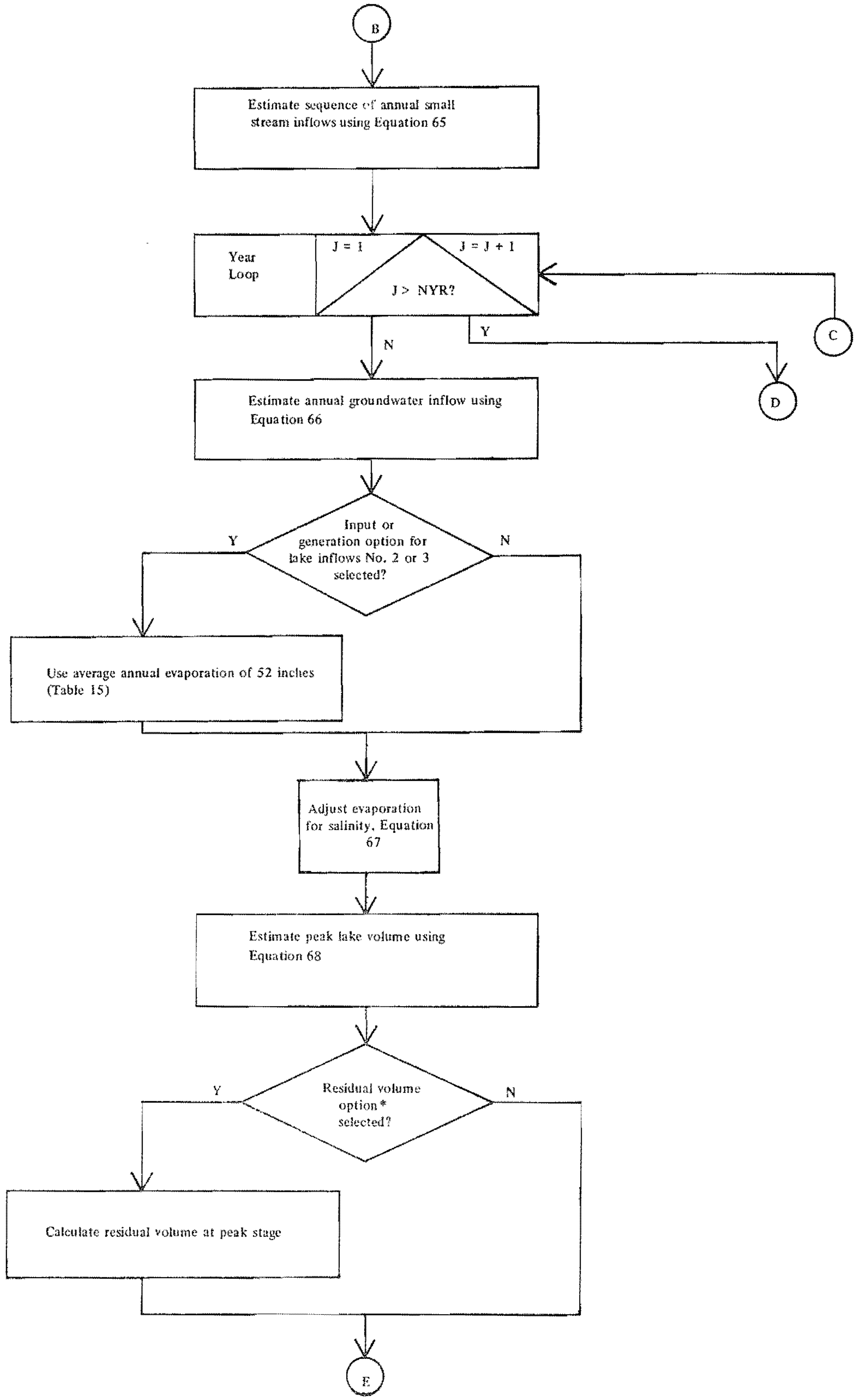


Figure 9. Flow diagram for the lake water balance model.



*The residual volume option calculates the volume of inflow or outflow necessary to match historic lake stages after accounting for all specified inflows.

Figure 9. Continued.

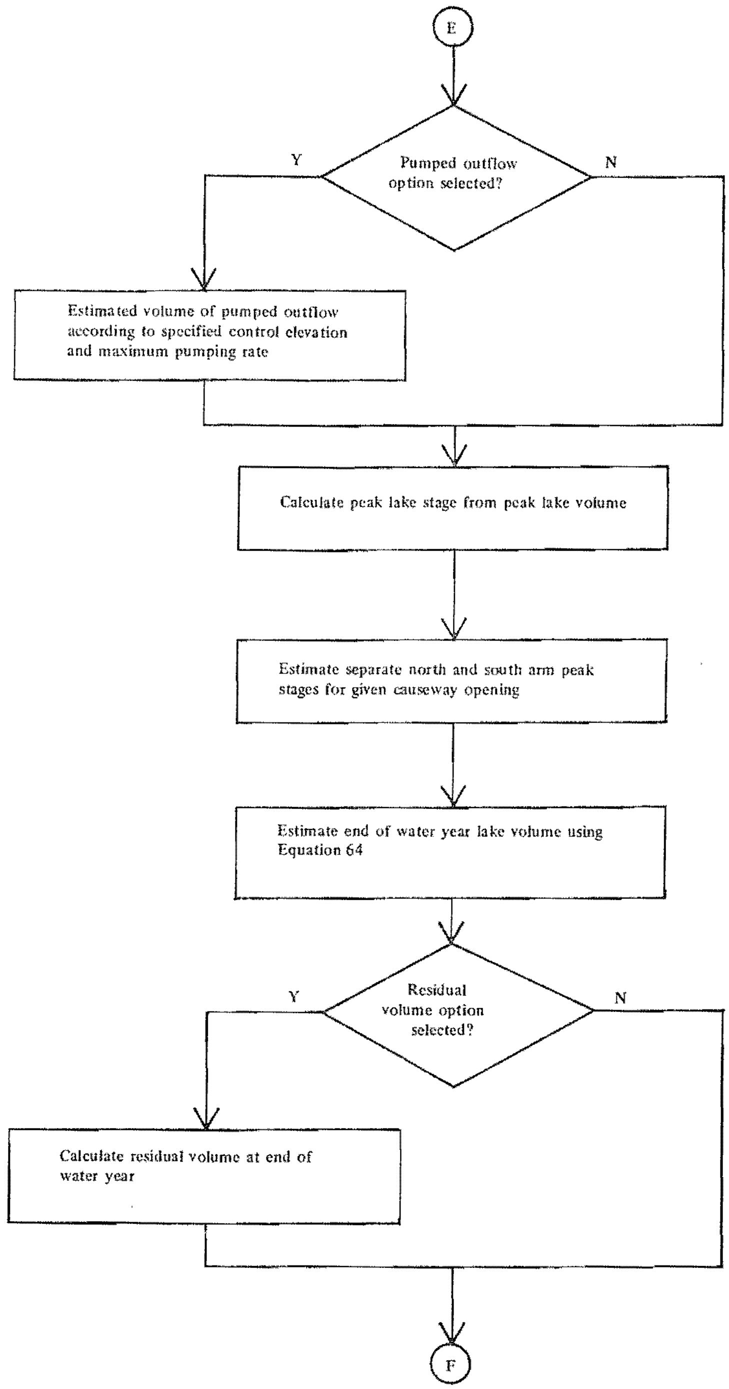


Figure 9. Continued.

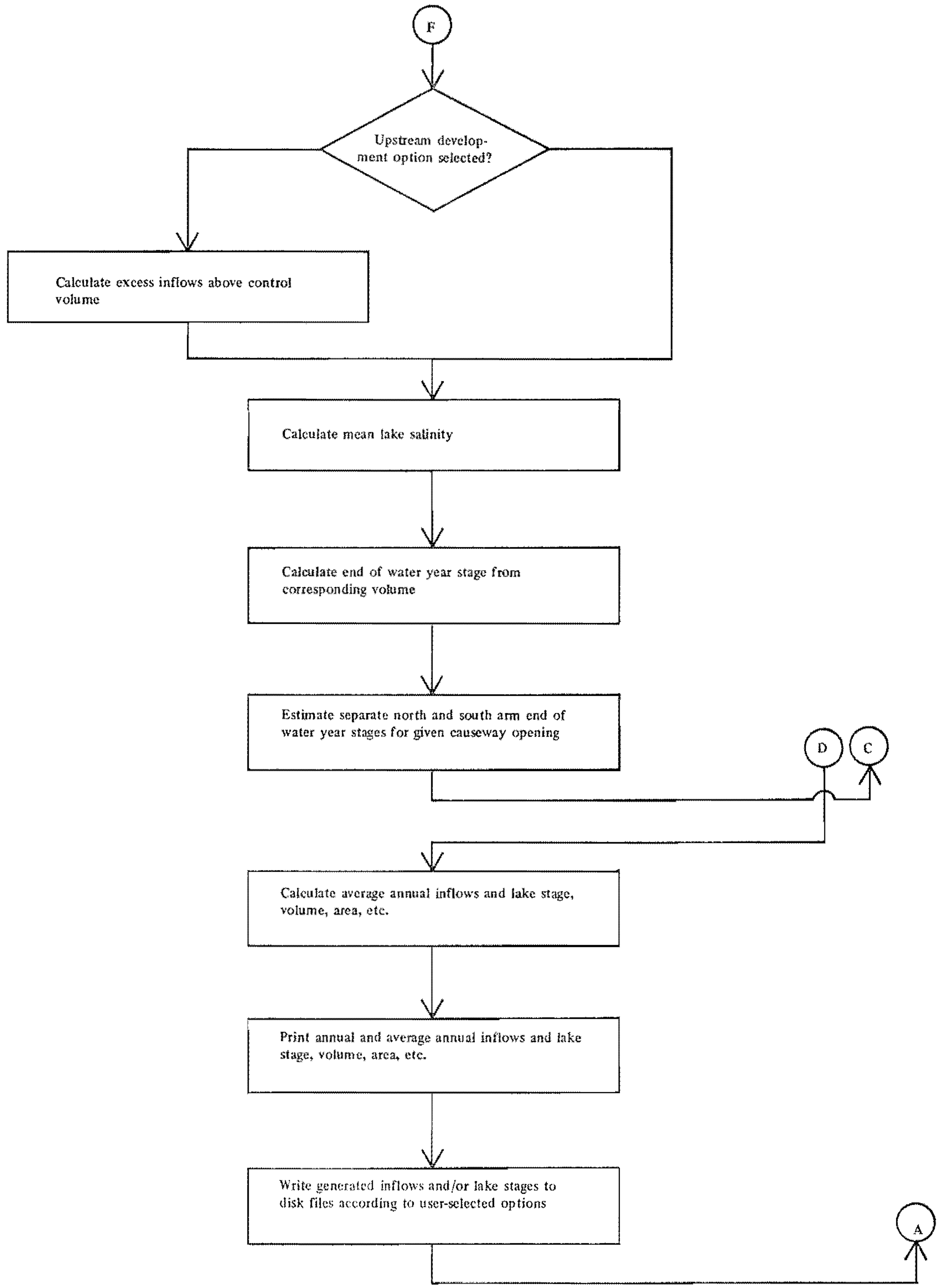


Figure 9. Continued.

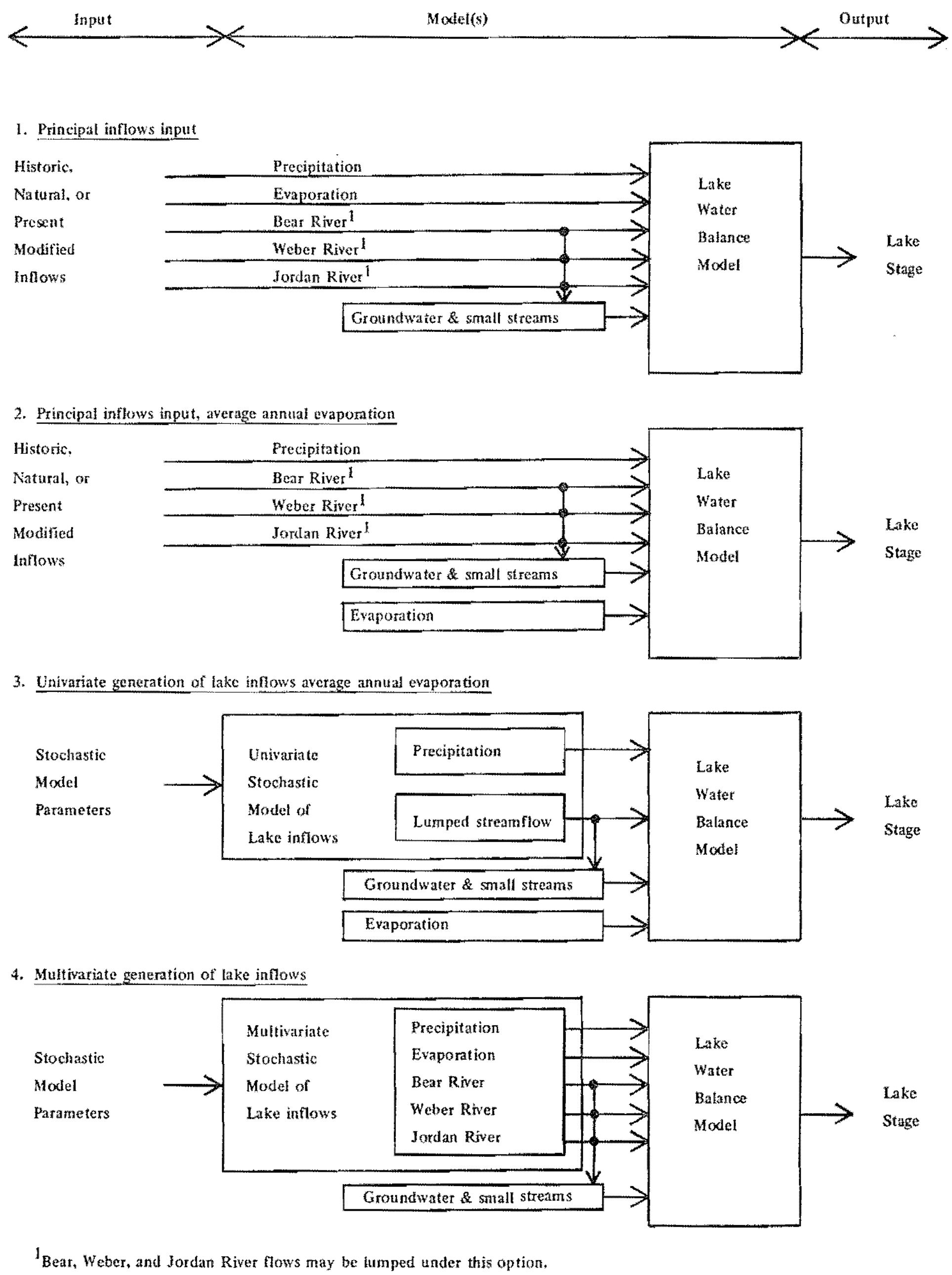


Figure 10. Outline of options for input or generation of lake inflows.

Options 3 and 4 are for stochastically generated lake inflows. Option 4, the one used in this study, uses multivariate stochastic generation of precipitation, evaporation, and surface inflows in the Bear, Weber, and Jordan Rivers. Option 3 uses separate univariate stochastic models of lake precipitation and lumped surface inflow to the lake. This option treats precipitation and lumped surface inflow as statistically independent variables (their cross-correlation in one application was found to be just significant at the 0.05 level; $\hat{\rho}_{Q,P}(0) = 0.24$). Option 3 was used in an early stage of the study to obtain approximate results in the question of whether or not to cut an opening in the Southern Pacific Railway causeway (Bowles et al., 1977).

Attempts to Model Residual Flows Explicitly

During development of the lake water balance model and the stochastic models to generate lake inflows, "residual" time series were calculated under options 1 and 2. The residual value calculated for a given year for this time series was defined as the net difference between the observed lake volume and the lake volume calculated using the inflow time series excluding the model estimates of groundwater and small stream inflows (and evaporation under option 2). Thus, the residual time series represents the sum of groundwater inflow, small stream inflow, evaporation under option 2, and error in the flow or lake stage data. Attempts were made to model the residual time series by 1) adding it to the multivariate stochastic model, and 2) regressing it against the variables in the univariate stochastic model. However, neither attempt was successful because use of the residual time series resulted in very extreme lake stages.

Upstream Development

Another feature of the adapted water balance model enables the user to evaluate the effects of upstream water development projects that increase consumptive use on lake levels. At present, nearly 1,500,000 acre feet annually are consumptively used in the Great Salt Lake Basin. The model provides for two alternatives for increasing that use. One plan would provide for a continuing increase in upstream consumptive use, most likely to occur by putting new land under irrigation. The other plan would provide for an intermittent increase in upstream consumptive use, most likely to occur if some lands are only to be irrigated during years when extra consumptive use is required to prevent high lake stages and their associate damages. The first plan is modeled by specifying an increase in consumptive use which the program subtracts from the streamflows. The second plan is modeled by specifying a control elevation, and the model then assumes that any flows that would cause this stage to be exceeded are instead diverted to irrigation that increases consumptive use. Under either option, one can use the damage simulation model described in Chapter 7 to determine the effect of a proposed increase in upstream (continuing or intermittent) consumptive use on average annual damages caused by fluctuating lake stages so that these benefits can be used in the necessary economic feasibility studies. A more refined analysis simulating more realistic reservoir operating policies can be developed later once specific schemes prove promising and are more carefully defined.

Pumped Outflow

A capability for representing the operation of a plant pumping water from the Great Salt Lake to the western desert was added to the lake water balance model by the Utah Division of Water Resources (1977). At a control elevation specified by the user, the simulation model begins to simulate pumped diversions from the lake at a maximum rate specified by the users. The pumping continues at this maximum rate as long as the water surface remains above the control elevation. The specified rate should be specified as a net pumping rate or actual pumping in excess of return flows. This difference would equal the annual evaporation loss from the surface area of the desert holding pond adjusted according to any change in storage during the year.

Applications of the Lake Water Balance Model

No lake level control. The multivariate model calibrated to match present modified flows for the period of 1937 to 1977 was used to generate 100 sequences (79 more than previously generated to compare with other models) of 125 years each. These sequences were then used as input to the lake water balance model to generate 100 125-year lake stage sequences. The generated sequences began from an initial lake stage on October 1, 1978, of 4198.6. The recorded high stage the previous spring was 4200.25 on June 1.

Various statistics for the distributions of 100 annual peak lake stages generated for selected future years are shown in Table 36. The tabulation shows that the probability distribution stabilizes in about 35 years in what is essentially a normal distribution around 4196.42 with a standard deviation of 4.56. This distribution indicates that in the long run one can expect one chance in ten of the annual peak for that lake being as high as 4202.3 or as low as 4190.6. Corresponding elevations for one chance in 100 are as high as 4207.0 and as low as 4185.8. End-of-the-year lake stages average 1.65 feet lower.

The recorded lake stages over the 1937-1977 period had a mean of 4197.6 and standard deviation of about 2.5. The mean lake stage over the entire 1847-1977 period was approximately 4200. The reduction in lake level with time can be explained by

Table 36. Statistics of the distribution of peak lake stages simulated for various years.

Year	Lower Decile	Mean	Upper Decile	Standard Deviation	Skewness
1978		4200.25			
1979	4199.48	4200.16	4200.72	0.51	0.74
1980	4198.59	4199.89	4201.18	1.08	0.73
1985	4194.46	4198.48	4201.98	2.82	0.03
1990	4192.63	4197.58	4201.82	3.76	-0.09
2000	4192.30	4196.92	4201.70	3.73	0.02
2010	4192.29	4196.52	4200.81	4.07	0.26
2020	4190.52	4196.28	4201.09	4.42	-0.13
2030	4189.26	4196.28	4203.64	5.14	-0.57
2040	4190.15	4196.59	4201.54	4.34	0.09
2050	4191.15	4196.51	4202.31	4.32	-0.14

increasing consumptive use. The higher standard deviation is explained by the reduced bias toward under estimating the standard deviation of highly serially correlated data from longer series.

Three kinds of probability information were identified in Chapter 2 as being potentially useful in making management decisions for property or facilities near the lake. The first, the lake stage probability distribution, is important in both the near term perspective of the next few years and in the longer term perspective. The results as plotted on Figure 11 show how lake stage probabilities are initially strongly influenced by known present conditions and gradually become stable by about 2013. The probabilities are labeled to indicate both the 0.01 probability high and then 0.01 probability low events rather than in terms of a cumulative probability distribution. A second useful form for expressing these probabilities are the chances of the lake rising to elevations 4200, 4205, and 4210 by various dates as plotted in Figure 12. The highest and lowest lake levels generated in any of the sequences were 4174 and 4220 respectively, and these values were used to guide gathering data for damage simulation as described in the next chapter. The probability distributions of the dates by which the lake will first fall to levels of 4198 and 4196 and then remain below these levels for five or more years are plotted in Figure 13.

The curves of Figures 11 and 12 could be plotted for any different elevations desired from the output obtained from the computer programs listed in the appendix. The curves plotted are based on the lake level existing on October 1, 1978, and they will thus be out of date after October 1, 1979. The program can be readily rerun to get new curves based on revised input data as desired. The option of normalizing the curves mentioned for information presentation in Chapter 1 did not prove feasible because of the large number of variables.

With lake level control. Because levees such as those shown on Figure 7 would not alter the lake stage-storage relationship very much, no additional runs were made to quantify their effect on lake stages. The probability distributions shown on Figures 11, 12, and 13 would still be good within the accuracy of the methodology. The model was rerun for the management alternatives of 1) increasing consumptive use of Bear River water by 10 percent and 2) pumping at a net rate of 310,000 af/year into the western desert when the water level passes a control elevation of 4202. The results for the first alternative are plotted in Figures 14, 15, and 16, and those for the second alternative are plotted in Figures 17, 18, and 19.

From these nine figures, one can see that neither management alternative has a large effect on lake stages and thus that much larger volumes of water than those used here to illustrate the model would have to be consumed or pumped to prevent major damages from being caused by high lake stages. A more careful inspection of the figures shows that increasing consumptive use of Bear River water lowers low lake stages much more than it does high lake stages, and one could only ameliorate this pattern by concentrating the consumptive use in high runoff years. In contrast the alternative of pumping into the desert has no effect on low lake stages but achieves a much larger reduction in high lake stages precisely because the measure is used only when the lake is high.

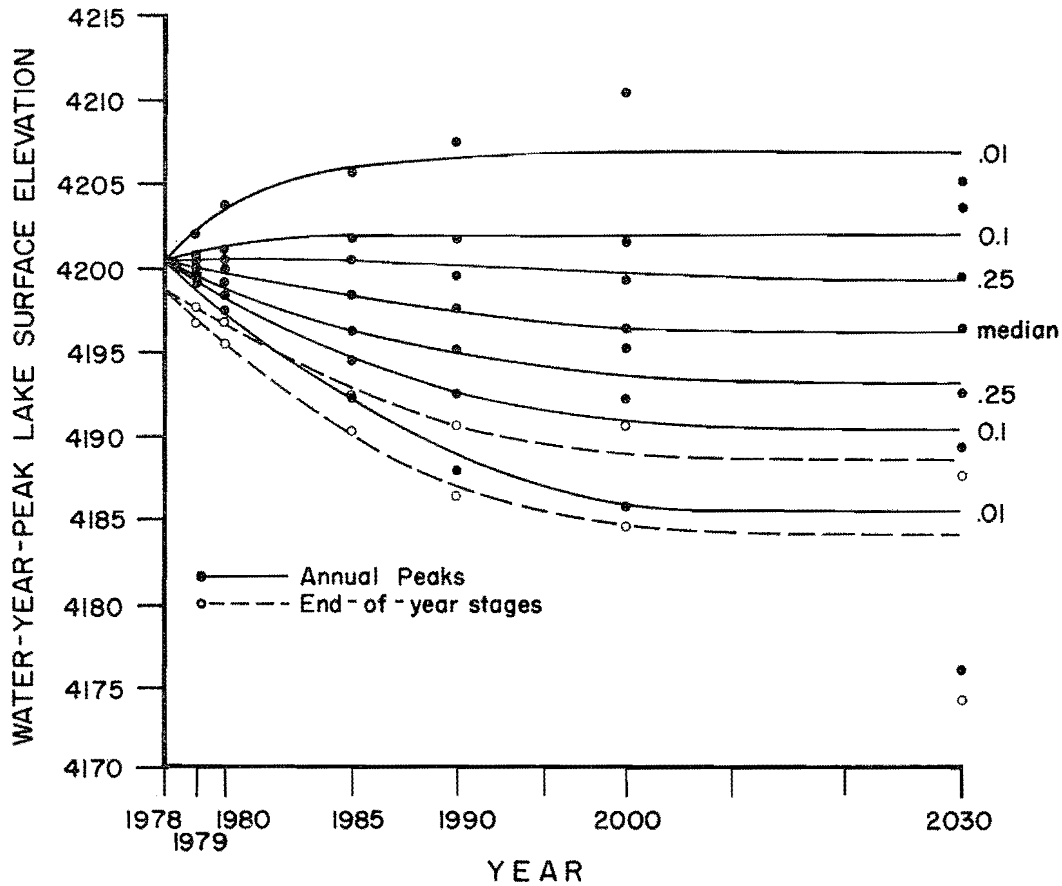


Figure 11. Probability distributions of future annual peak Great Salt Lake levels, given level of 4198.6 on October 1, 1978.

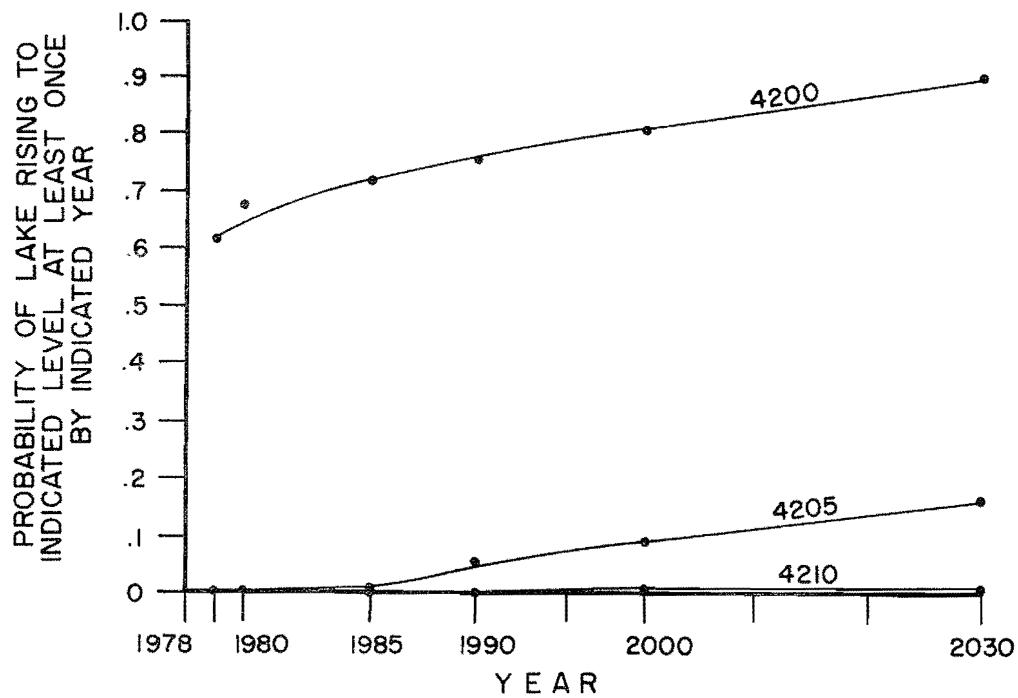


Figure 12. Probability distributions of number of years before lake first rises to various critical levels, given level of October 1, 1978.

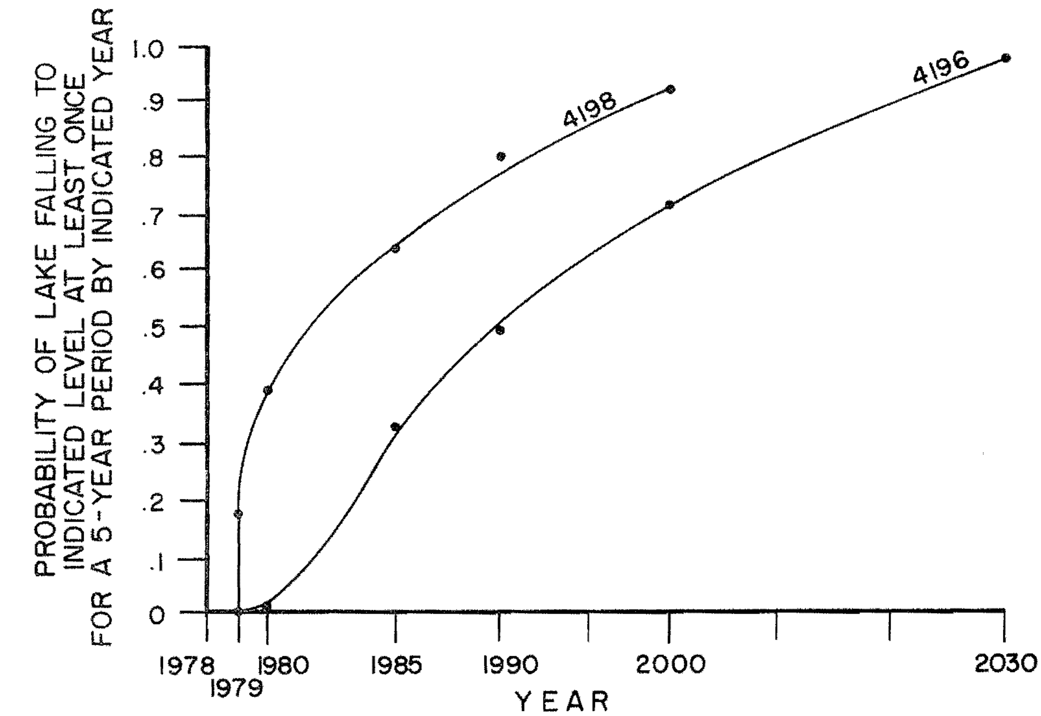


Figure 13. Probability distributions of number of years before lake first falls to various critical elevations and remains there at least five years, given level of October 1, 1978.

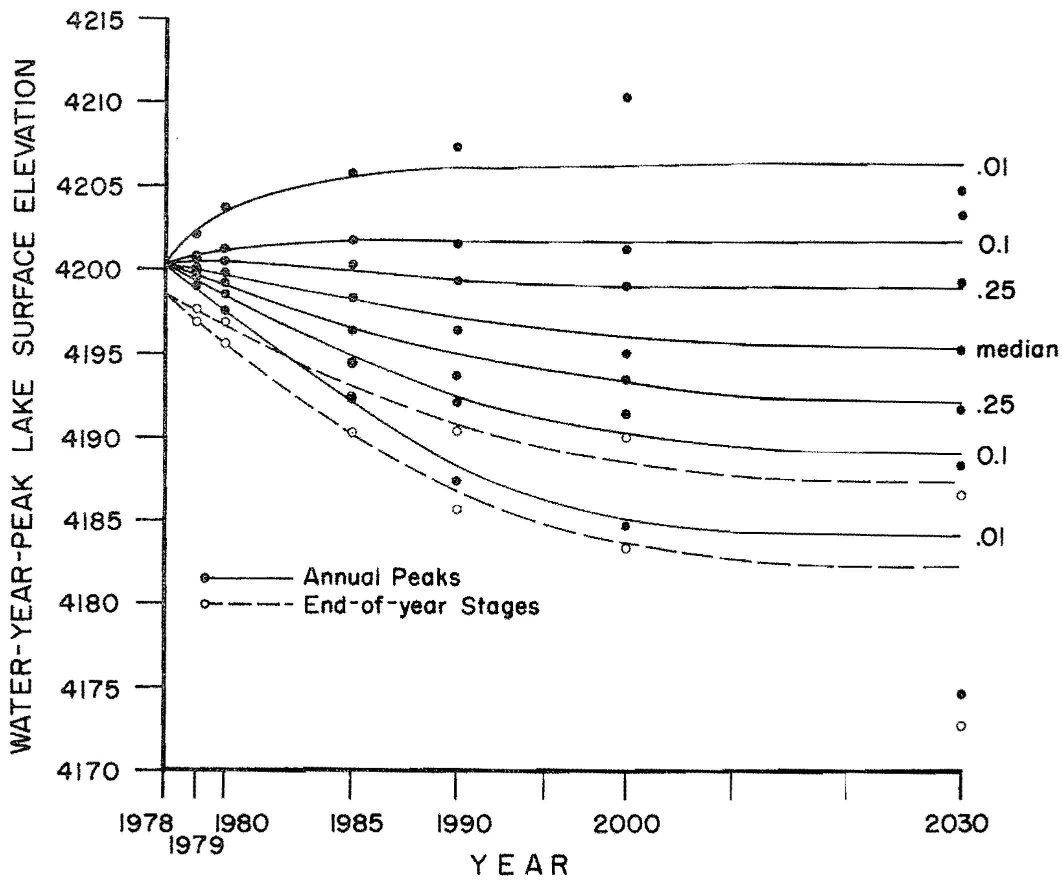


Figure 14. Probability distribution of future Great Salt Lake levels; given level of October 1, 1978, and a 10 percent increase in consumptive use of Bear River water beginning in 1983.

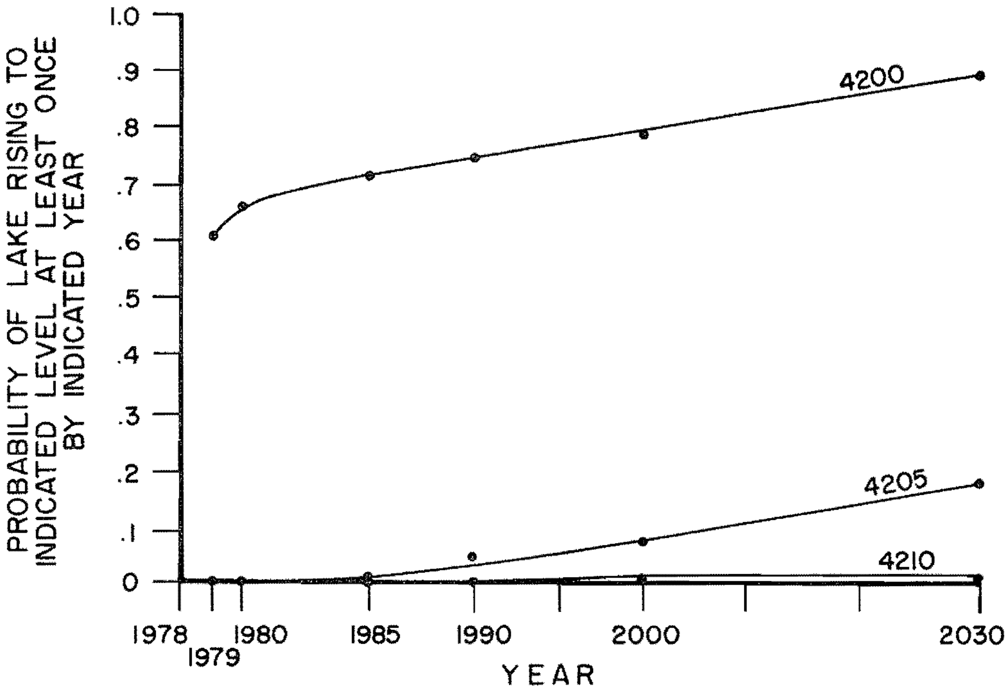


Figure 15. Probability distributions of number of years before lake first rises to various critical levels, given level of October 1, 1978, and a 10 percent increase in consumptive use of Bear River water beginning in 1983.

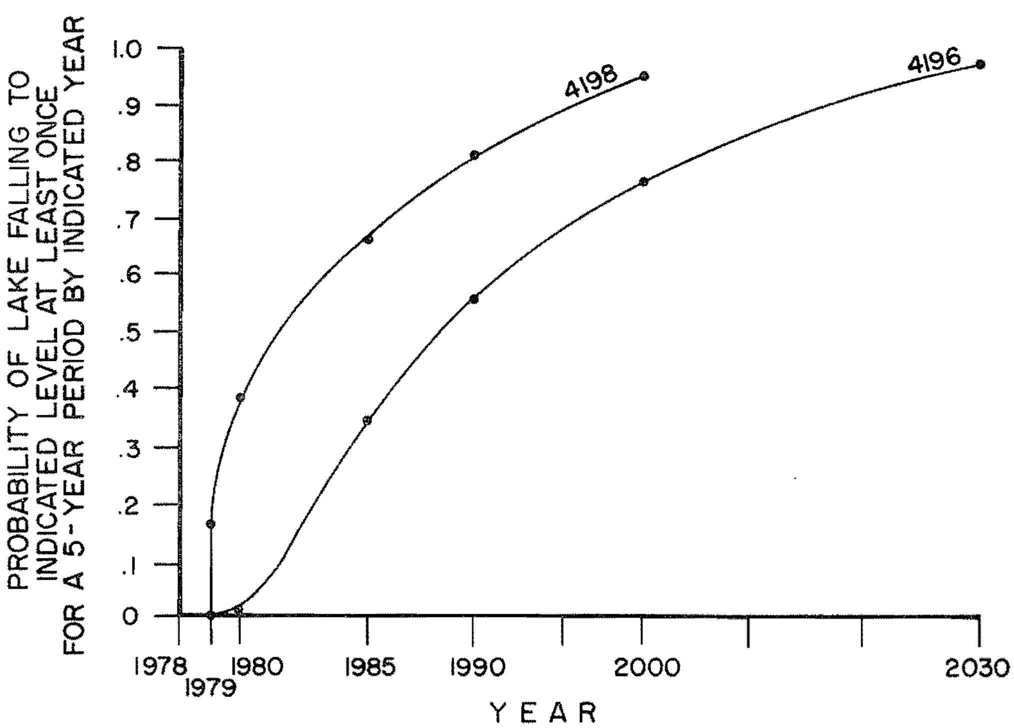


Figure 16. Probability distributions of number of years before lake first falls to various critical elevations and remains there at least five years, given level of October 1, 1978, and a 10 percent increase in consumptive use of Bear River water beginning in 1983.

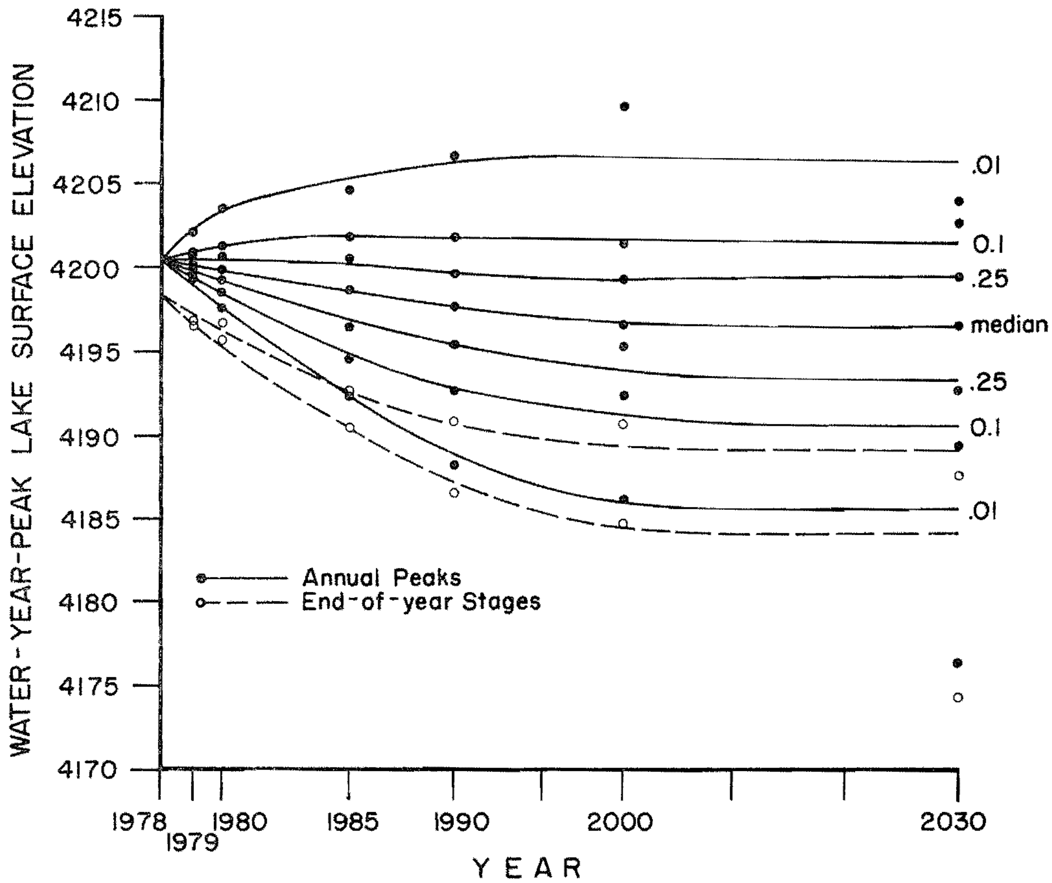


Figure 17. Probability distributions of future annual peak Great Salt Lake levels, given level of 4198.6 on October 1, 1978, and pumping 310,000 AF/year into the Western Desert when the lake elevation exceeds 4202.

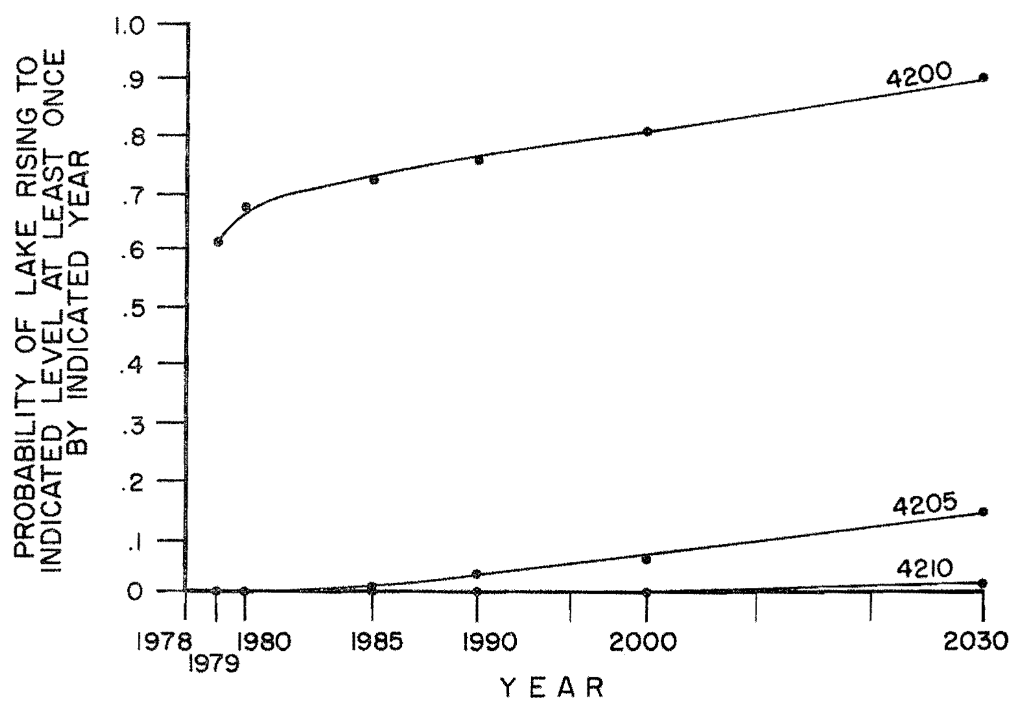


Figure 18. Probability distributions of number of years before lake first rises to various critical levels, given level of October 1, 1978, and pumping 310,000 AF/year into the Western Desert when the lake elevation exceeds 4202.

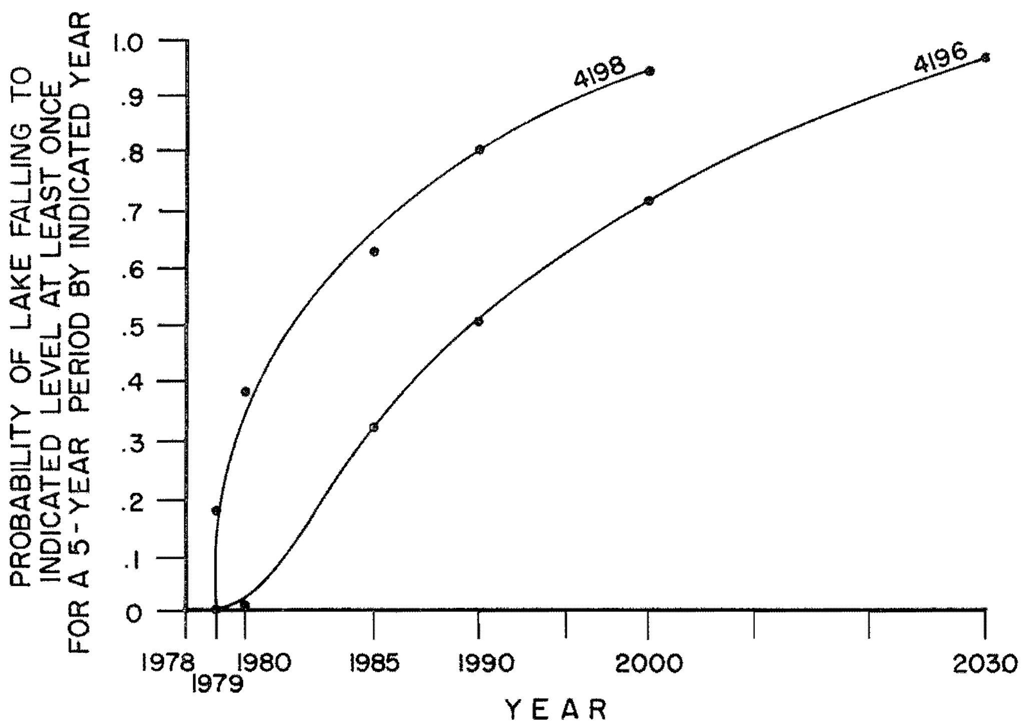


Figure 19. Probability distributions of number of years before lake first falls to various critical elevations and remains there at least five years given level of October 1, 1978, and pumping 310,000 AF/year into the Western Desert when the lake elevation exceeds 4202.

CHAPTER 7

DAMAGE SIMULATION MODEL

Reason for Damage Simulation

The economic justification of terminal lake level control requires that the damages be reduced by more than the measures cost. Since economic losses from high or low lake levels continue over many years rather than being limited to the short durations that characterize riverine flooding, the pattern of rising and falling stages over these long periods has a substantial effect on the amount of damage. For this reason, a dynamic programming sort of damage estimation procedure was devised for this study. The concept is to estimate damages in a given year from the peak stage during the year, given the history of peak lake stages and remedial measures of previous years. The input data are the time series of annual lake peaks taken from the stage sequence generated by the water balance model.

This sequential mode of estimating damages may be contrasted with the stage-damage relationship commonly used in riverine flood-damage estimation. Along rivers, the onset of flooding is usually sudden, the duration is seldom more than a few days, and an occurrence in one year does not increase the likelihood of a similar event in the next year. In contrast, flooding of lands surrounding terminal lakes takes place at a relatively slow rate and may last many years. Similarly, periods of low lake level also persist for many years. Property damages incurred as the lake rises are not reincurred in the following year if the lake remains at approximately the same high stage, but the losses from not being able to use flooded property continue as long as the inundation. In contrast in a riverine setting, a flood-damaged property would probably be restored soon after a flood, and property damages would be repeated in the following year if a similar flood occurred.

The time series of annual damage totals could be estimated first from a sequence generated to represent conditions with no lake level control and second from a sequence generated to represent any specified lake level control measure. The present worth of each sequence could be estimated, and the amount the present worth is reduced by lake level control would be the net benefits to compare with the present worth of the measured costs. The purpose of the terminal lake continuous damage simulation model is to estimate annual lake-stage damages and the present worth of the generated damage series from a sequence of annual lake stages generated using the terminal lake water balance model.

Stage-Related Damages for Terminal Lakes

Many types of activites are directly or indirectly affected by fluctuations in the levels of terminal lakes. Falling lake levels make lake access at beach areas more difficult, dry up marinas, and necessitate extra pumping of brines by mineral extraction industries. Rising lake levels flood and cause property damage to industry, recreation activities, agricultural lands, wildlife feeding areas, and transportation routes. One would expect the managers of these properties to protect their property from flood damage by such measures as raising or building dikes; but eventually a stage is reached at which the owner can no longer afford protective measures, the property is inundated, and the impacted activity is suspended, if not terminated, until the lake recedes. When changing stages restrict or prevent economic activities, revenues are lost by those whose investment is rendered less profitable, by various levels of government who obtain tax revenues from the affected activities, and by businesses which are economically linked to the affected entity. When the lake returns to levels which permit repair or rehabilitation of previously damaged facilities, capital investment must be made to cover the cost of reinstatement.

At the state and local level, expenditures for damage mitigation measures and for reinstatement of damaged facilities produce secondary benefits through the multiplier effect of the wages and salaries paid for by those funds (James and Lee, 1971, p. 200-204). Also, state and local governments benefit by taxing those who reap the secondary benefits. From the national viewpoint, however, local secondary benefits are neutralized by losses elsewhere in the economy if an assumption of full employment is made.

Taxonomy of Economic Effects

Estimation of the economic losses caused by lake level fluctuations requires classification of the kinds of losses that occur and examination of each one to develop a method for quantifying it. A two-way classification was used. Damages were classified according to party injured in the categories of railroads, highways, the road to Antelope Island, the federal and state bird refuges, the shoreline recreation facilities, the mineral extraction industry, and others. Viewpoints for evaluating damages were classified as 1) to whomsoever they may accrue or the national viewpoint, 2) to the public and private sectors in the State of Utah, and 3) to the public sector or state and local government in Utah. The first viewpoint provides numbers for project economic justification; the second provides information on how much state government is economically justified to put into lake level control; and the third indicates how government revenues and expenditures will be affected as an important input to their financial assessment of how much they can afford. Methods for estimating damages to each party from each viewpoint are discussed below, but only damage estimation from the first viewpoint was quantified with the damage estimation model developed in this study. Some programming to estimate damages from the other two viewpoints is in the damage simulation model developed for this study, but the procedures were neither completed nor debugged.

Railroads. Losses to railroads occur principally from the effects of high water on the causeway across the lake and to sections of four other lines near the lake. From the national viewpoint, these losses are the extra cost of maintenance as waves from the lake erode the roadbed embankment, capital costs for raising the roadbed or otherwise protecting it from the lake, losses from interruptions or delays in train movement during storms or prolonged highwater periods, and, if a route should have to be closed, the extra cost of routing traffic on an alternate route during the period of closure plus the cost of reinstating the original route once the lake level recedes to where that becomes advisable. Secondary effects associated with losses in profit to the railroads and taxes paid to various governments, if the railroads are unable to pass these losses onto shippers, or higher shipping prices, if they are, are not included because they are difficult to evaluate and probably small if one considers offsetting gains to other rail routes and other transportation modes.

From the Utah viewpoint, the monies spent on protecting the railroads from rising lake levels largely come from out of state (income generated from interstate transport through Utah), and spending it in Utah is a net gain. The gain from the state's viewpoint can be estimated as

$$U_R = D + Dp\ (f - 1) \quad \quad (69)$$

in which

- D = railroad expenditures for maintenance, preventative capital investment, and reinstating once-closed routes
- p = proportion of these costs paid in salaries and wages and estimated to average 0.3 (Harza, 1975)
- f = multiplier accounting for forward and backward linkages from these salaries and wages and estimated to average 3
- U_R = 1.6 D by substituting the above values for p and f in Equation 69

From the viewpoint of governments in Utah, monies the railroads spend in protecting themselves are partly captured through taxes and add to revenues. The amount of added revenues from taxes on wages and salaries received directly or indirectly as estimated by the multiplier effect average about 11 percent (BEBR, 1977) or 0.11 fpD = 0.099D. Additional revenues would come from additional property taxes on the new capital investment, and amounts can be estimated from the assessment percentages and mill levies in the respective counties.

Highways. Losses to highways occur to sections of four interstate or state routes near the lake when water levels rise to elevations that erode the embankment, saturate the subgrade, or produce waves that wash onto the roadway during storms. From the national viewpoint, the economic losses are of the same sorts described for railroads, and methods are available for estimating them as discussed in the literature review. The highways threatened by rises in the Great Salt Lake are all through routes where closure would cause major economic disruption. It was therefore decided to estimate the damage on the assumption that the least costly plan of action to keep the highways open would be followed. The costs were estimated by the highway agencies forecasting probable reactions to a pattern of lake level changes.

From the Utah viewpoint, monies spent to protect highways divide between federal funds which cover part of the capital costs of protection and relocation and state and local funds which cover capital costs not covered by federal programs plus all costs for maintenance. Thus the loss to the people of the state would be

$$U_H = (1 - q)\ C_H + M_H \quad \quad (70)$$

in which

- C_H = capital cost of protection or relocation
- M_H = annual maintenance cost added because of the effects of the high water on the highway

q = fraction of capital cost which can be obtained from federal highway programs

The net loss would be smaller than U_H because of the multiplier effect of spending additional federal funds in Utah. Spending state funds also has a multiplier effect but so would the way these funds would be spent if they did not have to go into protecting the highways. In the absence of information on how the source of funds for the money the state would obtain for highway protection would divide among funds that would otherwise be spent on other highways, funds taken from other state programs, or funds raised by additional taxes and of information on the variation in multiplier effects among such expenditures, the multipliers were assumed to cancel one another out. The reduction in the loss to Utah would thus be 1.6 qC_H.

From the viewpoint of governments in Utah, the monies spent on highway construction, $(1-q)C_H$. come from tax revenues and are divided among jurisdictions (state, county, city) by formula depending on the type of road. For highways threatened by rising waters from the Great Salt Lake, most of the nonfederal costs would come from the state. The costs would be partially offset by tax increases generated from the extra money being spent and amounting as estimated for the railroads to be 0.099 qC_H.

Antelope Island Causeway. The one highway that would probably be closed rather than relocated or protected if threatened by rising water is the causeway from the eastern shore of the lake to the Antelope Island recreation area. For this road, the economic loss from the national viewpoint would be whatever funds were spent to protect the causeway from rising water as long as it is kept open, the benefits from recreation on the island denied by lost access when the road is closed (plus the benefits from a relatively small amount of non-recreation use of the causeway), and the cost of reinstating the causeway if that is done after the lake recedes from a previous high.

From the national viewpoint, the costs of protecting the causeway against rising water are conceptually the same and can be estimated by methods already described for the other two transportation cases. Estimating the cost of reinstating a temporarily abandoned causeway requires an assumption on when to reinstate and what level of facility to build. For this study it was assumed that reinstatement of the causeway would cost 5 million (1978) dollars and that the reinstated facility would be designed to be safe at water surface levels up to 4207 feet.

The recreation benefits lost during periods of closure were estimated as the annual number of visitors to the island multiplied by an estimated benefit per user day of recreation on the island. Benefits per user-day were estimated (Bianchi, 1969) as

$$U = \beta d/(n-1) \quad \ldots\ldots\ldots\ldots (71)$$

in which

n = the exponent in the gravity model for estimating number of trips. Larger values suggest that fewer visitors are coming from long distance. Value of about 3.0 was found average for waterfowl hunting in Kentucky (Holbrook, 1970), 2.4 as an average for recreation reservoirs (James and Lee, 1971, p. 410), and 2.0 for sites that attract many visitors through their national or international reputation.

d = average distance that visitors travel out of the way to visit the recreation site (from home or by way of adding miles to a multipurpose trip), and

β = travel cost per mile per visitor day spent at the site as estimated (James and Lee, 1971, p. 411) by

$$\beta = R\frac{((1+a)\alpha + t/v)}{bp} \quad \ldots\ldots\ldots\ldots (72)$$

in which

R = ratio of round trip road distance to one-way air distance

a = cost of food and lodging above that spent at home expressed as a fraction of vehicle operating cost

α = vehicle operating cost per marginal vehicle mile

t = value of a vehicle-hour of traveling time

v = average vehicle velocity over distance d

b = average number of days a visitor spends at the site

p = average number of people traveling together in a vehicle

The basic data source used to estimate these parameters was a survey of recreation use of the island (Institute for Outdoor Recreation and Tourism, 1976). Recreation users were estimated as 86,600 Utah residents and 105,000 nonresidents annually. For these groups, b was given as 1, p as 3.1 for residents and 3.4 for non-residents. A national average value for R is 2.42. The numbers of visitors cited were computed from the Utah Division of Parks and Recreation figures multiplied by the factor 3.37/4. The Parks and Recreation figures are based on vehicle counts and an assumption of 4 persons per vehicle. The Institute of Outdoor Recreation and Tourism study counted 3.37 persons as an average vehicle load. Similar estimates are reported by Duering (1977).

Average distance traveled is estimated as 35 miles for Utah residents. This is an average airline distance to the major population center of the state. The average out-of-the-way distance traveled by nonresidents is estimated as 27 miles, the airline distance to the intersection of Interstate Highways 15 and 80. The value for "a" is estimated 0.1 for residents and 0.8 for nonresidents. Because visitor average only about one hour at the site, the resident value is low while the nonresident value is much higher because of dining and overnight accommodation requirements. A difference in average velocity (40 mph for residents and 50 mph for nonresidents) is anticipated because most nonresident travel through Utah on major traffic arteries that permit more rapid travel. The value for t is computed as one third of the average hourly household income as recorded by percent of total households in the Institute for Outdoor Recreation and Tourism study (Table 37). The hourly salary is estimated as 0.0481 percent of the annual salary following the average used for classified employees at Utah State University. The average annual salary for the lowest bracket (0 - $5000) is taken as $3500. The average for the highest bracket ($50,000+) is taken as $75,000. By substituting the above values in Equations 71 and 72, the annual recreation loss from closure of the Antelope Island causeway was estimated to be $1,105,000 (Table 37).

Table 37. Percentage of population by income bracket.

Income Bracket Annual Income/In Dollars			U.S. Percent (P_1)	Utah Percent (P_2)
Maximum	Minimum	Average (B)		
5,000	0	3,500	2.1	9.2
10,000	5,000	7,500	14.3	19.4
15,000	10,000	12,500	20.0	28.6
25,000	15,000	20,000	34.3	31.6
50,000	25,000	37,500	24.3	11.2
	50,000	75,000	5.0	0.0
Mean Income (ΣBP/100)				
United States		23,370		
Utah		15,872		

Source: Institute for Out. Rec. and Tourism. For comparison, also see Duering (1977, p. 2).

From the Utah viewpoint, funds spent to protect the causeway can be divided between federal and state funds in the same way described above for other highways. The loss in recreation value to Utah residents would equal the $527,000 annually calculated in Table 38. The loss to Utah from nonresidents not being able to visit the site would amount to the reduction in the amount they spend in the state multiplied by an appropriate factor to account for the forward and backward linkages from this reduction in money spent. If one assumes that 35

Table 38. Estimation of average annual recreation loss that would occur with closing Antelope Island Causeway.

Parameter	Utah Residents	Nonresidents
R	2.42	2.42
a	0.1	0.8
α	0.145	0.145
Family Income (I)	15,872	23,370
t = 0.000481 I/3	2.54	3.75
v	40	50
b	1	1
p	3.1	3.4
β (Eq. 70)	0.174	0.239
d	35	27
n	2	2
U (Eq. 69)	6.09	6.45
Visitors	86,600	105,000
Annual Loss	$527,000	$678,000
Combined Loss	$1,105,000/yr	

percent of the vehicle cost goes for mileage items (Winfrey, 1969, p. 313) that are more likely to be spent in the state of travel than in one's home state, β = 2.42 (0.35 + 0.80) 0.145/3.4 = $0.119 per visitor mile or $337,000 annually for the 105,000 out-of-state recreationists who travel out of their way an average of 27 miles to get to the site. A multiplier effect of 1.52 (Kalter and Lord, 1968) would inflate this estimate to $512,000 annually.

From the viewpoint of governments in Utah, the effects of expenditures for causeway protection would be estimated exactly the same way as those of other expenditures for highway protection. The losses in taxes collected directly or indirectly from out-of-state visitors to Antelope Island have been estimated at $118,000 annually (University of Utah, 1977). One can reasonably assume that taxes paid by instate visitors will be unaffected as Utahns shift expenditures from visits to Antelope Island to other items.

<u>Federal bird refuge</u>. The federal bird refuge areas encompass 65,000 acres of marshlands near the lake, 25,000 of which are protected by dikes (Table 39). Conceptually, one might approach estimation of the losses to bird refuge areas from information on the environmental harm to the species denied feeding and resting areas, the loss of recreational value to hunters of those species, and physical damage to property other than the feeding areas at the refuge. Because these losses, particularly the first ones, are difficult to quantify, one could alternatively use the expenditures required to preserve the area against threatened inundation. In principle, protection cost should only be used when it is less than the value protected. This principle was

followed for the Antelope Island causeway in using protection costs when the effort is justified and economic loss of not having a route available when it is not and the route is closed. The difficulty in applying this principle to the bird refuge is in quantifying the economic harm associated with the adverse environmental effects of flooding. Losses in hunter-recreation value foregone (approximately $7.00 per flooded acre annually) give no more than a gross approximation, but they were all that was available. Costs of protective measures can be estimated on what refuge managers would expect to do in given situations up to a lake level where they would abandon the refuge.

The annual loss from the national viewpoint was taken as the capital and maintenance costs of the levee system protecting the refuge areas taken in the years costs were forecast plus the hunting value of flooded marshland foregone when unprotected areas are flooded or when dikes are overtopped. When a levee is submerged and needs to be restored, the repair cost was estimated on the basis that only the freeboard part of the levee would have to be reconstructed and that the cost of the reconstruction would be

$$C_R = C_I RF \qquad (73)$$

in which

C_I = initial construction cost for the levee

R = fraction of the total levee volume above the freeboard elevation

F = a factor of 1.2 used to account for greater costs per cubic yard in repair than for initial construction

The hunting value foregone because of marshland flooding was estimated by multiplying the acreage flooded times the unit value of $7.00 per year. Protected areas were assumed to be flooded at the lake level that overtops the dike after accounting for probable future efforts to raise the dikes. As shown on Table 39, unprotected areas were estimated by assuming that about 90 percent of the total area is low enough to be flooded and that the area is linearly distributed between elevations 4200 and 4218 (total lake surface area varies nearly linearly with elevation over this range as shown in Table 35).

From the Utah viewpoint, the Federal Fish and Wildlife Service would pay for the necessary protective measures, and the state would gain from having that money spent here in exactly the same way as described for the federal highway expenditures. Clubhouse and related facility losses can be assumed to be entirely in state. Hunter recreation losses can be divided between instate and out-of-state recreationists using the rules described for lake recreation.

Table 39. Data used to estimate hunting value foregone when marshlands are flooded.

	Federal	State	Private
Acreages			
Total	65,000	60,000	40,000
Below 4218 Contour	59,000	54,000	36,000
Dike Protected	25,000	40,000	0
Exposed	34,000	14,000	36,000
Flooded per Foot Rise	1,890	780	2,000
Losses			
Flooding Exposed	13,230	5,460	14,000
Dike Overtopped	175,000	280,000	0

From the viewpoint of Utah governments, they would lose property taxes on the clubhouse should it be destroyed, gain tax revenues equalling about 10 percent of the federal funds spent in Utah, and lose taxes paid directly or indirectly by out-of-state hunters.

State bird refuge and private marshlands. Losses associated with rising lake levels infringing on the state bird refuges and private marshlands were estimated in exactly the same way described above for the federal refuges with the sole exception that since the state or its citizens rather than the federal government pays the protection bill, amounts paid must be considered a cost to the people of Utah and to the government of the state. Relevant figures are shown on Table 39.

Beach and marina areas. A public beach is operated by the State of Utah on the south shore of the Great Salt Lake and refreshment, souvenir, and marina facilities are operated at the site by a private concessionaire (Duering, 1977). Losses caused by lake level fluctuations occur both as the lake rises to flood shoreline facilities and as the lake falls to require moving facilities nearer the water. From the national viewpoint, rising water causes losses in benefit because of fewer recreationists, loss in revenue to the owners of the recreation facilities, and costs in protecting the facilities from high water. The same three components occur with falling water except that the third would be the cost of moving the facilities closer to the low water.

The average annual economic value associated with recreation on the lake's south shore is computed on Table 40 to be $4,170,000 to 1,119,000 visitors. Interviews with the managers of the facilities indicate that they have not experienced a significant change in the number of visitors as the lake level has fluctuated in the historical range, but loss was projected for this study should the water rise high enough to flood out existing areas and facilities.

Table 40. Estimation of average annual recreation loss that would occur with closing of South Shore Recreation Area on the Great Salt Lake.

Parameter	Utah Residents	Nonresidents
R	2.42	2.42
a	0.1	0.8
α	0.145	0.145
Family Income (I)	15,872	23,370
t = 0.000481 I/3	2.54	3.75
v	40	45
b	1	1
p	3.1	3.5
β (Eq. 66)	0.174	0.238
d	25	15
n	2	2
U (Eq. 65)	4.35	3.57
Visitors	227,500	891,500
Annual Loss	$990,000	$3,180,000
Combined Loss	$4,170,000	

If the lake should fall as low as 4193, a second marina would be required closer to the lake at an estimated cost of $300,000. Should that marina be flooded out and then have to be restored when the lake falls below 4193 a second time, the cost would be $100,000.

From the Utah viewpoint, all costs are paid with funds from either the public or private sector in the state and hence are identical to those from the national viewpoint as was the case for the state bird refuges. Any loss of out-of-state recreationists would be a loss to the state, but this amount was estimated as negligible because of the inability to detect any affect of lake levels on visitation by a clientel who primarily stop for an hour or two to see the lake on a cross-country trip.

From the viewpoint of Utah government, any governmental expenditures to protect recreation areas or facilities would be a loss. Tax revenue losses from decreases in out-of-state visitation would exceed $500,000 annually estimated at the same rate cited above for Antelope Island.

Mineral industry. Like recreation, the mineral industry is hurt by declining lake levels. The industry has to pay more to raise a brine of satisfactory quality to the evaporation ponds. The losses caused by rising lake levels are much larger. Major damages occur if the lake levels rise to flood the plant, and the loss is compounded as the constant salt content of the lake becomes dissolved in a much greater volume of water and hence more costly to extract.

From the national viewpoint, losses include the capital investment and extra maintenance cost to the industry in protecting itself, income losses because mineral extraction from fresher water is more expensive or the salt composition of the extracted brine is altered, income losses when plants close down during high water periods, and costs of reinstating once inactivated facilities should the lake level decline from its high levels. Company income losses were taken at 7 percent of gross sales. The standard assumptions of full employment and fully mobile resources mean that there would be no costs to the economy as workers or resources used by the industry became unemployed.

From the Utah viewpoint, the state would lose an important component of its industrial base should the mineral extraction industry cease operation. Since only one of the smaller plants is Utah owned and most of the salt products are sold in other states, the money spent by the industry to protect itself becomes a net gain for the economy equal to 1.6 times the expenditure, using the same values for f and p in Equation 69 as applied for the railroads. During periods when plants are closed down, the same reasoning would estimate losses to the economy from those industries no longer bringing money into the state as equal to 1.6 times the average annual amount of money the industries spend in Utah.

From the viewpoint of Utah government, some tax gains occur with industrial investment because of tax revenue increases (0.099 times the investment) and some additional may occur because of increased property taxes on facilities built with the invested funds. Should the plants be inactivated during high water, tax revenue losses would amount to most income and property taxes paid by the industry. The 0.099 times the loss in monies spent by the industry in the state would also apply to the extent workers moved out of state to find new jobs.

Others. No significant damages to the brine shrimp industry, the Salt Lake City Airport, and the wastewater treatment plants at Salt Lake City and Bountiful, Utah, were identified for this study up to the maximum elevation of 4220 used in the damage simulation model.

Damage Simulation Algorithm

The damages from the time sequences of annual stages was only simulated from the national viewpoint. That viewpoint is the one used to evaluate economic feasibility of lake level control, and economic feasibility is the issue that should be addressed first. For control measures that pass that test, the analyses from the viewpoints of the State of Utah and of governmental revenues and expenditures in Utah can be completed later and will provide valuable information for political evaluation of alternative proposals, assessing the financial feasibility of raising the necessary funds, and establishing an equitable division of the total cost for charging various beneficiaries. For example, a previous analysis of the feasibility of opening the causeway showed that the effort could not be justified unless the benefiting industries agreed to pay a substantial amount of the cost (BEBR, 1977). Summations of benefits and costs from these other viewpoints would be very helpful in determining equitable arrangements for any cost sharing.

Figure 20 shows the flow diagram for the damage simulation control which reads the stages and damage information and for each stage sequence supplied estimates damages and calculates their present worths and equivalent uniform annual amounts to various time horizons. Moments defining the distribution of these various present worths are also computed. The process used to simulate the damage in a given year is outlined on another flow diagram on Figure 21.

Estimation of lake stage in the north and south arms. The stages calculated by the lake water balance model assume the lake to be a single water body. Separate peak stages for the north and south arms were established for estimating damages by using curves (Figure 22) which relate peak head differences across the causeway, ΔH, to lake stage and width of causeway opening (Utah Division of Water Resources, 1977). Figure 22 was developed by running dynamic lake circulation models to a steady-state condition. Actual head differences across the causeway would be higher during years with high inflow and lower during years of low inflow because of the time lags required to reach a steady state. Stauffer (personal communication, 1977) proposed adjusting Figure 22 values for these time lag effects with the relationships

$$\Delta H^T = \Delta H \quad C_L \quad . . . . (74)$$

in which

ΔH^T = head difference across the causeway adjusted for time lag of flow through the causeway

ΔH = head difference across the causeway from Figure 22

C_L = coefficient to correct ΔH for the time lag effect of flow through the causeway (Figure 23)

Separate peak stages for the north and south arms are then estimated from ΔH^T as follows:

$$S_s = S_c + y \quad . . . . (75)$$

$$S_n = S_s - \Delta H^T \quad . . . . (76)$$

in which

S_s = south arm peak stage (see Figure 24)

S_c = peak stage from lake water balance model in which entire lake is treated as single water body

S_n = north arm peak stage

y = higher of south arm stage above elevation of a single water body, estimated from the ratio of areas in the north and south arms as $y = \Delta H^T A_n/(A_n+A_s)$

A_n = surface area of north arm

A_s = surface area of south arm

S_s and S_n are then rounded to the nearest foot for three reasons:

1. Stage-damage cost data for the Great Salt Lake were obtained in a discrete tabular form at one foot intervals of lake stage.

2. Management decisions to mitigate damages associated with fluctuating lake stages would probably be made to no finer resolutions than one foot (e.g., it is unlikely that a levee would be raised less than one foot).

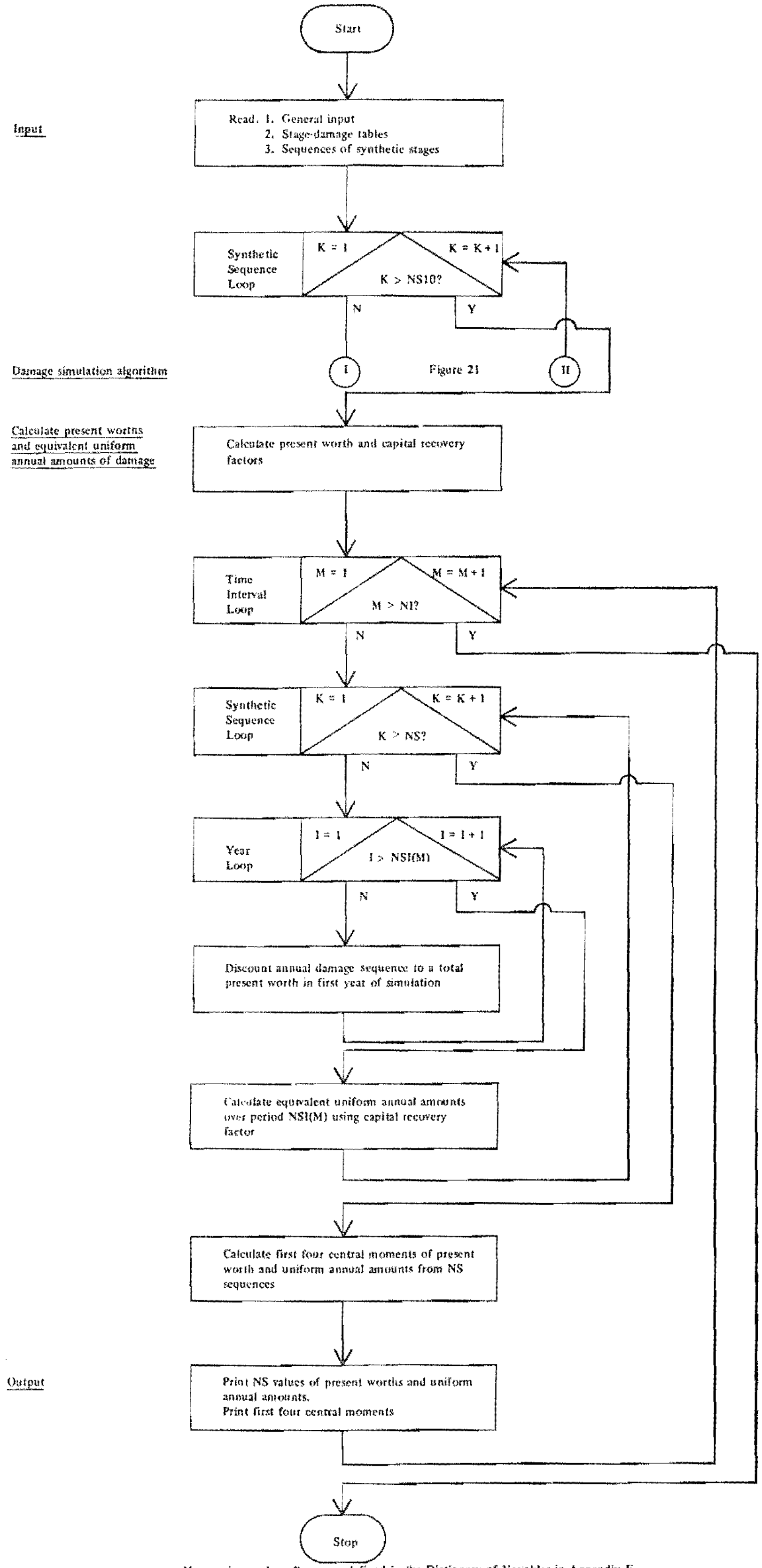
3. Elevation differences under one foot are easily absorbed in the six feet or so now used for freeboard.

Estimation of damage from a lake stage sequence. Figure 21 is a flow diagram for the damage simulation algorithm. The algorithm sums economic losses from the national viewpoint associated with rising or falling lake levels as classified into four groups:

1. Capital investment in damage mitigation measures.
2. Annual operation, maintennce, and repair costs caused by the effects of high or low water or to maintain mitigation measures.
3. Costs of reinstating facilities temporarily abandoned because of high water.
4. Losses that accrue to producers (mineral industries) or consumers (recreationists) when facilities have to be used to a lesser degree or cannot be used at all because of extreme lake levels.

In each year of the simulation, given the stage simulated by the water model, these four costs are estimated from tables of amounts estimated for them for various lake stages as constructed by the University of Utah Bureau of Economic and Business Research through a series of interviews and questionnaires with the managers of most of the relevant properties. Separate tables were compiled for each entity (i.e. railroads, roads, bird refuges, beaches, marinas, industrial plants).

Damages are simulated within an annual do-loop which covers NTE identified damage centers over the NYR years in the synthetic sequences of lake stage calculated with the lake water balance model. IWO accumulates the number of years that the lake stage has been continuously more than x feet below the



Mnemonics used on figure are defined in the Dictionary of Variables in Appendix F.

Figure 20. Overall flow diagram for the drainage simulation model (see also Figure 21).

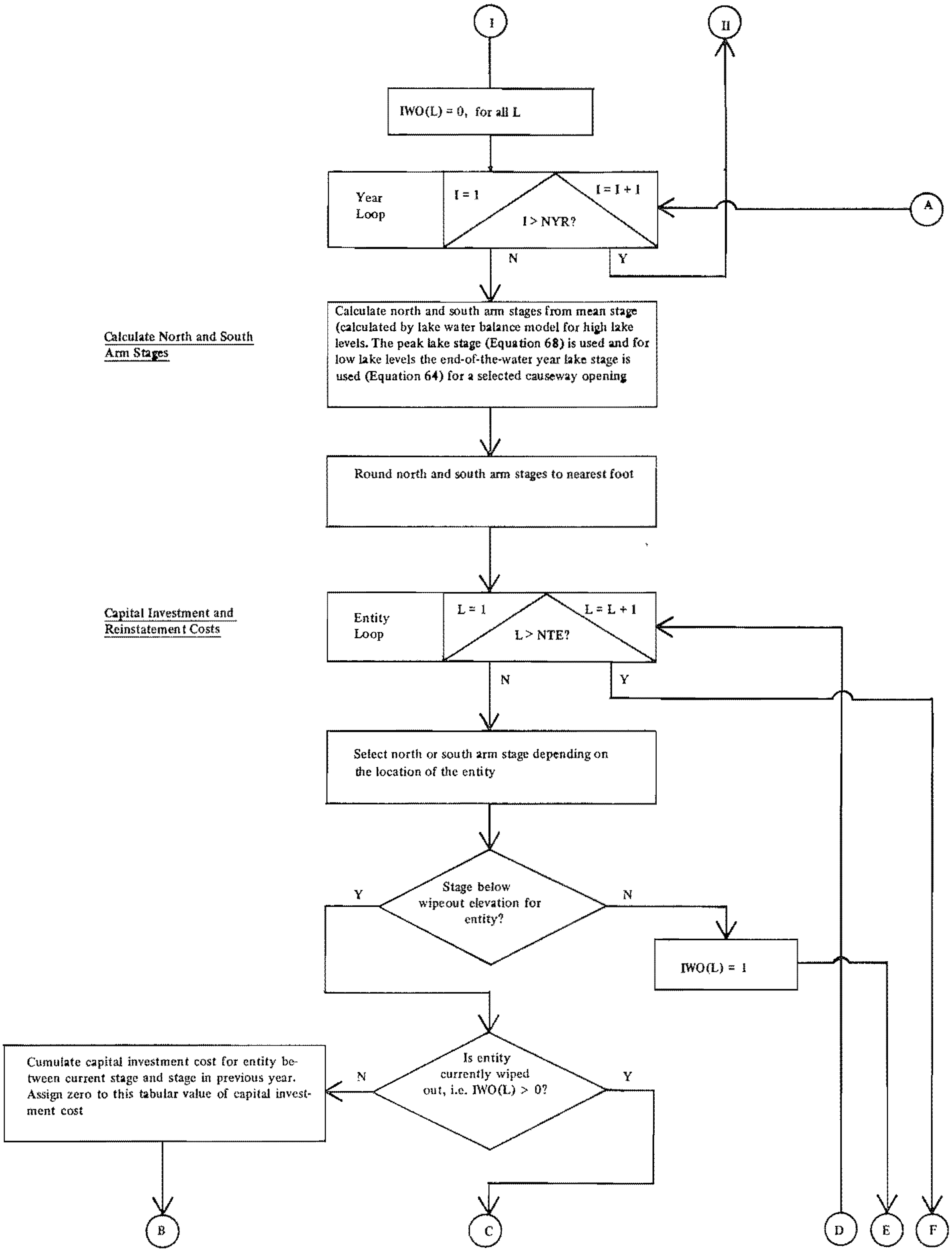


Figure 21. Flow diagram for the damage simulation algorithm.

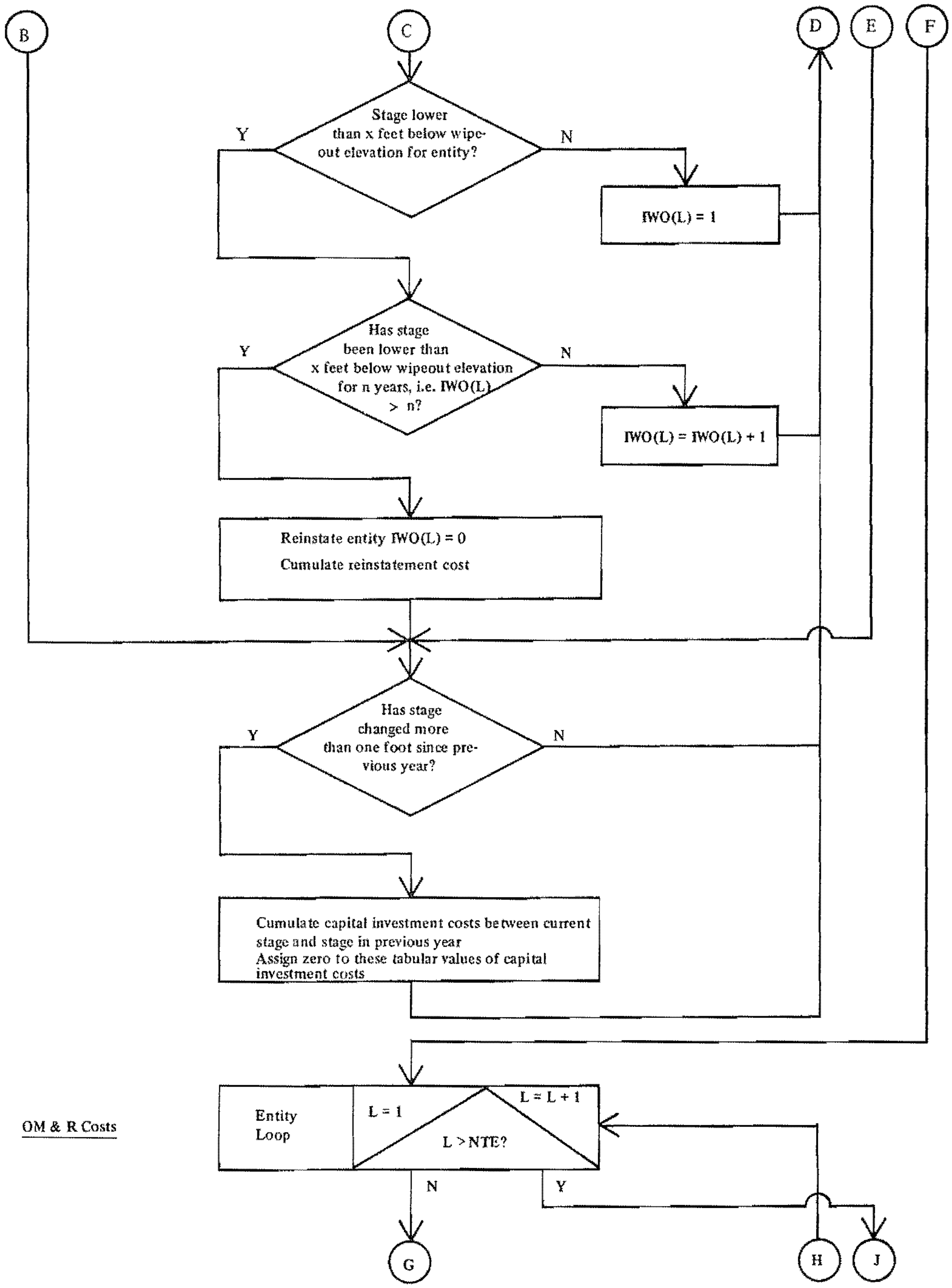


Figure 21. Continued.

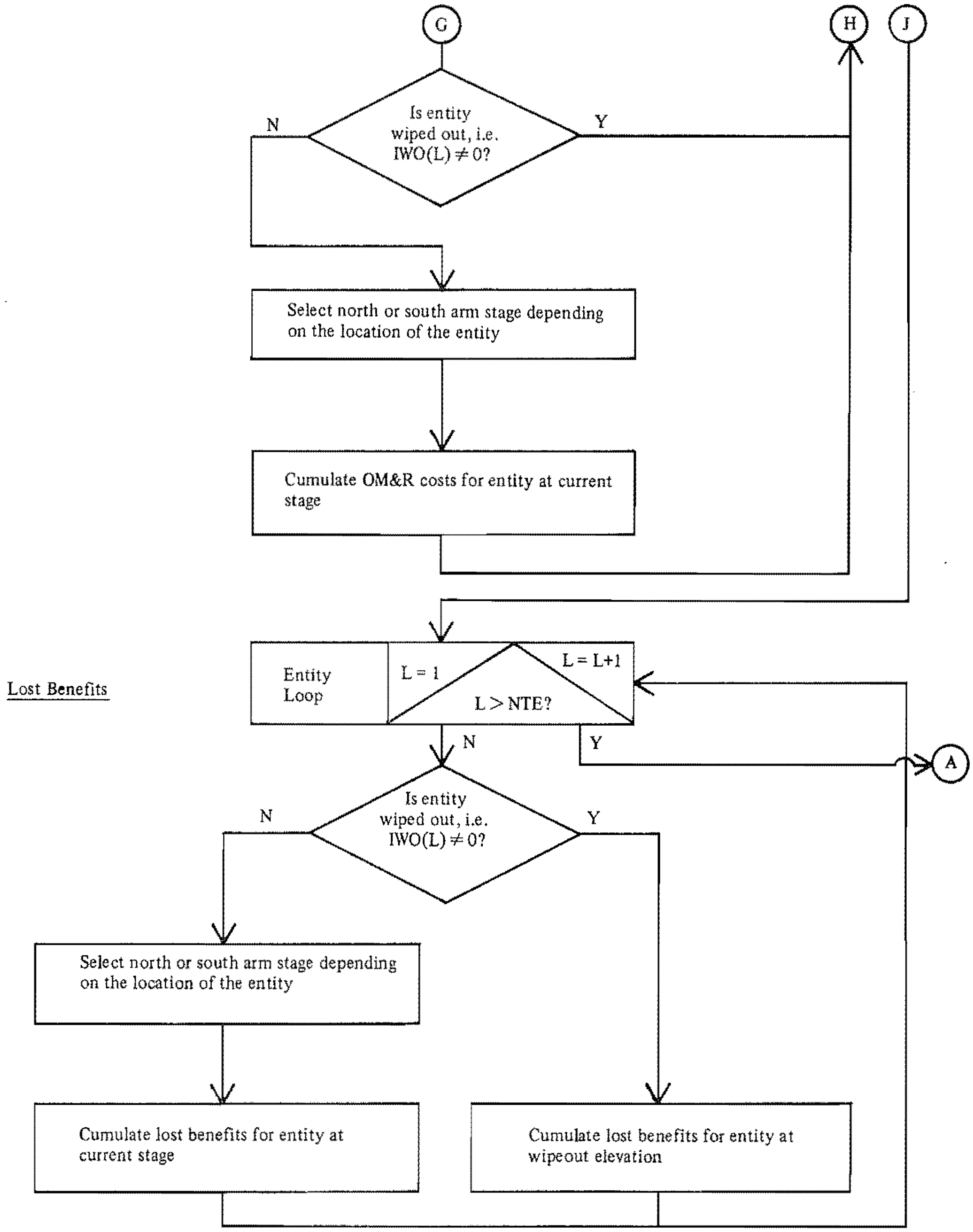


Figure 21. Continued.

wipeout elevation after a damage center L has been wiped out. Stages are estimated for the north and south arms in the first part of the algorithm. The remaining parts estimate capital investment and reinstatement costs, operation and maintenance costs, and lost benefits.

An entity threatened by damages during periods of rising lake stage may protect itself by the building or raising of levees. As such an entity experiences lake stages that are higher than it has previously had to face, it may raise its levees. If the lake subsequently falls and rises again, it will not be necessary to raise the levees until stages higher than those previously experienced occur.

The damages obtained from the Bureau of Economic and Business Research interviews were summarized in tables of capital investment and annual maintenance costs projected by each company or agency should the lake rise or fall so many feet from its present stage. Since the cost data were obtained by

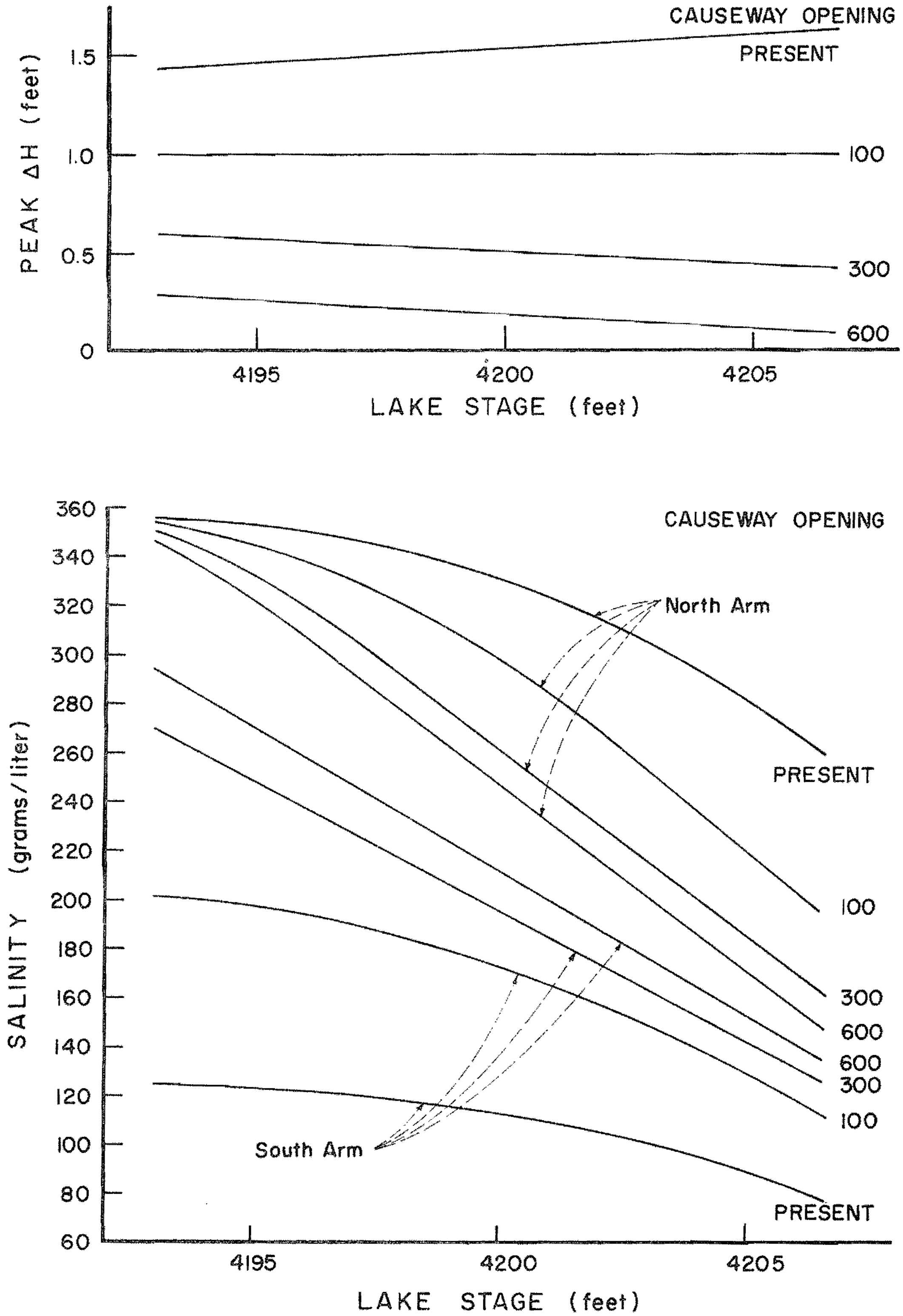


Figure 22. Summary of new causeway opening effects on salinity and elevation as a function of lake stage for Great Salt Lake.

giving an assurance of confidentiality, actual numbers cannot be published for the individual entities. The number of damage centers are so few that even accumulation of the results into collective stage-damage tables would reveal confidential information; however, the form of the information will be presented through a hypothetical example.

Table 41 shows capital investment and OM&R cost data for damage mitigation measures for a hypothetical mineral extraction company on the Great Salt Lake. When the lake level rose to 4202 feet above mean sea level in 1976 the hypothetical company raised its levees to provide protection up to approximately 4203 feet. If the lake rises to 4204 feet, the company estimates it will cost $1.8 million (1977 dollars) to raise its levee to provide an additional two feet of protection. Were the rise to continue to 4206 feet, an additional investment of $2.4 million would be required. A rise to 4208 feet would require still an additional $3.6 million to provide flood protection to approximately 4209 feet. At an elevation of 4210 feet, the company could no longer afford the costs of further flood protection, perhaps because they could no longer raise their existing levees because of foundation problems and would therefore have to build completely new structures. Thus, 4210 feet has been called the "wipe out elevation."

Even though the company has invested hundreds of thousands of dollars in raising their levees to provide protection to 4203 feet, these costs have already been incurred and therefore are not shown on Table 41. For the same reason, after a capital investment is read from the table and counted as a damage, that value in the table is set to zero so that it will not be counted again if the lake falls and then later rises to the same elevation in subsequent years. This assumes that once a protective levee is built that it will not need to be replaced even though the lake may recede to the point where it is no longer needed for years. In each year of the damage simulation, OM&R costs are taken from the table for the current stage. OM&R costs once changed are not eliminated in the way that capital costs are, and therefore OM&R costs associated with earlier capital investments below 4204 feet are included in Table 41 between 4200 feet and 4203 feet.

Table 41 also contains costs for purchasing and operating pumps and installing pipelines to deliver brines to the evaporation ponds when lake levels are low. A low-stage "wipeout elevation" would also be expected before the lake dries up; however, none of the mineral extraction companies gave a low-stage wipeout elevation.

In all, 21 cost centers were used. While most of the data were obtained from the referenced surveys, some supplemental losses were estimated directly from data accumulated in this study as reported above. These were 1) the recreation benefits lost by closure of access to Antelope Island equal to the amount shown on Table 38, 2) the recreation benefits lost by flooding of the beach areas at the south end of the lake beginning at elevation 4202 and reaching the full amount shown when the lake level reaches 4211, and 3) the hunting recreation losses estimated from the data shown on Table 39 when marshlands are flooded.

In estimating damages from the 21 cost center tables illustrated in Table 41, capital investments are considered to be required only once and that the first time the lake reaches a threatening stage. OM&R costs are suspended when an entity has discontinued operation due to extreme lake levels (i.e., been "wiped out") and restored when facilities are reinstated. Reinstatement may occur several times after wipe outs during a 125-year simulation. Some losses in the fourth group of damages may occur during periods of moderately high water, but the major losses are revenues or benefits unobtainable during periods of wipe out. Each cost center has a range of lake stages in which little or no damage occurs (costs incurred equally at all lake stages are not considered damages). Some cost centers suffer some damages at lower stages, and all suffer damages that are substantially larger at high stages.

Table 41. Costs of damage mitigation measures vs. stage for a hypothetical mineral extraction company on the Great Salt Lake.

Lake Stage Feet, msl	Capital Investment $000	Annual OM&R $000	Reinstatement[b] Cost $000	Lost Benefits $000
4185	0	18	0	0
4190	90	10	0	0
4193	0	6	0	0
4195	40	4	0	0
4196	0	0	0	0
4197	0	0	0	0
4198	0	0	0	0
4199	0	0	0	0
4200	0	50	0	0
4201	0	50	0	0
4202	0	100	0	0
4203	0	100	0	0
4204	1800	200	0	0
4205	0	200	4000	0
4206	2400	260	0	0
4207	0	260	0	0
4208	3600	400	0	0
4209	0	400	0	0
4210	0[a]	0[a]	0	1500
:	:	:	:	:
4220	0	0	0	1500

[a]Facility wiped out at 4210.

[b]In the computer model, this single number and elevation is read separately from the information in the other three columns.

Reinstatement. Because the trend in lake stages can reverse from falling to rising in any year, investors can be expected to wait until the lake is several feet below the wipe out elevation before they will reinvest in property that they previously abandoned. The timing of reinstatement in the damage simulation model is determined by summing within the model the number of years the lake has been continuously x feet below the wipe out elevation. When the number of years exceeds n, reinstatement is assumed at cost C. For the Great Salt Lake damage simulation, x was set to 3 feet, n to 0 years, and C was varied by entity.

Computer programming. The damage simulation algorithm programmed following the flow diagram in Figure 23 and nested in a simulation model following the flow diagram in Figure 24 is documented in Appendix F. The documentation includes a program listing, a description of the required input, explanation of the output, and a dictionary of variables.

Estimated Damage Costs

The damage simulation algorithm is executed once for each sequence of lake stages obtained from the lake water balance model to establish an annual damage sequence from the national viewpoint. Each annual damage sequence is converted to a present worth as of October 1, 1978, by using the current federal discount rate of 6 7/8 percent. Present worths are calculated from eight time horizons (2, 5, 10, 25, 50, 75, 100, 125 years). The computation for 125 years is to have a figure to compare with previous work by the Utah Division of Water Resources based on the 125-year period of record. In addition, an equivalent uniform annual series is calculated for each present worth by:

$$R_m = P_m \text{ (R/P, m years, 6.875\%)} \quad . . . . (77)$$

in which

R_m = uniform annual amount based on an m-year time interval

P_m = present worth based on m years of damages

(R/P, m years, 6.875%) = capital recovery factor for m years at 6.875 percent discount rate

Finally the first four moments of the distribution of these estimates for various simulated lake stage sequences are computed.

Results of the Damage Simulation

Since the purpose of this phase of the study was to develop a model that could be used to estimate and compare the benefits from alternative lake level control measures rather than to perform actual planning comparisons, two possible alternatives were selected for the purposes of illustration. These were the alternatives of 1) increasing consumptive use of Bear River water in all years by 10 percent and 2) pumping a net flow of 310,000 acre-feet annually into the Western Desert when the lake water level exceeds 4202 feet. As evaluated from 20 125-year synthetic lake stage traces, the estimated costs from the national viewpoint of accommodation to the lake level fluctuations expected if no measures and if each of these two measures are taken and the estimated benefits from the two measures are shown in Table 42. The 50- and 100-year estimates correspond with time horizons often used in water resources planning from the national viewpoint and give benefits to compare with the costs of implementing the measures to judge their economic feasibility. The short-term benefits (2, 5, and 10 year) provide data for judging the urgency in implementing the measures.

One can see from the figures on Table 42 that the alternative of increasing consump-

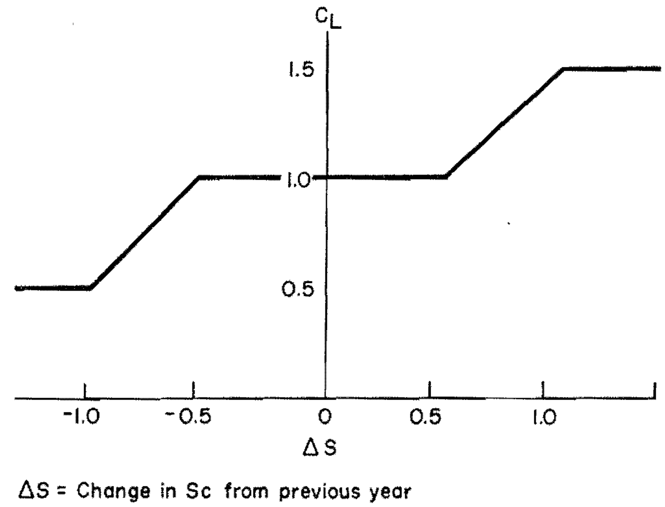


Figure 23. Coefficient for correcting ΔS for time lag effects of flow through the causeway.

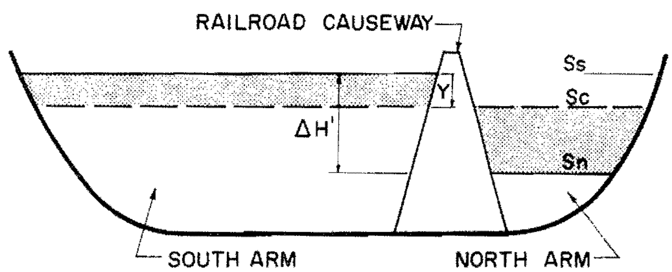


Figure 24. Schematic cross-section of the Great Salt Lake illustrating the technique for estimating north and south arm stages from the stage under combined-arm conditions.

Table 42. Average annual estimated lake level control benefits[d] from two possible control measures.

Years To Planning Horizon	Cost of Accommodation[a]	Consumptive Use Increase[b]		Pumping To Desert	
		Cost	Benefit	Cost	Benefit
2	1.076	1.076	0.000	1.076	0.000
5	1.169	1.169	0.000	1.168	0.001
10	1.168	1.272	-0.104	1.136	0.032
25	1.520	1.499	0.021	1.347	0.173
50	1.533	1.484	0.049	1.371	0.162
75	1.559	1.508	0.051	1.396	0.163
100	1.560	1.508	0.052	1.396	0.164
125	1.559	1.508	0.051	1.396	0.163

[a]Discounted average annual damage caused by lake level problems.

[b]Plan to increase consumptive use of Bear River water in all years by 10 percent.

[c]Plan to pump water into the Western Desert at a net rate of 310,000 AF/yr when lake water level is higher than a control elevation of 4202.

[d]All values are in million dollars annually.

tive use of Bear River water produces less than one-third as many benefits as does the alternative of pumping into the Western Desert. In some situations, the first alternative actually increases losses by causing the lake to drop more quickly to low stages causing more damages. One can also see that at present lake stages, neither measure provides significant benefit over the next five years. Only if planning and implementation periods exceed ten years would immediate action be justified.

CHAPTER 8

SUMMARY AND RECOMMENDATIONS

Summary of Results

This study produced a stochastic flow simulation model (described in Chapter 4 and documented in Appendix D) that provides input to a water balance model (described in Chapter 6 and documented in Appendix E) which in turn provides a basis for a damage simulation model (described in Chapter 7 and documented in Appendix F). The flow simulation model uses input sequences of evaporation, precipitation, and streamflow over a common historical period as a basis for generating simultaneous sequences of evaporation, precipitation, and up to three streamflows using a multivariate autoregressive ARMA (1,0) model. The water balance model inputs traces of these sequences to simulate corresponding traces of rises and falls in lake stage over a period beginning with present conditions and extending to a desired planning horizon of up to 125 years. The damage simulation model inputs traces of lake stages and information on the effects of various lake stages and lake stage sequences on damage centers near enough to the lake to be affected by stages less than 4220 feet above mean sea level to simulate corresponding damage traces and compute the damages to a variety of desired planning horizons on a present worth basis.

Since each trace represents an equally likely future scenario, a probabilistic estimation of lake stages for given dates in the future, of the time until a given high or low stage will be reached, or of average annual damages expected over a given time period with or without given control measures is established by generating many such sequences and averaging the results. Approximately 100 traces of stages or damages provide adequate representation for most purposes.

The primary users of the sort of information generated by these three models are people who manage property near the lake and public planning agencies concerned with lake level control. Property managers need information such as that shown in Figures 11, 12, and 13 on probable lake surface elevations and on durations the lake level can be expected to remain within elevations favorable to their operation. Public agencies considering lake level control programs need information such as that shown in Table 41 to establish benefits that they can compare with costs in evaluating program economic justification. They also need information such as that shown in Figures 14, 15, and 16 so that they can discuss program effects with people near the lake as part of their public participation process.

Figures 11, 12, and 13 present the best estimate of this study of probable future Great Salt Lake levels, based on flow and stage conditions existing October 1, 1978. Each year the curves will change because of 1) changing initial flow and stage conditions, 2) longer data series providing better estimates of model parameters, and 3) possible advances in model formulation. The computer programs presented in the appendices of this report can readily be used to make the first two sors of updates, and they will be rerun periodically with updated information for the Great Salt Lake. Interested users who want updated information after February 1980, should contact Utah Water Research Laboratory. Advances in model revisions will be made when appropriate.

UWRL is applying the damage simulation model to evaluate various lake level control alternatives, and those results should be published in 1980. The models presented in this report could be used to evaluate other alternatives as well, and those interested in doing so should contact the Laboratory for information on how to utilize this capability.

Recommended Directions for Model Refinement

The issues in model development and calibration raised in the first chapter were resolved as best they could under the time and cost constraints of this study as described in Chapters 2 through 7. Further refinements would be very helpful, and those recommended can be classified between the two general areas of methodological refinement and data refinement.

Methodological Refinement

1. The multivariate ARMA (1,0) model used in this study to generate hydrologic sequences produced the best results of any model tried, but the process of its develop-

ment suggested that a number of further efforts would be worthwhile in trying to improve the model or the estimation procedures for its parameters. The major needs are to develop a practical unbiased alternative to the method of moments for parameter estimation and to improve the model to do a better job of preserving persistence and higher order cross correlation matrices. The latter needs are particularly important in cases such as the Great Salt Lake where one has to use flows based on present conditions in which man-made storage significantly increases the magnitude of these effects. The homogeneous ARMA model is the most promising tool suggested by this study for this purpose. ARMA models other than ARMA (1,0) and ARMA (1,1) would also fit into the proposed homogeneous framework. The correlation matrices obtained in this study (Table 28) may be better represented by higher order autoregressive components; however, use of such models is handicapped by not having bias correction procedures similar to those provided by O'Connell (1974) for the first order process. Experimental work is needed to develop appropriate procedures. The consistent data series on Table 15 provide a ready information source that can be used in such efforts as program development.

2. The rejection of generation of natural flows was caused by the inability of the regression model used in this study to convert natural to present modified flows. It may be possible to alleviate this difficulty by developing a more sophisticated model for this purpose. Possible ideas in this direction include correlation of consumptive use with precipitation and evaporation data and direct use of operating rules for reservoirs and diversions. An added advantage to a more sophisticated model for this purpose is that present conditions change and the model would provide a convenient tool for quantifying the hydrologic effect of such changes sort of periodically changing the entire data set. The model should be dual directional so that one can estimate present from natural as well as natural from present flows. Such a model would also provide a valuable starting point for analyzing the effects of projected future watershed changes or proposed facility developments.

3. The modeling done in this study was entirely stochastic in that it did not recognize any effects on the hydrologic variables caused by long-period climatic cycles or by a feedback relationship between evaporation from the lake surface and precipitation on and runoff from downwind mountains. Either process could have a substantial effect on lake level probabilities, and both deserve continuing evaluation. A study that could develop definitive information in either area would make a real contribution. The information would need to quantify how precipitation and streamflow vary over established cycles as well as the periodicity of the cycles.

4. The damage simulation model can be extended to estimate damages from the viewpoints of the people of Utah and of governmental revenues and expenditures. These tasks were started and are contained in a partially developed state in the model documented in Appendix F, but further work is needed to make them useful for providing additional information to decision makers in state and local government in Utah.

5. A number of the principles used in damage simulation deserve further review. Storm wave damage is not directly included; neither are effects of lake level on lake salinity on mineral extraction industry profit. Marshlands and other lakeside property probably have economic values beyond those for hunting that could well be defined and included. Real estate values in the area would provide useful data. The scenarios of wipeout and reinstatement were established without actual empirical information.

<u>Data Refinement</u>

1. The present modified flows used in this study may not be the best possible estimates of flow series all expressed on a consistent present condition basis. Furthermore, present conditions change with time and a basic revision will become necessary in the future and may be already advisable because of watershed changes and facility development that have occurred since the present series were established. The entire set of present modified flow series could well be evaluated for homogeneity and adjusted as found advisable.

2. The flows used as a basis for stochastic flow generation in this model covered the period of common record for all five principal hydrologic variables of 1937-1977. Series extending back to 1890 are available for four of the five variables, more fragmentary hydrologic records extend back past 1850, and tree rings or other indicators provide some basis for extending back past 1700. Considerable value would exist in a careful empirical evaluation of various alternatives for ignoring or using these sorts of information and for developing guidance that others could use in developing a data base with maximum information content for their studies.

3. The existing water balance model is calibrated to estimate ungaged streamflow and subsurface flow into the lake by matching recorded lake stages. Additional stream gaging or aquifer discharge studies would provide a firmer data base. Other possible areas of information improvement could address lake precipitation and lake evaporation and how it varies over the lake surface and with salinity currents within the lake.

4. Damages are estimated from stage-damage information obtained from managers of 21 damage centers near the lake as supplemented by information on recreation benefits estimated in this study. A thorough assess-

ment of that data could probably significantly improve the damage assessment and the revised data cards could be processed directly. Some minor damage centers were not assessed even though they may well suffer some loss should lake levels rise to 4220 feet above mean sea level. At this higher elevation, several additional damage centers might well be revealed by a more thorough analysis.

5. Damages can also be expected to change because of changing land use around the lake, changes in demand for outputs produced near the lake, and inflation. Significant changes of these first two sorts should be used to alter the stage damage relationships. Annual inflation factors need to be applied to all stage-damage information.

Generalization to Other Terminal Lakes

The procedures outlined in this study can be applied to establish lake level probabilities on any terminal lake. The tabulated data provide an example that can be followed in data collection elsewhere, and the data collected elsewhere can then be used with the computer programs provided to estimate stage probabilities and the damages associated with stage fluctuations. Specific points to watch in this process include:

1. Special care should be exercised to estimate precipitation and evaporation over the lake surface.

2. One or two stream inflow sequences can be used where three are not needed.

3. At locations where there are few upstream storage reservoirs or diversions, it may be possible to establish a better model for relating flows between a natural and a present basis than was possible in the large and complex Salt Lake basin. If so, stochastic generation of natural flows and conversion to present conditions may work better than it did in this study, and trying and testing this approach is recommended. Generally, however, terminal lakes are found in arid climates where water is sought out and used so that available supplies have long since been put to beneficial use. Present flows into the lake would be expected to be much less than natural flows, and historical flows extending back over a long time period would be expected to have followed a decreasing pattern as more of the water has been beneficially used. Historical flows should not be used as model input unless it can be shown that conditions have not significantly changed over the period of record.

4. Application to one terminal lake does not provide a generally applicable rule for choosing between the ARMA (1,1) and the ARMA (1,0) model for stochastic modeling. If time is available, these models and perhaps others should be tried and compared. If a more approximate estimation is acceptable, the ARMA (1,0) model programmed in Appendix E can be used directly.

5. Any model application should be run against historic lake stages to check calibration. Such a run will show whether inflows and outflows are in reasonable balance and provide a basis for estimating ungaged quantities. The empirical equations used in this study for estimating ungaged streamflow and subsurface flow are applicable only to the Great Salt Lake and shall be modified as necessary to achieve the proper water balance as part of the calibration process at other sites.

6. If the periods of record for available data series are fairly short at a study site, it is wise to compare their distribution and correlation statistics with those of longer records as close to the site as possible. If the period of common record in the longer record has a quite different distribution than does the total longer record, adjustment should be considered.

7. Stage-damage information has to be collected or estimated for each terminal lake to which damage simulation is applied. One needs to be very careful in the interviewing process necessary to collect these data to probe managers on effects on their damage center in sufficient detail to get reliable results. Damage relationships are much more difficult to generalize than are hydrologic relationships, and additional programming will quite likely be necessary to apply the program to situations at other locations.

8. The hydrologic and benefit evaluations of lake level control measures are programmed for general applicability. The approaches used, however, should be reviewed for how well they match control measures being considered at other sites and modified as necessary.

Assessment of Results

Despite the possibilities for model and data refinement enumerated in the last section, the lake stage probability and damage estimates made through this study are believed to be quite reliable for guiding decision making dependent on short-term stage conditions such as might occur over the next five to ten years. Over the longer term, uncertainties are larger. The effects of persistence, downwind evaporation-runoff feedback, and longer climatic cycles would be greater. Damage estimation is less reliable at stages outside the range experienced by those making the estimates. Continued work at methodological and data improvement can reduce these uncertainties, but continual review is necessary, no matter how good the model, as a reliability check.

REFERENCES

American Association of State Highway Officials. 1960. Road-user benefit analyses for highway improvement, Part I, Passenger cars in rural areas. Washington, D.C.

Allen, D. E. 1977. Forecasting the level of Great Salt Lake. Unpublished Working Paper. Management Department, College of Business, University of Utah, Salt Lake City, Utah. 47 p.

Anderson, R. L. 1962. Distribution of the serial correlation coefficient. Annals of Mathematical Statistics 13:1-13.

Armbruster, J. T. 1978. Personal communication. June.

Assaf, Gad. 1977. The Great Salt Lake: An application of physical studies. Unpublished Utah Water Research Laboratory manuscript, Logan, Utah.

Beard, L. R. 1976. Application of stochastic methods in water resources studies. Chapter 7 in: H. W. Shen (ed.). Stochastic approaches to water resources. H. W. Shen, P.O. Box 606, Fort Collins, Colorado. p. 7.6.

Bianchi, D. H. 1969. The economic value of streams for fishing. Water Resources Institute Research Report No. 25. University of Kentucky, Lexington, Kentucky. 119 p.

Bowles, D. S., L. D. James, and W. R. James. 1977. Expected values of reductions in flooding damages on the Great Salt Lake with different causeway openings. Appendix III in: Great Salt Lake management study--causeway breach cost/benefits analysis. Report to the State of Utah Department of Development Services. pp. 43-47.

Box, G. E. P., and G. M. Jenkins. 1970. Time series analysis: Forecasting and control. Holden-Day, Inc., San Francisco, California. 553 p.

Breaden, John P. 1973. The generation of flood damage time sequences. Water Resources Institute Research Report No. 32. University of Kentucky, Lexington, Kentucky. 150 p.

Bureau of Economic and Business Research, College of Business, University of Utah. 1977. Section I, Executive summary, Great Salt Lake resource management study 1977. Salt Lake City, Utah. 25 p.

Bureau of Economic and Business Research, College of Business, University of Utah. 1977. Section II, Causeway breach cost/benefit analysis, Great Salt Lake resource management study 1977. Salt Lake City, Utah. 53 p.

Burges, S. J. 1970. Use of stochastic hydrology to determine storage reservoirs: A critical analysis. Program in Engineering Economic Planning, Report EEP-34. Stanford University, Stanford, California. 208 p.

Burges, S. J. 1978. Discussion of "Reservoir yield: An important environmental parameter." by L. M. Eisel. Water Resources Bulletin 14(5):1251-1253.

Burges, S. J., and Kiyoshi Hoshi. 1978. Approximation of a normal distribution by a three-parameter log normal distribution. Water Resources Research 14(4):620-622.

Burges, S. J., and D. P. Lettenmaier. 1975. Operational comparison of stochastic streamflow generation procedures. Charles W. Harris Hydraulics Laboratory Technical Report No. 45. University of Washington, Seattle, Washington. 112 p.

Business and Economic Research Center, Brigham Young University. 1977. Section VI, Recreational development of the south shore of the Great Salt Lake, Great Salt Lake resource management study 1977. Provo, Utah. 41 p.

Carson, W. D., Jr. 1972. An investigation of the determinants of reservoir recreation use and demand: The effect of water surface elevation. Davis: HEC Res Note November 2.

Cesario, F. J. 1976. Value of time in recreation benefit studies. Land Economics 52(1):32-41.

Charbeneau, R. J. 1978. Comparison of the two- and three-parameter log normal distributions used in streamflow synthesis. Water Resources Research 14(1):149-150.

Christiansen, J. E., and J. B. Low. 1970. Water requirements of waterfowl marshlands in northern Utah. Utah Division of Fish and Game Publication No. 69-12. Salt Lake City, Utah. 108 p.

Chura, Nicholas J. 1962. Food availability and selective utilization by juvenile mallards (Anas platyrphnchos platyrphnchos L.) on the Bear River Migratory Bird Refuge, Utah. PhD Thesis. Utah State University, Logan, Utah. 121 p.

Claffey, Paul J. 1965. Running costs of motor vehicles as affected by highway design--Interim report. National Cooperative Highway Research Program Report No. 13. Highway Research Board, National Academy of Sciences, Washington, D.C.

Clawson, Marion, and Jack L. Knetsch. 1966. Economics of outdoor recreation. The Johns Hopkins Press, Baltimore, Maryland. 328 p.

Cohenour, R. E. 1966. Industrial development and potential of Great Salt Lake with notes on engineering geology and operational problems. p. 153-163. In: W. L. Stokes (Ed.) Guidebook to the Geology of Utah. Utah Geological Society, Salt Lake City, Utah.

Curry, K., and R. L. Bras. 1978. Theory and applications of the multivariate broken line disaggregation and monthly autoregressive streamflow generators to the Nile River. Technology Adaption Program, Massachusetts Institute of Technology, Cambridge, Massachusetts. 246 p.

Duering, G. E. 1977. An examination of the recreational use of the south shore of the Great Salt Lake and Antelope Island State Parks. Institute for the Study of Outdoor Recreation and Tourism, Utah State University, Logan. 145 p.

Dwyer, J. F., J. R. Kelly, and M. D. Bowes. 1977. Improved procedures for valuation of the contribution of recreation to national economic development. Water Resources Center, Research Report No. 128. University of Illinois, Champaign-Urbana, Illinois. 218 p.

Feller, W. 1951. The asymptotic distribution of the range of sums of independent random variables. Ann. Math. Stat. 22:427-432.

Fiering, M. B. 1963. Use of correlation to improve estimates of the mean and variance. U.S. Geological Survey Professional Paper 434-C USGPO, Washington. 9 p.

Fiering, M. B. 1964. Multivariate techniques for synthetic hydrology. Journal Hydraulics Division, ASCE 90(HY5):43-60.

Fiering, M. B. 1967. Streamflow synthesis. The McMillan Press Ltd., London, England. 139 p.

Fiering, M. B., and B. B. Jackson. 1971. Synthetic streamflows. Water Resources Monograph 1. American Geophysical Union. 98 p.

Gilbert, G. K. 1890. Lake Bonneville. U.S. Geological Survey Monograph 1. U.S. Government Printing Office, Washington, D.C.

Glenne, B., D. W. Eckoff, and J. E. Paschal, Jr. 1977. Predictions of Great Salt Lake levels. In: D. C. Greer (Ed.) Desertic terminal lakes. Utah Water Research Laboratory, Utah State University, Logan, Utah. pp. 199-212.

Grant, E. L., and G. Ireson. 1970. Principles of engineering economy. Ronald Press Company, New York. 415 p.

Hahn, G. T., and S. S. Shapiro. 1967. Statistical models in engineering. Wiley, New York, 355 p.

Hammack, Judd, and G. M. Brown, Jr. 1974. Waterfowl and wetlands: Toward bioeconomic analysis. The Johns Hopkins University Press, Baltimore. 95 p.

Haney, Dan G. 1967. The value of time for passenger cars: A theoretical analysis and description of preliminary experiments. Vol. 1. Stanford Research Institute, Menlo Park, California.

Harza Engr. Co. 1975. Economic impact of fiscal constraints on water project construction. Chicago, Illinois. October.

Hillmer, S. C. 1976. Time series: Estimation, smoothing and seasonal adjusting. PhD Thesis, University of Wisconsin, Madison.

Holbrook, Kenneth G. 1970. The economic value of natural areas for recreational hunting. Water Resources Institute Research Report No. 24. University of Kentucky, Lexington, Kentucky. 132 p.

Holman, Mary A., and James T. Bennett. 1973. Determinants of use of water based recreational facilities. Water Resources Research 9(5):1208-1218.

Hughes, T. C., E. A. Richardson, and J. A. Franckiewicz. 1974. Water salvage potentials in Utah, Vol. 1, Open water evaporation and monolayer suppression potential. Utah Water Research Laboratory Report No. PRWA22-1, Utah State University, Logan, Utah. 78 p.

Hurst, H. E. 1951. Long term storage capacity of reservoirs. Trans. Am. Soc. Civ. Engrs. 116:779-808.

International Mathematical and Statistical Libraries Inc. 1977. Z series subroutines. Vol. 2. Sixth edition. Houston, Texas. (Pages not numbered.)

Institute for Outdoor Recreation and Tourism. 1976. Recreational use, south shore of Great Salt Lake and Antelope Island State Park. Utah State University, Logan, Utah.

James, L. Douglas, and Robert R. Lee. 1971. Economics of water resources planning. McGraw-Hill Book Co., New York. 615 p.

James, L. Douglas, and Jerry R. Rogers. 1976. Economics and water resources planning in America: 1776-1976. Water Resources Planning in America - 1776 to 1976, ASCE Annual Convention. Philadelphia, Pennsylvania. pp. 62-91.

Jettmar, R. U., and G. K. Young. 1975. Hydrologic estimation and economic regret. Water Resources Research 11(5):648-656.

Jones, D. K. 1933. A study of evaporation of the water of Great Salt Lake. Unpublished M.S. Thesis, University of Utah, Salt Lake City, Utah.

Kalinin, G. P. 1968. Global hydrology. Gidrometeoro-logicheskoe Izdatel'stovo, Leningrad. (Translated by Israel Program for Scientific Translations, Jerusalem, 1971.)

Kalter, R. J., and W. B. Lord. 1968. Measurement of the impact of recreation investments on a local economy. American Journal of Agricultural Economics 50(2):243-256.

Klemes, V. 1974. The Hurst phenomenon: A puzzle? Water Resources Research 10(4):675-688.

Knoph, F. L. 1974. Fluctuating levels of Great Salt Lake: Effects on island wildlife. Proc. Utah Acad. Sci., Arts, and Letters 51(2):34-41.

Landsberg, Helmut. 1962. Physical climatology. Gray Printing, Dubois, Pensylvania. 446 p.

Ledolter, J. 1978. The analysis of multivariate time series applied to problems in hydrology. Journal of Hydrology 36:327-352.

Lin, A. 1977. Wave tides of the Great Salt Lake. University of Utah, Salt Lake City, Utah.

Linsley, R. K., and J. B. Franzini. 1964. Water resources engineering. McGraw-Hill, New York. pp. 163-168.

Maass, A., et al. 1962. Design of water resource systems. Harvard University Press, Cambridge, Massachusetts. 660 p.

Mandelbrot, B. B., and J. W. Van Ness. 1968. Fractional Brownian motions, fractional noises and applications. Society for Industrial Applications Mathematical Review 10(4):422-437.

Mandelbrot, B. B., and J. R. Wallis. 1968. Noah, Joseph, and operational hydrology. Water Resources Research 4(5):909-918.

Mandelbrot, B. B., and J. R. Wallis. 1969a. Part 1, Averages and variances; computer experiments with fractional Gaussian noises. Water Resources Research 5(1): 228-241.

Mandelbrot, B. B., and J. R. Wallis. 1969b. Part 2, Rescaled ranges and spectra; computer experiments with fractional Gaussian noises. Water Resources Research 5(1):242-259.

Mandelbrot, B. B., and J. R. Wallis. 1969c. Part 3, Mathematical appendix; computer experiments with fractional Gaussian noises. Water Resources Research 5(1): 260-267.

Mandelbrot, B. B., and J. R. Wallis. 1969d. Some long-run properties of geophysical records. Water Resources Research 5(2):321-340.

Matalas, N. C. 1966. Time series analysis. Water Resources Research 3(3):817-829.

Matalas, N. C. 1967. Mathematical assessment of synthetic hydrology. Water Resources Research 3(4):931-935.

Matalas, N. C., and Barbara Jacobs. 1964. A corelation procedure for augmenting hydrologic data. U.S. Geological Survey Professional Paper 434-E. USGPO, Washington. 7 p.

Matalas, N. C., and J. R. Wallis. 1971. Correlation constraints for generating processes. Proceedings International Symposium of Mathematical Models in Hydrology. Int. Assn. Sci. Hydrol., Warsaw, Poland. pp. 372-376.

Matalas, N. C., and J. R. Wallis. 1974. Generation of synthetic flow sequences. In: A. K. Biswas (Ed.) Systems Approach to Water Management. American Elsevier, New York.

Mejia, J. M. 1978. Personal communication.

Mejia, J. M., I. Rodriguez-Iturbe, and J. R. Cordova. 1974. Multivariate generation of mixtures of normal and log normal variables. Water Resources Research 10(4):691-693.

Mejia, J. M., I. Rodriguez-Iturbe, and D. R. Dawdy. 1972. 2-The broken line process as a potential model for hydrologic simulation: Streamflow simulation. Water Resources Research 9(4):931-941.

Mendenhall, W. 1971. Introduction to probability and statistics. Third edition. Duxbury Press. 466 p.

Miernyk, William H. 1966. The elements of input-output analysis. Random House, New York.

Morgan, D. L. 1947. The Great Salt Lake. University of New Mexico Press, Albuquerque, New Mexico. 432 p.

Morrison, Donald F. 1976. Multivariant statistical methods. Third edition. McGraw-Hill, New York. 415 p.

Nelson, James R. 1968. The value of travel time. In: Samuel B. Chase, Jr. (Ed.). Problems in Public Expenditure Analysis. The Brookings Inst., Washington. pp. 78-126.

O'Connell, P. E. 1971. A simple stochastic modelling of Hurst's law. Proceedings International Symposium on Mathematical Models in Hydrology. Int. Assn. Hydrol. Sci., Warsaw, Poland.

O'Connell, P. E. 1974. Stochastic modelling of long-term persistence in streamflow sequences. Civil Engineering Department, Imperial College, London, England. 309 p.

O'Connell, P.E. 1978. Personal communication.

Rawley, E. V. 1976a. The Great Salt Lake wildlife system. An unpublished report to the Division of Great Salt Lake and the Great Salt Lake Board. Salt Lake City, Utah.

Rawley, E. V. 1976b. Small islands of the Great Salt Lake. Utah Division of Wildlife Resources Publication No. 76-19. Salt Lake City, Utah. 109 p.

Riley, J. P. 1978. The feasibility of utilizing additional water resources development with the Bear River Basin as a means of regulating the levels of the Great Salt Lake, Utah Water Research Laboratory, Logan, Utah.

Rodriguez-Iturbe, I., J. M. Mejia, and D. R. Dawdy. 1972. 1 - A new look at Markovian models, fractional Gaussian noise and crossing theory: Streamflow simulation. Water Resources Research 8(4):921-930.

Salas, J. D., D. C. Boes, V. Yevjevich, and G. G. S. Pegram. 1977. On the Hurst phenomenon. Presented at the Third International Hydrology Symposium, Fort Collins, Colorado. 33 p.

Sanderson, Glen C. (Ed.). 1977. Management of migratory shore and upland game birds in North America. International Association of Fish and Wildlife Agencies, Washington, D.C. 358 p.

Saville, T., Jr., E. W. McClendon, and A. L. Cochran. 1962. Freeboard allowances for waves in inland reservoirs. J. Waterways and Harbors Division, ASCE. pp. 93-124.

Seckler, David W. 1966. On the uses and abuses of economic science in evaluating public outdoor recreation. Land Economics 42(4):485-494.

Seneca, J. J. 1969. Water recreation, demand, and supply. Water Resources Research 5(6):1179-1185.

Smith, David M. 1971. Industrial location: An economic geographical analysis. John Wiley and Sons Inc., New York. 553 p.

Snellman, L. 1977. Extended weather forecasting in relation to future lake levels. Oral presentation to Fifth Annual Conference of the Utah Section of the American Water Resources Association.

Stauffer, N.E. 1977. Personal communication.

Stauffer, N.E. 1979. Perconal communication.

Steed, J. N. 1972. Water budget of the Great Salt Lake, Utah, 1944-1970. Unpublished M.S. Thesis, Civil Engineering Department, University of Utah, Salt Lake City, Utah.

Thomas, H. A., and M. B. Fiering. 1962. Mathematical synthesis of streamflow sequences for the analysis of river basins by simulation. In: A. Maass et al. (Ed.). Design of Water Resource Systems. Harvard University Press, Cambridge, Massachusetts. pp. 459-493.

Thomas, T. C. 1967. The value of time for passenger cars: An analysis and description of preliminary experiments. Stanford Research Institute, Menlo Park, California. Vol. II.

University of Utah. 1977. Great Salt Lake management study--causeway breach cost/benefit analysis. Report to the State of Utah Department of Development Services. 47 p.

U.S. Army Coastal Engineering Research Center. 1973. Shore protection manual. 2 volumes. USGPO, Washington.

U.S. Army Corps of Engineers. 1976. Great Salt Lake study; west desert pumping concept.

USBR. 1967. Hydrologic data, Bear River, below Bear Lake, Utah and Idaho. Studies 1, 2, and 3 compiled by the Logan, Utah Area Office.

U.S. Department of Commerce, Bureau of the Census. . Census of Agriculture. U.S. Government Printing Office, Washington, D.C. 1890-1974.

U.S. Geological Survey. 1941. Surface water supply of the United States, Part 10, Great Basin. Water Supply Paper 880, Plate 2. U.S. Government Printing Office, Washington, D.C. p. 126.

U.S. Geological Survey. 1973. Map of Great Salt Lake and vicinity, Utah. Denver, Colorado.

U.S. Water Resources Council. 1971. Selected data supplement water resources. Appendix V. Great Basin Region Comprehensive Framework Study. Washington, D.C.

U.S. Water Resources Council. 1973. Principles and standards for planning water and related land resources. Federal Register 38(174):24778-24869.

U.S. Water Resources Council. 1976. Guidelines for determining flood flow frequency. Bulletin 17. Washington.

Utah Division of Water Resources. 1970. Great Salt Lake elevations adjusted for the effects of man-caused reduction of the inflow to the lake. Salt Lake City, Utah. 11 p.

Utah Division of Water Resources. 1974. Great Salt Lake: Climate and hydrologic system. Report to Utah Legislative Council. Salt Lake City, Utah. 84 p.

Utah Division of Water Resources, Department of Natural Resources. 1977. Great Salt Lake hydrologic system management alternatives report. Salt Lake City, Utah. 92 p.

Utah Division of Water Resources. 1977. Section III, Great Salt Lake causeway analysis - salinity. Great Salt Lake Resource Management Study 1977. Salt Lake City, Utah. 31 p.

Utah Division of Water Resources and the Utah Water Research Laboratory. 1977. Section IV, Great Salt Lake damage analysis for selected management alternatives. Great Salt Lake Resource Management Study 1977. Salt Lake City, Utah. 54 p.

Utah Water Research Laboratory. 1977. Section V, Preliminary consideration of diking alternatives to provide flood protection at the Great Salt Lake. Great Salt Lake Resource Management Study 1977. Utah State University, Logan, Utah. 157 p.

Waddell, K. M., and E. L. Bolke. 1973. The effects of restricted circulation on the salt balance of Great Salt Lake, Utah. U.S. Geological Survey and Utah Geological and Mineral Survey, Salt Lake City, Utah. 54 p.

Waddell, K. M., and F. K. Fields. 1977. Model for evaluating the effects of dikes on the water and salt balance of Great Salt Lake, Utah. U.S. Geological Survey and Utah Geological and Mineral Survey. Water Resources Bulletin 21, Salt Lake City, Utah. 54 p.

Wallis, J. R., and N. C. Matalas. 1970. Small sample properties of H and K estimators of the Hurst coefficient h. Water Resources Research 6(6):1583-1594.

Wang, B. H. 1971. Working paper related to a Weber River Basin model. Utah Water Research Laboratory, Logan, Utah.

Watts, D. G. 1972. Discussion on "Evaluation of seasonal time-series models application to mid-west river flow data" by A. I. McKerchar and J. Delleur. In: Proc. International Symposium on Uncertainties in Hydrologic and Water Resource Systems, University of Arizona, Tucson, 3:1407-1409.

Weakly, H. E. 1965. Recurrence of drought in the Great Plains during the last 700 years. Agric. Eng. 46(2):85.

Willett, H. C. 1977. The prediction of Great Salt Lake levels on the basis of recent solar-climatic cycles. Desertic Terminal Lakes. pp. 37-52.

Wilson, G. 1973. The estimation of parameters in multivariate river series models. Journal of the Royal Statistical Society, Series B, 35:76-85.

Winfrey, Robley. 1969. Economic analysis for highways. International Textbook, Scranton, Pennsylvania. 923 p.

Yevjevich, V. 1972. Probability and statistics in hydrology. Water Resources Publications. 332 p.

Young, G. K. 1968. Discussion of "mathematical assessment of synthetic hydrology." Water Resources Research 4(3): 681-682.

APPENDIX A

EXTENSION OF BEAR RIVER FLOW RECORDS FROM TREE-RING DATA

Paul A. Kay
Department of Geography
University of Utah

Introduction

Streamflows have been recorded on the Bear River for almost 90 years, but even this period may not be long enough for the statistics calculated from that record to be truly representative of the total hydrologic pattern. In order to seek some general idea of how well the flow record beginning in 1890 represents longer termed climatic patterns, tree ring measurements were taken and examined. Although tree growth is not linked by a direct physical tie to streamflow, the two are logically correlated by both being climatic response functions. In order to maximize the correlation, drought sensitive species were sought because these were thought to respond to precipitation patterns in a way not too different than would streamflow. The dendrohydrologic techniques employed were patterned after those successfully applied by Stockton (1975, 1976) and discussed by Fritts (1976).

Dendrochronological Data

Initially six sample sites, where numbers of old trees were known to be growing, were selected with a view to obtaining coverage for the entire Great Salt Lake Basin (Figure A-1). Only the sampling work at the Rex Peak site in the Bear River Basin, however, was completed in time to report here and that is based on only one rather than at the several stands recommended for optimal results. One site is likely to bias the results with strictly local factors associated with microclimate, soil, disease or some other factor not general to the basin as a whole.

The Rex Peak site is located in the Crawford Mountains southeast of Bear Lake. The cores were taken from 12 trees of *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco (douglas-fir) on the steep west-facing flank of Rex Peak. Douglas-fir tends to be particularly sensitive to moisture supply. Some of the cores collected proved difficult of analysis; but chemicals recently obtained for a staining process may enhance the visibility of ring structure, allowing later addition of these cores to the stand chronology. For this report, a master chronology was constructed from 18 cores. The maximum age recorded is 280 years, thus adding nearly two centuries to the historic Bear River flow record.

The mean sensitivity (a first-order difference measure, indicating low-frequency response) of the individual cores was in the range of 0.34-0.47. An empirical rule of thumb in the southwest is that workable series have mean sensitivities of 0.3 and greater (Fritts, 1976). Cross-dating was achieved and checked for the cores in the stand, ensuring the proper assignments of dates. The mean sensitivity for the master chronology, however, was only 0.21. A re-examination of the individual cores indicated that, while key years appeared in all series, they were not always proportionately narrow. The master chronology, therefore, shows less variability than any of its constituent cores. The annual indices of the master chronology are presented in Table A-1. Particularly narrow rings grew in 1977, 1970, 1961, and 1940, for example. These were all abnormally dry years in the rainfall record at Woodruff, Utah, the closest precipitation gage.

Transfer Functions

Transfer functions, relating streamflow to tree-ring indices, are constructed by regression and have the form:

$$\hat{Q}_t = b_0 + b_1 I_t + \epsilon$$

where $\hat{Q}$ are the predicted streamflows, b_0 and b_1 are the regression coefficients, I are the tree-ring indices, and ϵ are the residuals, for years t. The regression was based on the historic period of record for the Bear River (1890-1977) and the annual tree-ring indices for Rex Peak and gave:

$$\hat{Q}_t = 585300 + 558900\, I_t \quad . \ . \ . \ . \ . \ . \quad \text{(A-1)}$$

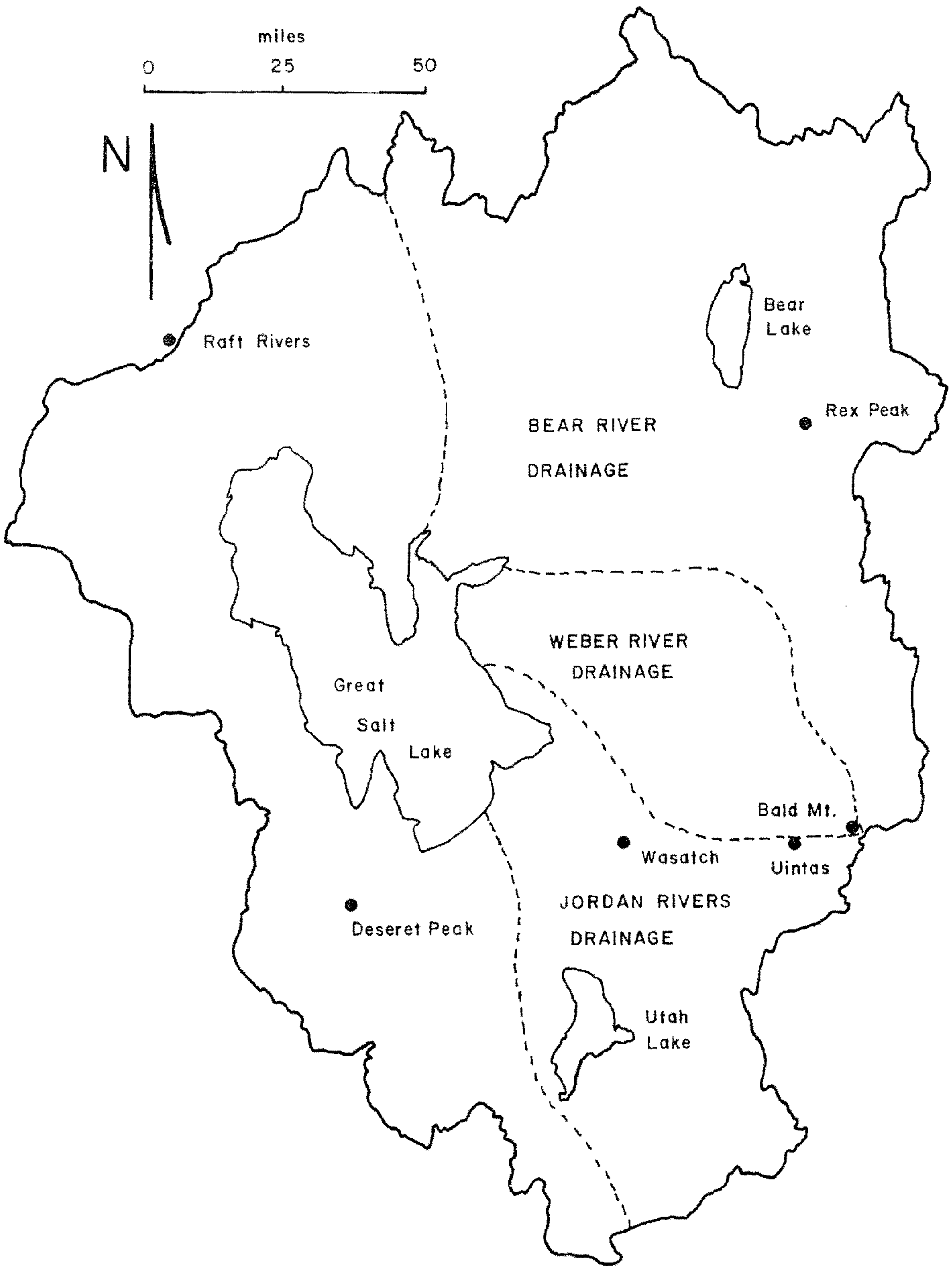


Figure A-1. Great Salt Lake basin, showing the location of some of the tree-ring sites.

Table A-1. Rex Peak master chronology.

Year	Index									
	0	1	2	3	4	5	6	7	8	9
1698									2.4105	1.3484
1700	0.7396	0.5363	0.9720	0.3458	1.0038	0.8541	0.6285	0.3281	0.4225	0.5940
1710	0.7311	1.0422	0.7050	0.8245	0.8075	0.8252	1.0290	1.0509	0.6887	0.9649
1720	0.6820	1.1396	0.9728	1.1556	1.3109	1.3762	1.2004	1.0917	1.3713	1.3657
1730	0.8363	1.0970	1.1418	0.9921	1.3351	1.2735	1.2723	1.2263	1.0913	1.1731
1740	0.8856	0.6419	0.9597	1.1171	0.9244	0.9365	1.0473	1.1370	1.2768	1.1619
1750	1.1018	1.4448	1.5834	1.5417	1.1874	1.2565	1.1863	0.9304	0.9602	1.2266
1760	1.0276	0.9163	1.0494	1.1667	0.9911	0.9701	1.1087	1.0121	1.4794	1.3702
1770	1.3728	1.3394	1.3521	1.0620	0.9970	0.5509	0.7666	0.5412	0.5074	0.5093
1780	0.5625	0.5771	0.5692	0.5362	0.6046	0.6829	0.7498	0.7324	0.8324	0.9719
1790	0.9166	0.9150	1.1873	1.1081	0.9754	1.0722	0.9661	0.6363	1.0875	0.8218
1800	0.9641	1.1097	0.9334	0.9659	0.7853	0.9115	0.9668	0.7503	0.8924	0.7991
1810	0.7787	0.9078	1.0102	1.2577	0.9966	0.6141	0.9503	0.8857	1.0695	0.8214
1820	1.0748	0.9276	1.1127	0.7715	0.9006	0.7839	0.8280	1.1764	1.2646	1.3508
1830	1.0730	0.9213	0.9054	0.9236	0.8828	0.8344	0.6827	0.8341	0.9846	1.0490
1840	1.3226	1.1461	1.3914	1.2144	1.1918	1.1628	0.8127	0.7477	0.5360	0.8779
1850	0.9702	1.0656	0.9534	0.9791	1.2386	1.5967	0.9401	0.6708	0.6164	0.8341
1860	0.8138	0.6393	0.6227	0.7870	0.6431	0.4695	0.4591	0.8412	1.0605	1.1209
1870	1.2740	1.2446	0.4869	0.5974	0.9751	0.9984	1.0607	1.2142	1.0247	0.7439
1880	0.3411	0.7186	0.7343	0.5509	0.5664	0.6960	0.8573	0.6402	0.5115	0.5713
1890	0.4797	0.6698	0.9048	0.8712	0.8529	1.1126	1.1891	1.0715	1.1872	1.1098
1900	0.5791	0.8705	0.8306	0.6515	0.7148	0.8734	0.9203	1.1992	1.6825	1.4103
1910	1.3347	1.2125	1.4976	1.7816	1.9545	1.9027	1.3762	1.3970	1.1334	0.7981
1920	0.5991	1.0592	1.2293	1.3667	1.3775	1.3795	0.9302	0.7222	0.8469	0.8186
1930	0.8862	0.9366	0.6797	0.8083	0.6690	0.7961	0.5816	0.9316	1.0734	0.8886
1940	0.5017	1.3110	1.2789	1.0656	1.3681	1.0475	1.4139	1.5774	1.6616	1.5464
1950	1.6663	1.3947	1.4476	1.1223	0.6090	1.0655	1.1553	1.1370	0.7046	0.9225
1960	0.8712	0.3779	1.0359	1.0883	0.7355	0.9564	1.2031	1.0581	1.0355	1.1883
1970	0.4957	1.1809	1.3457	1.4691	1.0804	0.9998	1.2569	0.3725		

Year	Number of Cores									
	0	1	2	3	4	5	6	7	8	9
1698									1.	1.
1700	1.	1.	1.	1.	2.	2.	2.	2.	3.	3.
1710	3.	4.	4.	5.	5.	5.	5.	5.	5.	5.
1720	5.	5.	5.	6.	6.	7.	7.	7.	7.	7.
1730	7.	7.	7.	7.	7.	8.	9.	9.	9.	9.
1740	9.	9.	9.	9.	9.	9.	9.	9.	9.	9.
1750	9.	9.	9.	9.	9.	9.	9.	9.	9.	9.
1760	9.	9.	9.	9.	9.	9.	9.	9.	9.	9.
1770	9.	9.	9.	9.	9.	9.	9.	9.	9.	9.
1780	9.	9.	9.	9.	9.	9.	9.	10.	12.	12.
1790	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1800	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1810	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1820	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1830	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1840	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1850	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1860	12.	12.	12.	12.	12.	12.	12.	12.	12.	12.
1870	12.	12.	12.	12.	12.	12.	12.	12.	14.	14.
1880	14.	14.	14.	14.	15.	15.	15.	15.	16.	16.
1890	16.	16.	16.	16.	16.	18.	18.	18.	18.	18.
1900	18.	18.	18.	18.	18.	18.	18.	18.	18.	18.
1910	18.	18.	18.	18.	18.	18.	18.	18.	18.	18.
1920	18.	18.	18.	18.	18.	18.	18.	18.	18.	18.
1930	18.	18.	18.	18.	18.	18.	18.	18.	18.	18.
1940	18.	18.	18.	18.	18.	18.	18.	18.	18.	18.
1950	18.	18.	17.	17.	17.	17.	17.	17.	17.	17.
1960	17.	17.	17.	16.	16.	16.	16.	16.	16.	14.
1970	14.	14.	14.	14.	14.	13.	13.	12.		

Missing Rings. Percent Missing = .12   Average Ring Width = 769.83

For Anova Period, 1895-1951

Missing Rings. Percent Missing = .29   Average Ring Width = 925.24

The standard error of estimate is 450,000, and the R^2 is 0.155.

The model was improved by including, as predictor variables, the values of indices from previous years. Tree-rings possess considerable serial correlation, as food reserves may be stored or used, thus buffering sensitivity to the current year's weather. Since the dependent variable, streamflow, also possesses considerable persistence, the best model incorporated both lagged indices and lagged streamflows:

$$\hat{Q}_t = 1799 + 380550\ I_t - 222140\ I_{t-1} + 89140\ I_{t-2} + 0.374\ Q_{t-1} + 0.381\ Q_{t+1} \quad . \quad . \quad . \quad . \quad \text{(A-2)}$$

The standard error is 326,800, and R^2 is 0.563. The residuals for the period of calibration, 1900-1977, were examined and found to be randomly distributed.

Since Equation A-2 includes as a predictor variable the streamflow in the year subsequent to the year being predicted, its use requires an initial series of $\hat{Q}$. To obtain the estimated series of Bear River flows, a two-step approximation is used. First, Equation A-1 provides an initial estimate of the series $\hat{Q}$ (Table A-2). These estimates are then used in Equation A-2 to obtain a second approximation, and this process was repeated until the solution converged on the values shown in Table A-2. Convergence required 39 iterations to reach a sum of squares of the differences in 278 flows of less than 1.0.

Discussion

Table A-3 shows how the mean, standard deviation, and range of the 1890-1977 Bear River flow series estimated from tree rings compares with 1) the present modified flow series for the same years and 2) the series reconstructed from tree rings for the entire 1700-1977 period. The comparisons show the tree ring mean to be 90.5 percent of the present modified mean but the standard deviation to be only 61.8 percent and the range between high and low extremes to be 54.5 percent. This percentage of the range preserved by the model is seen to be about the same as the percentage of the variance in the flows explained by the model of Equation A-2 (56.3 percent).

According to the flow sequence reconstructed from the tree rings, one can also see that 1890-1977 averages a little wetter, has a greater standard deviation, and contains the peak flows in the entire 278-year

Table A-2. Sequence of Bear River flows at Corinne, 1700-1977, as reconstructed from tree rings.

Year	Index									
	0	1	2	3	4	5	6	7	8	9
1700	435	620	775	589	876	689	594	512	596	679
1710	769	864	754	859	853	899	972	929	836	960
1720	888	1102	1050	1202	1265	1272	1211	1222	1300	1195
1730	1034	1177	1142	1141	1287	1230	1234	1185	1113	1082
1740	919	888	1026	1024	969	1036	1107	1166	1224	1206
1750	1276	1439	1447	1383	1250	1260	1152	1052	1093	1137
1760	1024	1031	1093	1098	1036	1082	1152	1184	1381	1309
1770	1334	1292	1218	1033	926	718	753	590	581	571
1780	584	585	589	602	659	710	757	792	877	940
1790	944	1008	1105	1041	1013	1025	931	864	1025	896
1800	1006	1016	937	946	879	933	904	833	895	846
1810	885	966	1022	1067	912	843	986	931	996	922
1820	1034	958	1002	864	939	902	1002	1159	1177	1177
1830	1040	991	964	933	889	957	836	947	1028	1109
1840	1227	1187	1287	1176	1149	1049	869	833	783	944
1850	964	1017	1014	1099	1213	1211	882	823	793	825
1860	752	687	702	723	631	612	705	908	1005	1065
1870	1105	983	727	880	987	982	1035	1041	885	732
1880	618	751	667	614	663	715	727	618	601	627
1890	629	764	861	879	958	1090	1099	1071	1089	963
1900	787	906	810	773	859	963	1072	1286	1451	1346
1910	1394	1429	1614	1728	1755	1642	1405	1348	1115	959
1920	954	1160	1207	1273	1256	1176	954	898	918	867
1930	882	854	759	809	744	797	763	942	942	877
1940	892	1241	1153	1171	1313	1246	1479	1532	1568	1535
1950	1541	1381	1323	1089	952	1132	1060	990	842	923
1960	813	726	1018	937	882	1048	1100	1036	1057	1052
1970	889	1250	1235	1239	1075	1062	1016	694		

All flows in 1000 AF.

Table A-3. Comparisons among flow series estimated from tree rings and presented modified series.

	Pres. Mod. Series 1890-1977	Tree Ring Series 1890-1977	1700-1977
Mean	1,182,000	1,070,000	996,000
Std. Deviation	484,000	299,000	233,000
Maximum	2,294,000	1,755,000	1,755,000
Minimum	343,000	623,000	435,000
Range	1,951,000	1,126,000	1,320,000

sequence. One should also look at the episodes of above and below average flow. Some confidence can be put in these episodes as real, for two reasons. First, although the predicted values for the calibration do not match the magnitude of the real values, the general features are similar. In particular, low flow years such as 1970, 1961, 1954, and the mid-1930s, and high flows at the beginning of the record, coincide in both series. The prolonged period of high flow from 1742 to 1773, however, suggests that the lake may have risen to quite high levels at the end of this period.

More rigorous testing of this correspondence should be undertaken with spectral and cospectral analyses. Second, many of the general features of the estimated series correspond to features on the Upper Colorado River as determined by Stockton (1975, 1976). For example, episodes of below average flow in 1700-1710, 1770-1790, early 1800s, 1880-1890, 1930s, and of above average flow in 1900-1920, appear in both records. This coincidence suggests that the Rex Peak' chronology and the Bear River flows indeed respond to regional climate patterns. Again, spectral and cospectral analyses should be used to test the correspondence of the series.

Although the results presented here are less than entirely satisfactory, several avenues to improvement are apparent. Improvements center on the tree-ring data, and are in progress. Stain should enhance the readability of several Rex Peak cores, allowing their incorporation into the chronology. Stockton (1975, 1976) used several stands in each subbasin in his analyses on the Colorado River; this study used only one stand in the Bear River drainage. Construction of further chronologies from other sites in the Bear River basin will allow site-specific variation to be filtered out, and will provide a more representative proxy for the regional water balance.

References Cited

Fritts, H. C. 1976. Tree Rings and Climate. New York: Academic Press, 567 p.

Stockton, C. W. 1975. Long-Term Streamflow Records Reconstructed from Tree Rings. Tucson: University of Arizona Press, Laboratory of Tree-Ring Research Paper 5, 111 p.

Stockton, C. W. 1976. Long-Term Surface-Water Supply and Streamflow Trends in the Upper Colorado River Basin. Los Angeles: Lake Powell Research Project Bulletin 18, 67 p.

APPENDIX B

ESTIMATION OF ARMA (1,0) PARAMETERS BY THE METHOD OF MOMENTS

The ARMA (1,0) model may be written

$$\underline{X}(t) = A\underline{X}(t-1) + B\underline{\varepsilon}(t) \quad . . . . \quad (B-1)$$

where $\underline{\varepsilon}(t)$ is assumed to be a random vector with independent components, each having the standard normal distribution. Let M_0 and M_1 represent the correlation matrix and the lag-one auto and cross-correlation matrices of process, respectively, i.e.,

$$M_0 = E[\underline{X}(t)\ X(t)^T] \quad . . . . \quad (B-2)$$

$$M_1 = E[\underline{X}(t)\ \underline{X}(t-1)^T] \quad . . . . \quad (B-3)$$

Substituting the right side of (B-1) into (B-2) and (B-3)

$$M_0 = E[\underline{X}(t)\ (A\underline{X}(t-1) + B\underline{\varepsilon}(t))^T] = AM_1^T + BB^T \quad . . . . \quad (B-4)$$

$$M_1 = E[(A\underline{X}(t-1) + B\varepsilon(t))\ \underline{X}(t-1)^T] = AM_0 \quad . . . . \quad (B-5)$$

It follows that

$$A = M_1 M_0^{-1} \quad . . . . \quad (B-6)$$

Substituting this expression into (B-4) and solving for BB^T

$$BB^T = M_0 - M_1 M_0^{-1} M_1^T \quad . . . . \quad (B-7)$$

Estimates of M_0 and M_1 are obtained from historic sequences. The elements of M are

$$m_{ij}^0 = \sum_{k=0}^{n} x_i\ (t-k)\ x_j\ (t-k)/n \quad . . . . . \quad (B-8)$$

where m_{ij} is the ijth element of M_0, and $x_i(t-k)$ is the standardized value of the ith component of x(t) observed at time t-k. Also

$$m_{ij}^1 = \sum_{k=0}^{n-1} x_i\ (t-k)\ x_j\ (t-k-1)/(n-1) \quad . . \quad (B-9)$$

where m_{ij}^1 is the ijth element of M_1 and the $x_i(\ )$'s are defined as before. These estimates are substituted into (B-6) and (B-7) to estimate A and BB^T.

Since BB^T is symmetric, a unique solution for B does not exist. It is convenient to assume a lower triangular form for B which then permits a simple solution.

APPENDIX C

ESTIMATION OF ARMA (1,1) PARAMETERS BY THE METHOD OF MOMENTS

The ARMA (1,1) model may be written

$$\underline{X}(t) = C\,\underline{X}(t-1) + D\,\underline{\varepsilon}(t) - E\,\underline{\varepsilon}(t-1) \quad \ldots \quad (C-1)$$

where $\underline{\varepsilon}(t)$ is assumed to be a random vector with independent standard normal components. Let M_0, M_1, and M_2 represent the correlation, lag-one auto and cross-correlation and lag-two auto and cross-correlation matrices respectively, i.e.,

$$M_0 = E[\underline{X}(t)\,\underline{X}(t)^T] \quad \ldots \quad (C-2)$$

$$M_1 = E[\underline{X}(t)\,\underline{X}(t-1)^T] \quad \ldots \quad (C-3)$$

$$M_2 = E[\underline{X}(t)\,\underline{X}(t-2)^T] \quad \ldots \quad (C-4)$$

Substituting the right side of (C-1) into (C-2), (C-3), and (C-4)

$$M_0 = E[\underline{X}(t)\,(C\,\underline{X}(t-1) + D\,\underline{\varepsilon}(t) - E\,\underline{\varepsilon}(t-1))^T]$$

$$= M_1C^T + DD^T - CDE^T + EE^T \quad \ldots \quad (C-5)$$

$$M_1 = E[(C\underline{X}(t-1) + D\,\underline{\varepsilon}(t) - E\,\underline{\varepsilon}(t-1)\,\underline{X}(t-1)^T]$$

$$= CM_0 - ED^T \quad \ldots \quad (C-6)$$

$$M_2 = E[(C\underline{X}(t-1) + D\,\underline{\varepsilon}(t) - E\,\underline{\varepsilon}(t-1))\,\underline{X}(t-2)^T]$$

$$= CM_1 \quad \ldots \quad (C-7)$$

From (C-7)

$$C = M_2\,M_1^{-1} \quad \ldots \quad (C-8)$$

Substituting (C-6) and (C-8) into (C-5) results in

$$DD^T + EE^T = M_0 - M_2\,M_1^{-1}\,M_1^T + M_2\,M_1^{-1}\,M_0\,M_1^{T^{-1}}\,M_2^T$$

$$- M_1\,M_1^{-1^T}\,M_2^T = S \quad \ldots \quad (C-9)$$

From (C-6)

$$E = (C\,M_0 - M_1)\,D^{-1^T} = T\,D^{-1^T} \quad \ldots \quad (C-10)^1$$

where

$$T = C\,M_0 - M_1 \quad \ldots \quad (C-11)$$

As in Appendix B, estimates of M_0, M_1, and M_2 are obtained from historic data. In addition the estimates of M_0 and M_1 defined in (B-8) (B-9), the ijth element of M_2 is

$$m_{ij}^2 = \sum_{k=0}^{n-2} x_i(t-k)\,x_j(t-k-2)/(n-2)$$

O'Connell (1974) has provided an iterative solution for DD^T by substituting (C-10) into (C-5) which results in

$$DD^T + T\,D^{-1^T}\,D^{-1}\,T^T = DD^T + T(DD^T)^{-1}\,T^T = S$$

Let U_0 be an initial estimate of DD^T. Then the first iterate of DD^T is

$$U_1 = S - T\,U_0^{-1}\,T^T$$

In general, the i+1 st iterate is obtained from the ith as

$$U_{i+1} = S - T\,U_i^{-1}\,T^T \quad \ldots \quad (C-12)$$

Convergence of (C-12) may be observed by using the behavior of

$\max |U_{jk}^{i+1} - U_{jk}^i|$ where U_{jk}^i is the j,kth element of U_i.

When a satisfactory value of DD^T (U) is found, the solution for D may be obtained

---

1The symbol T has a different meaning here than in Chapter 4.

as in Appendix B. Then E may be computed from (C-10).

O'Connell (1974) has also given conditions which are necessary in order that (C-9) and (C-10) yield solutions. These are that $S + T + T^T$ and $S - T - T^T$ be positive semidefinite matrices. Experience with the data associated with the Great Salt Lake indicate that these conditions are not easily satisfied. Even when subsets were found which did satisfy this condition, (C-12) would not converge to a solution. It was found that in the two dimensional case an analytic solution can be obtained for DD^T. This analytic solution was used in conjunction with principle components to provide an approximate solution for the ARMA (1,1) parameters.

APPENDIX D

DATA PREPARATION PROGRAM

Table D-1a. Listing: Data Preparation Program.

```
C**********************************************************************
C
C     MVARMA = A MULTIVARIATE GENERATION PROGRAM
C      PROGRAM TO COMPUTE FROM N PHYSICAL VARIABLES THE SKEW IN ORDER TO
C     DETERMINE WHETHER TO LOG TRANSFORM TO MAKE LOG-NORMAL THE CRITERIA
C   FOR NORMAL DIST. IS + OR- .1 OR CAN BE SET BY READING IN SLN
C     THEN MSTAT COMPUTES THE STATISTICS : MEAN, STANDARD DEVIATION, AND
C   THE LAG 0,1,AND2 CORRELATION MATRICES A COMBINATION OF THE N VARIABLE
C    MIXTURE OF TRANSFORMATIONS IE. NORMAL OR LOG NORMAL. ALSO A
C    SCALE FACTOR IS USED TO SET EACH VARIABLE TO EQUAL DIMENSIONS
C    THE PROPER SCALE(I) FOR EACH VARIABLE IS NECESSARY BEFORE COMPUTING
C    THE COVARIANCE MATRIX AT LAG 0 AND THE EIGIN VECTORS OR PRINCIPLE
C    COMPONENTS FOR THE N VARIABLES.  MODEL TAKES THE CORRELATION MATRICE
C    AND ACCORDING TO THE MARKOV OPTION 1,2,OR3 COMPUTES AN A,B, OR C
C    MATRIX FOR MULTIVARIATE GENERATION  IN MGEN.
C    MARKOV=1, IS THE ARIMA(1,0,1) GEN FOR MULTIVAR. PRINCIPAL COMPONENT
C     PAIRWISE COMBINATIONS;  MARKOV=2, IS THE ARIMA(1,0,0) MULTIVAR. GEN
C     MARKOV=3, IS THE MARKOV MULTIVAR. GEN. WITH AN A MATRIX THAT IS
C    DIAGONAL.    THE  PROGRAM IS OPTIONED TO RUN A NUMBER OF GENERATIONS
C    AND CORRESPONDING STATS.  AND COMPARE WITH ORIGINAL PHYSICAL VARIABL
C   ES .    THE ORIGINAL PHYSICAL VARIABLES CAN BE EITHER PMF(PRESENT
C    MODIFIED STREAMFLOWS) OR NATURAL STREAMFLOWS WITH THE OPTION TO
C    CONVERT THE NATURAL GENERATED FLOWS TO PMF BY CNAT.
C    IF P.C. (PRINCIPAL COMPONENTS) ARE USED THEN THE GENERATED VARIABLES
C     ARE CONVERTED BACK TO PHYSICAL VARIABLES BY UNTR  AND THE P.C.
C     COEFFICIENTS MUST HAVE BEEN READ IN AS PCA.

C**********************************************************************
C     PARAMETERS IN MAIN PROGRAM AND S/R

C    N= # OF VARIABLES; NYR=# OF YEARS IN THE INPUT TIME SERIES;
C     NYG=# OF YEARS OF GEN. T.S.; NPC= # OF PC TS; IPC= IF 1 THEN DO PC;
C    MARKOV= SEE ABOVE; NTRACE= # OF INTERVALS IN GEN. COMPARISONS;
C    ISKEW= IF 1 THEN ALL TRANSFORMS ARE FORCED TO NORMAL VICE LOG NORMAL;
C     NX= # OF LEFT OVER TIME SERIES IF PC COMPS ARE USED IE. IF 2PC THEN
C     NX=3, IF N=5.;   NAT= IF 1 THEN CONVERT NAT TO PMF; IONE= IF 1 THEN
C    ONLY DO ONE GEN.; IW=1, PRINT DEBUG STATEMENRS =2, SUPPRESS WRITE
C    II=# OF GEN. IN EACH INTERVAL NTRACE; MSI= 1 IF WANT TO READ FROM F
C    FILE 8 THE ACCUMULATED SUMS FOR STAT. COMPARISONS;
C**********************************************************************
C     PARAMETERS FOR SUBROUTINE MODEL

C    LUP=1 IF UPPER TRIANGULAR MATRIX FOR BBT IN MODEL; NI= DIMENSION
C     OF MATRIX FOR SOLUTI TO DERIVE B FROM BBT; NN= # OF ITERATIONS;
C    NM=# OF LINES TO SKIP IN MODEL 'S WRITE OF THE ITERATIOBS; IADIAG=1
C   IF A MATRIX IS TO BE FULL IE. A=M2M1-1, =0 IF A IS DIAGONAL;
C    LAM =1. OR LES FOR CONVERGENCE OF BBT; CRITV= CRITERIA FOR SETTING
C    NONSIG. COOR. ELEMENTS TO 0.; DELTA= CONVERGENCE CRITERISA.; SLN=
C   SEE ABOVE.
C**********************************************************************
```

```
C     PARAMETERS FOR SUBROUTINE CNAT

C      CU= CONSUMPTIVE USE FOR EACH RIVER; DV= DIVERSIONS FOR EACN RIVER;
C    CSNB(I)= REGRESION CONSTANT FOR CHANGE IN STORAGE FOR EACH RIVER;
C    CSNM= L.R. COEFF.;    CSLAG= LAG ONE LR COFFF.; STUR= END OF YEAR
C RESERVOIR STORAGE FOR EACH RIVER;

      INTEGER V
      DOUBLE PRECISION RHDG,CHDG
      COMMON/HDG/RHDG(10),CHDG(10)
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALE(10),NTRACE,IW,IN
     *,IA
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),V(10),PCA(1
     *0,10),NCORE,NX
      COMMON/COM3/T(2,10),U(108),COR(3,10,10),WXM(10),SDY(10),XMNY(10)
     *,YIC(10),VOR(10),BA(10),FMEAN(10)
      COMMON/COMM/NUP,NI,NN,DELTA,LAM,CRITV,IADIAG,NM
      COMMON/COMS/TT(2,10,150),UT(108,150)
      COMMON/COMB/A(10),SLN,WSD(10),A2(10)
      COMMON/COMG/AMP(10,10),BMP(10,10),CMP(10,10)
      COMMON/MWNAT/CU(5),DV(5),CSNB(5),CSNM(5),CSLAG(5),STUR(5,1),NAT
      DIMENSION SUM(2,10),SUMV(2,10),AVER(2,10),STDEV(2,10),SMT(108),AVT
     *(108),SMTV(108),STDC(108),FU(108),FSIG(10)
 9000 FORMAT(16I5)
 9002 FORMAT(8F10.0)
 9003 FORMAT(1H ,8E15.9)
 9005 FORMAT(13A6)
 9500 FORMAT(1H ,'AVER. MEANS',10F10.2)
 9501 FORMAT(1H ,'AVER. CORR.',10F10.5)
 9502 FORMAT(1H ,'STDEV. CORR.',10F10.5)
 9503 FORMAT(1H ,'AVER. STDEV.',10F10.2)
 9504 FORMAT(1H0,'MEANS AND STANDARD DEVIATIONS OF',I3,' GENERATIONS ON'
     *,I3,' VARIABLES')
 9505 FORMAT(1H ,'ORIG. STATS',10F10.2)
 9506 FORMAT(1H ,'ORIG. CORR.',10F10.5)
 9507 FORMAT(1H ,51(1H+))
      READ(5,9005)(RHDG(I),I=1,N)
      READ(5,9005)(CHDG(I),I=1,N)
      READ(5,9000)N,NYR,NYG,NPC,IPC,MARKOV,NTRACE,ISKEW,NX,NAT,IONE,IW
     *,II,MSI,INABC
      WRITE(6,*/)N,NYR,NYG,NPC,IPC,MARKOV,NTRACE,ISKEW,NX,NAT,IONE,IW
     *,II,MSI,INABC
      IF(INABC.NE.1)GOTO 3
      DO 1 I=1,NPC
1     READ(5,9002)(AMP(I,J),J=1,NPC)
      DO 2 I=1,NPC
2     READ(5,9002)(BMP(I,J),J=1,NPC)
      DO 3 I=1,NPC
      READ(5,9002)(CMP(I,J),J=1,NPC)
3     CONTINUE
      IN=0
      READ(5,9000)NUP,NI,NN,NM,IADIAG
      WRITE(6,*/)NUP,NI,NN,NM,IADIAG
      READ(5,9002)(SCALE(I),I=1,N)
      WRITE(6,/)(SCALE(I),I=1,N)
      READ(5,9002)LAM,CRITV,DELTA,SLN
      WRITE(6,*/)LAM,CRITV,DELTA,SLN
      READ(5,9002)(A(I),I=1,N)
      WRITE(6,/)(A(I),I=1,N)
      IF(NAT.NE.1)GOTO 90
      READ(5,9002)(CU(I),I=3,N)
      READ(5,9002)(DV(I),I=3,N)
      READ(5,9002)(CSNB(I),I=3,5)
      READ(5,9002)(CSNM(I),I=3,5)
      READ(5,9002)(CSLAG(I),I=3,5)
      READ(5,9002)(STUR(I,1),I=3,5)
90    CONTINUE
      IF(IPC.NE.1)GOTO 101
      DO 100 I=1,NX
      BA(I)=A(I)
      READ(5,9002)(PCA(I,J),J=1,NX)
      WRITE(6,/)(PCA(I,J),J=1,NX)
 100  CONTINUE
 101  CONTINUE
      CALL READS(X,N,NYR)
      DO 185 I=1,N
      DO 180 K=1,NYR
      Y(K,I)=X(K,I)/SCALE(I)
 180  CONTINUE
C   LOWER BOUNDS
      AB(I)=A(I)
C   PHYSICAL SCALED LOWER BOUDS A(I)
      A(I)=A(I)/SCALE(I)
 185  CONTINUE
      IF(IPC.EQ.1)GOTO 190
      GOTO 195
C     PHYSICAL STATS FOR PC GEN COMPARISONS  IN 945 LOOP
 190  CALL MSTAT
      DO 1900 I=1,N
      FMEAN(I)=T(1,I)
      FSIG(I)=T(2,I)
 1900 CONTINUE
      DO 1905 JU=1,NCORE
      FU(JU)=U(JU)
 1905  CONTINUE
C     PRINC CHANGES THE A'S
      CALL PRINC
      DO 1906 I=1,N
      A2(I)=A(I)
 1906 CONTINUE
      N=NPC
C     PC MSTAT FOR PC MODEL GEN.
 195  CALL MSTAT
      IF(IPC.EQ.1)GOTO 192
      DO 191 I=1,N
      FMEAN(I)=T(1,I)
      FSIG(I)=T(2,I)
 191  CONTINUE
      DO 192 JU=1,NCORE
      FU(JU)=U(JU)
 192  CONTINUE
      DO 1920 I=1,N
      VOR(I)=V(I)
      YIC(I)=Y(NYR,I)
 1920 CONTINUE
      IF(IW.EQ.1)WRITE(6,9003)(YIC(I),I=1,N)
      IF(INABC.EQ.1)GOTO 790
      CALL MODEL
 790  IF(IONE.NE.1)GOTO 800
      CALL MGEN
      GOTO 1600
 800  CONTINUE
      IF(MSI.NE.1)NTOT=0
      IF(MSI.NE.1)GOTO 805
      READ(8,/)NTOT,(SUM(1,I),I=1,N),(SUM(2,I),I=1,N),(SUMV(1,I),I=1,N),
     *(SUMV(2,I),I=1,N),(SMT(JU),JU=1,NCORE),(SMTV(JU),JU=1,NCORE)
 805  CONTINUE
      NYG=NYG
      IF(IPC.EQ.1)IA=1
      DO 950 IN=1,NTRACE
      NTI=NTOT+IN*II
      DO 945 K=1,II
      CALL MGEN
      CALL MSTAT
```

```
          DO 90C I=1,N
          TT(1,I,K)=T(1,I)
          TT(2,I,K)=T(2,I)
          SUM(1,I)=SUM(1,I)+T(1,I)
          SUM(2,I)=SUM(2,I)+T(2,I)
          DO 945 JU=1,NCORE
          FT(JU, )=U(J )
    945   CONTINUE
    905   CONTINUE
    945   CONTINUE
          B=FLOAT(NTI)
          BB=B-1.
          DO 906 I=1,N
          AVER(1,I)=SUM(1,I)/B
          AVER(2,I)=SUM(2,I)/B
    906   CONTINUE

          DO 910 K=1,II
          DO 905 I=1,N
          SUMV(1,I)=SUMV(1,I)+(TT(1,I,K)-AVER(1,I))**2
          SUMV(2,I)=SUMV(2,I)+(TT(2,I,K)-AVER(2,I))**2
    905   CONTINUE
    910   CONTINUE
          DO 915 I=1,N
          STDEV(1,I)=SQRT(SUMV(1,I)/BB)
          STDEV(2,I)=SQRT(SUMV(2,I)/BB)
    915   CONTINUE
          DO 930 JU=1,NCORE
          DO 920 K=1,II
          SMT(JU)=SMT(JU)+UT(JU,K)
    920   CONTINUE
          AVT(JU)=SMT(JU)/B
          DO  925 K=1,II
          SMTV(JU)=SMTV(JU)+(UT(JU,K)-AVT(JU))**2
    925   CONTINUE
          STDC(JU)=SQRT(SMTV(JU)/BB)
    930   CONTINUE
          WRITE(6,9504)NTI,N
          WRITE(6,9505)(FMEAN(I),I=1,N),(FSIG(I),I=1,N)
          WRITE(6,9500)(AVER(1,I),I=1,N),(AVER(2,I),I=1,N)
          WRITE(6,9503)(STDEV(1,I),I=1,N),(STDEV(2,I),I=1,N)
          WRITE(6,9507)
          I=0
          LL=1
          DO 935 JU=1,NCORE/N
          I=I+1
          LU1=((LL-1)*N+I-1)*N+1
          LU2=LU1+4
          WRITE(6,9506)(FU(LU),LU=LU1,LU2)
          WRITE(6,9501)(AVT(LU),LU=LU1,LU2)
          WRITE(6,9502)(STDC(LU),LU=LU1,LU2)
          IF(I.EQ.N)I=0
          IF(LU2.EQ.25.OR.LU2.EQ.50)LL=LL+1
          IF(LU2.EQ.25.OR.LU2.EQ.50)WRITE(6,9507)
    935   CONTINUE
    950   CONTINUE
          NTOT=NTI
          WRITE( ,/)NTOT,(SUM(1,I),I=1,N),(SUM(2,I),I=1,N),(SUMV(1,I),I=1,N)
         *,(SUMV(2,I),I=1,N),(SMT(JU),JU=1,NCORE),(SMTV(JU),JU=1,NCORE)
          WRITE( ,/)NTOT,(SUM(1,I),I=1,N),(SUM(2,I),I=1,N),(SUMV(1,I),I=1,N)
         *,(SUMV(2,I),I=1,N),(SMT(JU),JU=1,NCORE),(SMTV(JU),JU=1,NCORE)
          LOCK A
   1000    STOP
           END

      SUBROUTINE XSTAT
C***** PROGRAM TO COMPUTE  THE  CROSS-COVARIANCES AND THE CROSS-CORRELATIONS
      INTEGER V,VV
      DOUBLE PRECISION RHOG,CHOG
      COMMON/HOS/RHOG(10),CHOG(10)
```

```
      COMMON/COM1/N,NYR,LYG,NPC,IPC,MARKCV,AB(10),SCALE(10),NTRACE,IW
     *,IG,IA
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),V(10),PCA(1
     *0,10),NCORE,NX
      COMMON/COM3/T(2,10),U(100),COR(3,10,10),WXM(10),SDY1(10),XMNY1(10)
     *,YIC(10)
      COMMON/COMB/A(10),SLR
      DIMENSION XMN(10),XMNO(10),S(10),SDO(10),   (10),SDY(10),M(10,
     *10),VV(10,10),SDY(10),XMN(10,10),T(10,10),W(10),RX(10,10),
     *SP(10),RX1(10,10)
9000 FORMAT(16I5)
9001 FORMAT(13A6)
9002 FORMAT(8F10.0)
9400 FORMAT(1H ,8F10.2)
9450 FORMAT(1H ,27HPHYSICAL CORRELATION MATRIX)
9450 FORMAT(1H ,29HTRANSFORMED COVARIANCE MATRIX)
9500 FORMAT(1H ,11HERROR IN VV)
9510 FORMAT(6E15.9)
9515 FORMAT(1H ,16I5)
9520 FORMAT(1H ,10A6)
9525 FORMAT(1H ,5E14.8)
9526 FORMAT(1H ,10E12.5)
9530 FORMAT(1H ,17X,3HLAG,I3,21X,5HMEANS)
9531 FORMAT(1H ,17HLAGGED MEANS,XMNO)
9532 FORMAT(1H ,44X,9HSTD. DEV.)
9535 FORMAT(1H ,32HPHYSICAL CROSS'COVARIANCE MATRIX)
9540 FORMAT(1H ,15HTRANSFORMED,SDY)
9543 FORMAT(1H ,20HLAG TRANSFORMED,SDYO)
9544 FORMAT(1H ,16HTRANSFORMED,XMNY)
9545 FORMAT(1H ,61HCROSS'CORRELATIONS,UNTRANSFORMED,PX,TRANSFORMED,510,
     *MIXED,515)
9546 FORMAT(1H ,24HLAGGED TRANSFORMED,XMNYO)
9550 FORMAT(1H ,34HLOG TRANSFORMED CORRELATION MATRIX,1HM,I3,6HMATRIX)
9555 FORMAT(1H ,9H3PLN,A(I))
9600 FORMAT(3HI=,I5,2HJ=,I5,3HPX=,E15.9)
9650 FORMAT(1H ,8H510 I,J=,2I5)
9675 FORMAT(1H ,8H515 I,J=,2I5)
C*********************************************************************

C****** LAG LOOP

C*********************************************************************
      IF(IA.NE.1)GOTO 78
      DO 75 I=1,NX
      A(I)=AB(I)/SCALE(I)
 75   CONTINUE
 78   DO 800 LL=1,3
      LAG=LL-1
      NYR1=NYR-LAG
      K1=1+LAG

C**** MEANS CA
      XMN(I)=0.
      DO 150 K=K1,NYR
      XMN(I)=XMN(I)+Y(K,I)
 175  CONTINUE
      DO 200 I=1,N
      XMN(I)=XMN(I)/NYR1
 200  CONTINUE
      IF(IW.NE.2)WRITE(6,953 )LAG
      DO 205 I=1,N
      WXM(I)=XMN(I)*SCALE(I)
      IF(LAG.NE.0)GOTO 205
      T(1,I)=WXM(I)
 205  CONTINUE
      IF(IW.NE.2)WRITE(6,9400)(WXM(I),I=1,N)

C****  VARIANCES
      DO 230 I=1,N
```

```
      SD(I)=0.
      DO 220 K=K1,NYR
      SD(I)=SD(I)+(Y(K,I)-XMN(I))**2
 220  CONTINUE
 230  CONTINUE

C*** STANDARD DEV
      DO 240 I=1,N
      SD(I)=SQRT(SD(I)/NYR1)
 240  CONTINUE
      IF(IW.NE.2)WRITE(6,9532)
      WSD(I)=SD(I)*SCALE(I)
      IF(LAG.NE.0)GOTO 241
      T(  ,I)=WSD(I)
 241  CONTINUE
      IF(IW.NE.2)WRITE(6,9510)(WSD(I),I=1,N)
      CALL SKEW(XMN,SD,VV,LAG,S  N,ISKEW)
      IF(LAG.EQ.0)GOTO 257

C**** LAGGED MEANS CALCULATED
      DO 245 I=1,N
      XMN0(I)=0.
      DO 243 K=1,NYR1
      XMN0(I)=XMN0(I)+Y(K,I)
 243  CONTINUE
 245  CONTINUE
      DO 247 I=1,N
      XMN0(I)=XMN0(I)/NYR1
 247  CONTINUE
      IF(IW.EQ.2)GOTO 248
      WRITE(6,9531)
      WRITE(6,9510)(XMN0(I),I=1,N)

C**** LAGGED VARIANCES
 248  DO 255 I=1,N
      S  (I)=0.
      DO 250 K=1,NYR1
      S  (I)=SD0(I)+(Y(K,I)-XMN (I))**
 250  CONTINUE
      CONTINUE

C**** LAGGED STANDARD DEV
      DO 256 I=1,N
      SD0(I)=SQRT(SD0(I)/NYR1)
 256  CONTINUE
      IF(IW.EQ.2)GOTO 2565
      WRITE(6,9542)
      WRITE(6,9510)(SD0(I),I=1,N)
 2565 GOTO 259
 257  DO 258 I=1,N
      XMN0(I)=XMN(I)
      SD0(I)=SD(I)
 258  CONTINUE
C*****************************

C*** CROSS-COVARIANCE

      DO 275 I=1,N
      DO 260 J=1,N
      M(I,J)=0.
 260  CONTINUE
 275  CONTINUE
      DO 400 K=1,NYR1
      DO 350 I=1,N
      DO 300 J=1,N
      M(I,J)=M(I,J)+(Y(K,I)-XMN0(I))*(Y(K+LAG,J)-XMN(J))
 300  CONTINUE
 350  CONTINUE
 400  CONTINUE
      DO 500 I=1,N
```

```
      DO 450 J=1,N
      M(I,J)=M(I,J)/NYR1
 450  CONTINUE
 500  CONTINUE
      IF(IW.EQ.2)GOTO 501
      WRITE(6,9535)
      CALL MOUT(M,N,N,IOUT,RHOS,CHOG,5)
 501  DO 502 I=1,N
      DO 502 J=1,N
      RX(I,J)=M(I,J)/(SD0(I)*SD(J))
      IF(LAG.NE.1)GOTO 502
      RX1(I,J)=RX(I,J)
 502  CONTINUE
      IF(IW.EQ.2)GOTO 5025
      WRITE(6,9450)
      CALL MOUT(RX,N,N,IOUT,RHOS,CHOG,6)
C**** TRANSFORMATION OF MEANS AND STANDARD DEV.
 5025 DO 505 I=1,N
      SDY(I)=SD(I)
      SDY0(I)=SD0(I)
C**** IF V(I)=-1 THEN IT IS TRANSFORMED IF =2 THEN IT IS NOT
      IF(V(I).NE.-1)GOTO 503
      SDY(I)=SQRT(ALOG((SD(I)**2)/((XMN(I)-A(I))**2)+1.))
      SDY0(I)=SQRT(ALOG((SD0(I)**2)/((XMN0(I)-A(I))**2)+1.))
 503  XMNY(I)=XMN(I)
      XMNY0(I)=XMN0(I)
      IF(V(I).NE.-1)GOTO 505
      XMNY0(I)=ALOG(XMN0(I)-A(I))-((SDY0(I)**2)/2.)
 505  CONTINUE
      IF(LAG.NE.0)GOTO 507
      IF(IN.NE.0)GOTO 507
      DO 506 I=1,N
      SDY1(I)=SDY(I)
      XMNY1(I)=XMNY(I)
 506  CONTINUE
 507  CONTINUE
      IF(IW.EQ.2)GOTO 508
      WRITE(6,9540)
      WRITE(6,9510)(SD (I),I=1,N)
      WRITE(6,9543)
      WRITE(6,9510)(SDY(I),I=1,N)
      WRITE(6,9544)
      WRITE(6,9510)(XMNY(I),I=1,N)
      WRITE(6,9546)
      WRITE(6,9510)(XMNY0(I),I=1,N)
C*****************************

C**** TRANSFORMATION LOOP FOR COVARIANCES

C*****************************
 508  DO 530 I=1,N
      IF(V(I).EQ.-1)ESDYI1=EXP(SDY0(I)**2)-1.
      DO 525 J=1,N
      PX=RX(I,J)

C****  IF VV(I)=1 THEN BOTH VARIABLES ARE TRANSFORMED IF =-2 THEN
C      THE VARIABLES ARE A MIXED COMBINATION
      IF(VV(I,J).EQ.-2)GOTO 515
      GOTO 525
 510  M(I,J)=ALOG(1.+PX*SQRT(ESDYI1*((EXP(SDY(J)**2))-1.)))
      GOTO 525
 515  IF(V(I).EQ.-1)GOTO 516
      ESDYI1=EXP(SDY0(J)**2)-1.
      GOTO 517
 516  SDIJ=SD(J)
 517  M(I,J)=SDIJ*(SQRT(ESDYI1))*PX
      ESDYI1=EXP(SDY0(I)**2)-1.
 525  CONTINUE
 530  CONTINUE
      IF(IW.EQ.2)GOTO 535
```

```
      WRITE(6,9490)
      CALL OUT(Y,N,N,LCET,NJ,CHUG,6)
C*****************************
C*** CORRS-CORRELATIONS
C*****************************
 6C5  DO 700 I=1,N
      DO 605 J=1,N
      TM(J,I)=Y(I,J)/(NYG(I)*SDY(J))
 600  CONTINUE
 700  CONTINUE
      DO 605 I=1,N
      DO 605 J=1,N
      M(I,J)=TM(I,J)
      COR(LL,I,J)=M(I,J)
      JU=((LL-1)*N+I-1)*N+J
      U(JU)=COR(LL,I,J)
 605  CONTINUE
      IF(IW.EQ.2)GOTO 800
      WRITE(6,9550)LAG
      DO 750 I=1,N
      WRITE(6,9526)(M(I,J),J=1,N)
 750  CONTINUE
 800  CONTINUE
      DO 805 I=1,N
      SD(I)=T(2,I)
 805  CONTINUE
      IF(IN.NE.0)GOTO 8052
      DO 8052 I=1,N
      SDY(I)=SDY1(I)
 8052 CONTINUE
      CALL FILER(SDY,SD,...)
      DO 806 I=1,N
      T(2,I)=SD(I)
      IF(IN.NE.0)GOTO 806
      SDY1(I)=SDY(I)
 806  CONTINUE
      NCORE=3*N*N
      RETURN

      SUBROUTINE MGEN
C     MULTIVARIATE GENERATION ARIMA(1,0,1) PROGRAM
C**** PROGRAM TO GENERATE ARMA 101 SYNTHETIC MULTIVARIATE TIME SERIES
      REAL MU
      INTEGER SEED,V
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALL(10),NTRACE,IW
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),W(10),PCA(1
     *0,10),NCORE,NX
      COMMON/COM3/T(2,10),U(100),COR(3,10,10),WXM(10),SDY(10),XMNY(10)
     *,YIC(10),V(10)
      COMMON/COM8/A1(10),SLN,WSD(10),A2(10)
      COMMON/COVG/A(10,10),B(10,10),C(10,10)
      COMMON/MWNAT/CU(5),CV(5),CSUB(5),CSNM(5),CSLAG(5),STOR(5,1),NAT
      DIMENSION XIC(10,1),MU(10,1),Z1(10,1),EE(10,150),EE1(1500),E1(10,1
     *),E(10,1),DUM1(10,1),DUM2(10,1),Z(10,1),BETA(10,1),XMIN(10,1),SIG(
     *10,1),SCALE(10,1)
 9000 FORMAT(16I5)
 9001 FORMAT(13A6)
 9005 FORMAT(5E15.9)
 9010 FORMAT(6F10.0)
 9500 FORMAT(1H ,16I5)
 9510 FORMAT(1H ,13A6)
 9520 FORMAT(1H ,6E15.9)
 9530 FORMAT(1H ,6F10.0)
      IF(IPC.EQ.1)N=NPC
      DO 9 I=1,N
      MU(I,1)=XMNY(I)
      SIG(I,1)=SDY(I)
      BETA(I,1)=AB(I)/SCALL(I)
      IF(IPC.EQ.1)BETA(I,1)=A2(I)
      XMIN(I,1)=AB(I)
      IF(IPC.EQ.1)XMIN(I,1)=A2(I)
      SCALE(I,1)=SCALL(I)
      XIC(I,1)=YIC(I)
    9 CONTINUE
      IF(IW.NE.1)GOTO 9F
      WRITE(6,/)(MU(I,1),I=1,N)
      WRITE(6,/)(SIG(I,1),I=1,N)
      WRITE(6,/)(BETA(I,1),I=1,N)
      WRITE(6,/)(XIC(I,1),I=1,N)
      SEED=TIME(11)
 10   IF(SEED.LT.2097152)GO TO 15
      GO TO 10
 15   IF(SEED.GT.524286)GO TO 20
      SEED=SEED*2
      GO TO 15
 20   FSEED=FLOAT(SEED)/2.0
      ISEED=IFIX(FSEED)
      SEED2=2*ISEED
      IF(SEED-SEED2)30,25,30
 25   SEED=SEED-1
 30   NN=N*NYG
      DO 40 J=1,NN
 40   CONTINUE
      DO 100 I=1,N
      DO 50 J=1,NYG
      JJ=(I-1)*NYG+J
      EE(I,J)=EE1(JJ)
 50   CONTINUE
 100  CONTINUE
      DO 125 I=1,N
      Z1(I,1)=XIC(I,1)-MU(I,1)
      IF(V(I).EQ.-1)Z1(I,1)=ALOG(XIC(I,1)-BETA(I,1))-MU(I,1)
      Z1(I,1)=Z1(I,1)/SIG(I,1)
      XX(I,1)=XIC(I,1)*SCALE(I,1)
      IF(IPC.EQ.1)XX(I,1)=XIC(I,1)
      E(I,1)=0.
 125  CONTINUE
      DO 250 J=2,NYG
      DO 150 I=1,N
      E1(I,1)=E(I,1)
      E(I,1)=EE(I,J)
 150  CONTINUE
      CALL MMULT(A,Z1,DUM1,N,1,V,10,10,10,1,10,1)
      CALL MMULT(B,E,DUM2,N,1,N,10,10,10,1,10,1)
      CALL MADSUB(DUM1,DUM2,DUM1,N,1,1,10,1,10,1,10,1)
      IF(MARKOV.NE.1)GOTO 180
      CALL MMULT(C,E1,DUM2,N,1,V,10,10,10,1,10,1)
      CALL MADSUB(DUM1,DUM2,2,N,1,-1,10,1,10,1,10,1)
      GOTO 185
 180  DO 185 I=1,N
      Z(I,1)=DUM1(I,1)
 185  CONTINUE
      DO 200 I=1,N
      Z1(I,1)=Z(I,1)
      XX1=(Z(I,1)*SIG(I,1))+MU(I,1)
      IF(IPC.NE.1)GOTO 1855
      IF(IW.EQ.1)WRITE(6,*)J,I,XX1
 1855 IF(V(I).EQ.-1)XX1=BETA(I,1)+EXP(XX1)
      IF(IPC.EQ.1)GOTO 186
      XX1=XX1*SCALE(I,1)
 186  IF(XX1.LT.XMIN(I,1))XX1=XMIN(I,1)
      XX(I,J)=XX1
 200  CONTINUE
 250  CONTINUE
      IF(IW.NE.1)GOTO 500
      WRITE(6,/)(XX(I,J),J=1,NYG)
```

```
500   CONTINUE
      IF(IPC.NE.1)GOTO 515
      DO 510 I=1,N
      DO 505 J=1,NYG
      YPC(I,J)=XX(I,J)
505   CONTINUE
510   CONTINUE
      CALL UNTR
515   CONTINUE
      IF(NAT.EQ.1)CALL CNAT
      DO 525 I=1,N
      DO 520 J=1,NYG
      Y(J,I)=XX(I,J)/SCALE(I)
520   CONTINUE
525   CONTINUE
      RETURN
      END
      SUBROUTINE CNAT
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALE(10),NTRACE,IW
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),V(10),PCA(1
     .0,10),NCORE,NX
      COMMON/MWNAT/CU(5),DV(5),CSNB(5),CSNM(5),CSLAG(5),STOR(5,1),NAT
      DIMENSION CS(5,150),S(5,150),XN(10,150)
      DO 50 I=3,N
      IF(IW.EQ.1)WRITE(6,/)CU(I),DV(I),STOR(I,1),CSNB(I),CSNM(I),CSLAG(I
     .)
      DO 25 J=1,NYG
      XN(I,J)=XX(I,J)-(CU(I)+DV(I))
25    CONTINUE
      IF(IW.EQ.1)WRITE(6,/)((XN(I,J),J=1,NYG))
50    CONTINUE
      DO 100 I=3,N
      S(I,1)=CS(I,1)+STOR(I,1)
      XX(I,1)=XN(I,1)-CS(I,1)
      IF(XX(I,1).LT.AB(I))XX(I,1)=AB(I)
      DO 75 J=2,NYG
      CS(I,J)=CSNB(I)+(CSNM(I)*XN(I,J))+(CSLAG(I)*S(I,J-1))
      S(I,J)=CS(I,J)+S(I,J-1)
      XX(I,J)=XN(I,J)-CS(I,J)
      IF(XX(I,J).LT.AB(I))XX(I,J)=AB(I)
75    CONTINUE
      IF(IW.EQ.2)GOTO 100
      PRINT /,'CNAT PMF'
      WRITE(6,/)(CS(I,J),J=1,NYG)
      WRITE(6,/)(XX(I,J),J=1,NYG)
100   CONTINUE
      RETURN
      END
      SUBROUTINE UNTR
C     PROG TO TRANSFORM PRINCIPAL COMPONENT MATRICES BACK TO PHYSICAL
C     VARIABLES        LOG TRANSFORM AND A SCALE FACTER
      INTEGER SEED
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALE(10),NTRACE,IW
      COMMON/COM2/YP(150,10),XX(10,150),Y(10,150),U(150,10),V(10),PCA(10
     .,10),NCORE,NX
      COMMON/COM3/T(2,10),U(108),COR(3,10,10),WXM(10),S(10),XTQ(10),WZ(1
     .0),W(10),BA(10),FMEAN(10)
      DIMENSION X(10,150),XMIN(10),AT(5,5),A(5,5),YB(10,150),XMN(10),YS(
     .10,150)
9000  FORMAT(16I5)
9001  FORMAT(13A6)
9002  FORMAT(8F10.0)
9003  FORMAT(1H ,16I5)
9005  FORMAT(1H ,10E12.5)
9510  FORMAT(1H ,5F12.6)
9511  FORMAT(5F10.1)
9520  FORMAT(1H ,8F10.2/(1H ,8F10.2))
9525  FORMAT(8F10.2)
      ND=NPC+1
C     A(I,J)=PRINCIPAL COMPONENT COEFFICIENTS
30    DO 100 I=1,NX
      XMIN(I)=BA(I)
      XMN(I)=FMEAN(I)/SCALE(I)
      DO 90 J=1,NX
      A(I,J)=PCA(I,J)
90    CONTINUE
      IF(IW.EQ.1)WRITE(6,/)(A(I,J),J=1,NX)
100   CONTINUE
      IF(IW.NE.1)GOTO 140
      PRINT /,'XMIN(I),XMN(I)'
      WRITE(6,/)(XMIN(I),I=1,NX),(XMN(I),I=1,NX)
140   CONTINUE
C     COMPUTE MEAN AND VARIANCE FOR REMAINING PRINCIPAL COMPONENTS
      DO 110 I=ND,NX
      YB(I,1)=0.
      DO 105 J=1,NX
      YB(I,1)=YB(I,1)+(A(I,J)*XMN(J))
105   CONTINUE
110   CONTINUE
      DO 150 K=1,NYG
      DO 125 I=ND,NX
      Y(I,K)=YB(I,1)
125   CONTINUE
150   CONTINUE
      DO 160 I=1,NX
      DO 157 J=1,NYG
      Y(I,J)=Y(I,J)
      IF(IW.EQ.1)WRITE(6,/)(Y(I,J),J=1,NYG)
160   CONTINUE
155   CALL MTRANS(A,AT,NX,NX)
      IF(IW.NE.1)GOTO 156
      PRINT /,'AT'
      DO 161 I=1,NX
      WRITE(6,/)(AT(I,J),J=1,NX)
161   CONTINUE
156   CALL MMULT(AT,Y,X,NX,NX,NYG,5,5,10,150,10,150)
      DO 250 K=1,NYG
      DO 200 I=1,NX
      XX1=X(I,K)*SCALE(I)
      IF(XX1.LT.XMIN(I))XX1=XMIN(I)
      XX(I,K)=XX1
200   CONTINUE
250   CONTINUE
      IF(IW.NE.1)GOTO 260
      DO 260 I=1,NX
      WRITE(6,9520)(XX(I,K),K=1,NYG)
260   CONTINUE
      N=NX
      RETURN
      END
      SUBROUTINE PRINC
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALE(10),NTRACE,IW
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),V(10),PCA(1
     .0,10),NCORE,NX
      COMMON/COMB/A1(10),SUM
      DIMENSION A(10)
9002  FORMAT(8F10.0)
9500  FORMAT(1H ,7HA(J,L)=,5F10.4)
9503  FORMAT(1H ,12E10.4,(/1H ,12E10.4))
9504  FORMAT(1H ,31HPRINCIPAL COMPONENT TIME SERIES)
9507  FORMAT(1H ,9HSPECT(J))
9508  FORMAT(1H ,5E14.4)
      WRITE(6,9506)
C**** NPC= NO. OF PRINCIPAL COMPONENT VARIBLES INPUT, A(J,I)=COEFF
C**** OF EACH PHYSIVAL VARIBLE INPUT
      DO 300 J=1,NPC
      A(J)=15.E25
      DO 200 K=1,NYR
```

```
      Y(K,J)=0.
      DO 200 I=1,N
      Y(K,J)=Y(K,J)+PCA(J,I)*(X(K,I)/SCALE(I))
 200  CONTINUE
      IF(Y(K,J).LT.A(J))A(J)=Y(K,J)
 300  CONTINUE
      WRITE(6,9505)(Y(K,J),K=1,NYR)
      A(J)=A(J)/2.

      IF(A(J).LT.0.)A(J)=-A(J)
 400  CONTINUE
      WRITE(6,9507)
      WRITE(6,9508)(A(J),J=1,NPC)
      DO 650 J=1,NPC
      A1(J)=A(J)
 650  CONTINUE
      RETURN
      END

      SUBROUTINE MODEL
      REAL M0,M1,M2
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AR(10),SCALE(10),NTRACE
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),V(10),PCA(1
     +0,10),NCORE,NX
      COMMON/COM3/PT[2,10],UE10],COR[3,10,10],W>C[10]
      COMMON/COMM/NUP,NI,NN,DELTA,LAM,CRITV,IADIAG,NW
      COMMON/COMG/A(10,10),B(10,10),C(10,10)
      DIMENSION S(10,10),T(10,10),M0(10,10),
     1M1(10,10),M2(10,10),NM(10)
      TEST=0.0
 100  FORMAT(4I5,3F10.6)
 101  FORMAT (8E12.5)
 102  FORMAT (12F10.5)
 103  FORMAT (' NO. ITERATIONS = 'I5,' XMAX = ',F15.5)
 105  FORMAT (' LOWER TRIANGULAR MATRIX')
 106  FORMAT (' THE OTHER MATRIX')
 300  FORMAT(6I3)
 301  FORMAT(3I5)
 310  FORMAT (4E15.8)
 501  FORMAT (9H0A MATRIX )
      NW=6
      DO 1 I=1,N
      DO 1 J=1,N
      M0(I,J)=COR(1,I,J)
      M1(I,J)=COR(2,I,J)
      M2(I,J)=COR(3,I,J)
 1    CONTINUE
C     MARKOV
C     1=ARIMA(1,0,1)
C     2=ARIMA(1,0,0)
C     3=MARKOV
      GOTO(45,8000,9000),MARKOV
C     SETS TO ZERO ANY NONSIGNIFICANT ELEMENTS
 45   DO 900 I=1,N
      DO 900 J=1,N
      IF(ABS(M0(I,J)).LT.CRITV)M0(I,J)=0.0
      IF(ABS(M1(I,J)).LT.CRITV)M1(I,J)=0.0
 900  IF(ABS(M2(I,J)).LT.CRITV)M2(I,J)=0.0
      PRINT /,'M0 MATRIX'
      DO 905 I=1,N
 905  WRITE (6,7) (M0(I,J),J=1,N)
      PRINT /,'M1 MATRIX'
      DO 910 I=1,N
 910  WRITE (6,7) (M1(I,J),J=1,N)
      PRINT /,'M2 MATRIX'
      DO 915 I=1,N
 915  WRITE (6,7) (M2(I,J),J=1,N)
C     T=M1, S=M1T
      DO 4 I=1,N
      DO 4 J=1,N
      T(I,J)=M1(I,J)
    4 S(J,I)=M1(I,J)
      IF(IADIAG.EQ.1) GO TO 490
C     SET A MATRIX TO DIAGONAL MATRIX
      DO 1010 I= 1, N
      DO 1010 J= 1, N
      IF(I.NE.J) GO TO 1009
      A(I,J) = M2(I,J)/M1(I,J)
      GOTO 1010
 1009 A(I,J)=0.00000
 1010 CONTINUE
      GOTO 505
C     CALCULATES A MATRIX FROM EQUATION A=M2(M1-1)
C
C     T=M1-1
 490  CALL MINV(T,1,N,0,0,0,TEST,N1)
      PRINT /,'M1-1 MATRIX'
      DO 500 I=1,N
      WRITE(6,110)(T(I,J),J=1,N)
 500  CONTINUE
C     CALCULATE A=M2M1-1
      CALL MMULT (M2,T,A,N,N,N,10,10,10,10,10,10)
 505  WRITE (6,501)
      DO 309I=1,N
 309  WRITE (6,110) (A(I,J),J=1,N)
C     T=AS=AM1T=(M2M1-1)M1T
      CALL MMULT (A,S,T,N,N,N,10,10,10,10,10,10)
C     S=M0-T=M0-AM1T=M0-(M2M1-1)M1T
      CALL MADSUB (M0,T,S,N,N,-1.,10,10,10,10,10,10)
C     M2=M2T(M1-1T)M1
      DO 5 I=1,N
      DO 5 J=1,N
    5 M2(I,J)=T(J,I)
C     T=S-M2=M0-AM1T-M2T(M1-1T)M1
      CALL MADSUB (S,M2,T,N,N,-1.,10,10,10,10,10,10)
C     S=AM0
      CALL MMULT (A,M0,S,N,N,N,10,10,10,10,10,10)
C
C     M0=AM0-M1= T =CBT
C
      CALL MADSUB (S,M1,M0,N,N,-1.,10,10,10,10,10,10)
C     M2=AT=M2T(M1-1T)
      DO 6 I=1,N
    6 M2(I,J)=A(J,I)
C     A=AM0(AT)=M2M1-1)M0(M2T)(M1-1T)
      CALL MMULT (S,M2,A,N,N,N,10,10,10,10,10,10)
C
C     S=M0-(AM1T)-M2T(M1-1T)M1+M2(M1-1)M0(M2T)(M1-1T)
C        S=BBT+CCT
C
      CALL MADSUB (T,A,S,N,N,1.,10,10,10,10,10,10)
      PRINT /,'S=(M0-(AM1T)-M2T(M1-1T)M1+M2(M1-1)M0(M2T)(M1-1T)) MATRIX'
      DO 40 I=1,N
      WRITE (NW,102)(S(I,J),J=1,N)
 40   CONTINUE
      DO 41 I=1,N
      WRITE (NW,102)(M0(I,J),J=1,N)
 41   CONTINUE
      DO 11 I=1,N
      DO 11 J=1,N
 11   T(I,J)=M0(J,I)
      GO TO 12
C     T= M0=AM0-M1
 10   DO 7 I=1,N
      DO 7 J=1,N
    7 T(I,J)=M0(I,J)
C     M0=TT
```

```
      DO 13 I=1,N
      DO 13 J=1,N
   13 M0(I,J)=T(J,I)
   12 CONTINUE
C   M2,B=IDENTITY MATRICES
      DO 8 I=1,N
      DO 9 J=1,N
      M2(I,J)=0.
      B(I,J)=0.
    9 M1(I,J)=0
      B(I,I)=1.
    8 M1(I,I)=1.
C
C    CONVERGENCE LOOP
C
      DO 14 I=1,NN
C   CALCULATE INVERSE OF B IDENTITY MATRIX
      CALL MINV (B,1,N,0,0,0,TEST,NI)
      IF(IWRITE.EQ.0)GOTO 7000
      WRITE(6,9888)
      DO 7000 I=1,N
      WRITE(6,102)(B(I,J),J=1,N)
 7000 CONTINUE
C   CALCULATE (B-1)TT=A
      CALL MMULT(B,M0,A,N,N,N,10,10,10,10,10,10)
      IF(IWRITE.EQ.0)GOTO 7010
      WRITE(6,8998)
 8998 FORMAT(1H ,7H(B-1)TT)
      DO 7010 I=1,N
      WRITE(6,102)(A(I,J),J=1,N)
 7010 CONTINUE
C   CALCULATE T(B-1)TT=B
      CALL MMULT(T,A,B,N,N,N,10,10,10,10,10,10)
      IF(IWRITE.EQ.0)GOTO 7020
      WRITE(6,6996)
 6996 FORMAT(1H ,8HT(B-1)TT)
      DO 7020 I=1,N
      WRITE(6,102)(B(I,J),J=1,N)
 7020 CONTINUE
C   LAM INTRODUCED FOR CONVERGENCE IF NECESSARY
      IF (ABS(LAM-1.E0).LT.1.E-10) GO TO 21
      DO 22 J=1,N
      DO 22 K=1,N
   22 B(J,K)=LAM*B(J,K)
   21 CONTINUE
C   CALCULATE S-T(B-1)TT=M2
      CALL MADSUB(S,B,M2,N,N,-1.,10,10,10,10,10,10)
      IF(IWRITE.EQ.0)GOTO 7030
      WRITE(6,7896)
 7896 FORMAT(1H ,10HS-T(B-1)TT)
      WRITE(6,102)(M2(I,J),J=1,N)
 7030 CONTINUE
C   COUNTS NUMBER OF NEGATIVE ELEMENTS IN M2
      DO 51 IX=1,N
      IF(M2(IX,IX).GE.0.)GOTO 51
      NNN(IX)=NNN(IX)+1
      NEG=NEG+1
   51 CONTINUE
C   COMPARES NEW M2 WITH PREVIOUS (M2=M1) SETS DIFFERENCE IN B
      CALL MADSUB(M2,M1,B,N,N,-1.,10,10,10,10,10,10)
      XMAX=1.E-5
      SBSQ=0.
      DO 15 J=1,N
      DO 15 K=1,N
      BSQ=ABS(B(J,K))
      SBSQ=SBSQ+BSQ
      IF (BSQ.LT.XMAX) GO TO 15
      XMAX=BSQ
   15 CONTINUE
C     PUTS NEW M2=B,AND M1
      DO 16 J=1,N
      DO 16 K=1,N
      M1(J,K)=M2(J,K)
   16 B(J,K)=M2(J,K)
      SBSQ=SBSQ/(N*N)
      IF (MOD(I,NM).EQ.0) WRITE(6,*/)XMAX,DELTA,SBSQ,D
C   COMPARES NEW LARGEST ELEMENT WITH CONVERGENCE CRITERIA DELTA
C    IF LESS THAN DELTA THEN CONVERGENCE HAS OCCURRED
      IF (XMAX.LT.DELTA) GO TO 200
   14 CONTINUE
  200 CONTINUE
      WRITE(6,*/) NEG,(NNN(IX),IX=1,N)
  301 FORMAT(10I5)
      WRITE (6,103) I,XMAX
      PRINT /,'BBT MATRIX'
      DO 30 I=1,N
C     WRITE (NW,102) (B(I,J),J=1,N)
   30 WRITE (6,102)(B(I,J),J=1,N)
C
C     CALCULATES B MATRIX AS LOWER TRIANGULAR MATRIX SETS NEG ELEMENTS
C       TO ZERO
      CALL SOLUTI   (B,N,NI)
      WRITE(6,105)
C     CALCULATES BT
      DO 17 I=1,N
      DO 18 K=1,N
   18 M1(I,K)=B(K,I)
   17 WRITE (6,102) (B(I,J),J=1,N)
C     CALCULATES INVERSE OF BT=(BT-1)
      CALL MINV (M1,1,N,0,0,0,TEST,NI)
C
C       CALCULATES     C=T(BT-1)
C
      CALL MMULT(T,M1,M2,N,N,N,10,10,10,10,10,10)
      WRITE (6,106)
      DO 19 I=1,N
   19 WRITE(6,102)(M2(I,J),J=1,N)
      GOTO 9050
C   COMPUTE MULTIVARIATE AUTOREGRESSIVE ARMA(1,0,0)
C     CALCULATE (M0-1)
 8000 DO 8001 I=1,N
      DO 8001 J=1,N
 8001 CONTINUE
      CALL MINV(S,1,N,0,0,0,TEST,NI)
C     CALCULATE A=M1(M0-1)
      CALL MMULT(M1,S,A,N,N,N,10,10,10,10,10,10)
      WRITE(6,1235)
 1235 FORMAT(1H ,8HA MATRIX)
      DO 8005 I=1,N
      WRITE(6,102)(A(I,J),J=1,N)
 8005 CONTINUE
C   CALCULATE M1T
      DO 8010 I=1,N
      DO 8010 J=1,N
      M2(I,J)=M1(J,I)
 8010 CONTINUE
C    CALCULATE AM1T
      CALL MMULT(A,M2,T,N,N,N,10,10,10,10,10,10)
C    CALCULATE B(BT)=M0-A(M1T)
      CALL MADSUB(M0,T,B,N,N,-1.,10,10,10,10,10,10)
      CALL SOLUTI(B,N,NI)
      WRITE(6,4785)
 4785 FORMAT(1H ,8HB MATRIX)
      DO 8015 I=1,N
      WRITE(6,102)(B(I,J),J=1,N)
 8015 CONTINUE
      GOTO 9050
C   CALCULATE A MATRIX =M1(I,I)
```

```
      DO 9005 I=1,N
      M1(I,I)=M1(I,I)
 9005 CONTINUE
      DO 9006 I=1,N
      WRITE(6,102)(A(I,J),J=1,N)
 9006 CONTINUE
C     CALCULATE NEW M1(I,J) WHERE M1(I,J)=M1(I)*M0(I,J)
C     S=M1*M0
      DO 9010 I=1,N
      DO 9010 J=1,N
      S(I,J)=M1(I,I)*M0(I,J)
 9010 CONTINUE
C     CALCULATE M1T ,T=M1T
      DO 9015 I=1,N
      T(I,J)=S(J,I)
 9015 CONTINUE
C   CALCULATE BBT=M0-A*M1T
C     FIRST A*M1T=M2
      CALL MMULT(A,T,M2,N,N,N,10,10,10,10,10,10)
      CALL MADSUB(M0,M2,B,N,N,-1,10,10,10,10,10,10)
      CALL SOLUTI(B,N,NI)
      WRITE(6,4785)
      DO 9020 I=1,N
      WRITE(6,102)(B(I,J),J=1,N)
 9020 CONTINUE
 9050 RETURN
      END
```

```
      SUBROUTINE FIER(SD0,SD,NY,N,R)
      COMMON/COM1/K,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALE(10),NTRACE,IW
      DIMENSION SD0(10),R(10,10),S(10),SU(10),SO(10),F(10)
 9500 FORMAT(1H ,I10,F11.5,4E12.5)
 9502 FORMAT(1H ,' VARIABLE ','FIERINGS F. UNCORR. SD. ',3X,'CORR. SD.',
     .'UNCORR SD0.',2X,'CORR. SD0')
      DO 20 I=1,N
      S(I)=SD(I)
      SO(I)=SD0(I)
      A=NY
      B=A*(A-1.)
      B2=2./B
      R1=1.-R(I,I)
      RN=1.-R(I,I)**A
      C=(A*R(I,I)*R1)-(R(I,I)*RN)
      C2=C/(R1**2)
      C3=B2*C2
      F1=1.-C3
      F(I)=SQRT(1./F1)
      SD(I)=S(I)*F(I)
      SD0(I)=SO(I)*F(I)
 20   CONTINUE
      IF(IW.EQ.2)GOTO 30
      WRITE(6,9502)
      DO 30 I=1,N
      WRITE(6,9500)I,F(I),S(I),SD(I),SO(I),SD0(I)
 30   CONTINUE
      RETURN
      END
""          THIS CARD STOPS THE 1004
      SUBROUTINE SKEW(XMN,SD,VV,LAG,SLN,IOPT)
      INTEGER VV(10,10)
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALE(10),NTRACE,IW
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),V(10),PCA(1
     .0,10),NCORE,NX
      DIMENSION XMN(10),SD(10),SK(10)
      IF (LAG.NE.0) GO TO 10
      YR=NYR-1
      DO 1 I=1,N
      SK(I)=0.
      DO 2 J=1,NYR
    2 SK(I)=SK(I)+(Y(J,I)-XMN(I))**3
      SK(I)=SK(I)/(YR*SD(I)**3)
      IF(IOPT.EQ.1)GO TO 7
      IF (ABS(SK(I)).GT.SLN) GO TO 8
 7    V(I)=2
      GO TO 1
 8    V(I)=-1
    1 CONTINUE
      IF(IW.EQ.2)GOTO 90
      WRITE (6,100) (SK(I),I=1,N)
  100 FORMAT (' SKEWS ' ,5E15.8)
      WRITE (6,101) (V(I),I=1,N)
 90   DO 5 I=1,N
      DO 3 J=1,N
    3 VV(I,J)=V(I)*V(J)
      IF(IW.NE.2)WRITE(6,101)(VV(I,J),J=1,N)
  5   CONTINUE
  101 FORMAT (1H,16I5)
   10 RETURN
      END
```

```
      SUBROUTINE SKEW(XMN,SD,VV,LAG,SLN,IOPT)
      INTEGER VV(10,10)
      COMMON/COM1/N,NYR,NYG,NPC,IPC,MARKOV,AB(10),SCALE(10),NTRACE,IW
      COMMON/COM2/Y(150,10),XX(10,150),YPC(10,150),X(150,10),V(10),PCA(1
     .0,10),NCORE,NX
      DIMENSION XMN(10),SD(10),SK(10)
      IF (LAG.NE.0) GO TO 10
      YR=NYR-1
      DO 1 I=1,N
      SK(I)=0.
      DO 2 J=1,NYR
    2 SK(I)=SK(I)+(Y(J,I)-XMN(I))**3
      SK(I)=SK(I)/(YR*SD(I)**3)
      IF(IOPT.EQ.1)GO TO 7
      IF (ABS(SK(I)).GT.SLN) GO TO 8
 7    V(I)=2
      GO TO 1
 8    V(I)=-1
    1 CONTINUE
      IF(IW.EQ.2)GOTO 90
      WRITE (6,100) (SK(I),I=1,N)
  100 FORMAT (' SKEWS ' ,5E15.8)
      WRITE (6,101) (V(I),I=1,N)
 90   DO 5 I=1,N
      DO 3 J=1,N
    3 VV(I,J)=V(I)*V(J)
      IF(IW.NE.2)WRITE(6,101)(VV(I,J),J=1,N)
  5   CONTINUE
  101 FORMAT (1H,16I5)
   10 RETURN
      END
```

```
      SUBROUTINE SOLUTI(B,N,NI)
      DIMENSION       B(NI,NI)
      B(1,1)= SQRT(B(1,1))
      DO 1 I=2,N
      B(I,1)=B(1,I)/B(1,1)
      PRINT /,'B(I,1)'
      WRITE(6,*/)I,B(I,1)
    1 B(1,I)=0.
      DO 4 J=2,N
      DO 2 K=1,J-1
      DO 2 K1=J,N
 2    B(J,K1)=B(J,K1)-B(K1,K)*B(J,K)
      PRINT /,'B(J,K1),B(J,J)'
```

```
      WRITE(6,*/)J,K1,B(J,K1),J,K,B(J,J)
      IF(B(J,J).LT.0.)B(J,J)=0.
      B(J,J)= SQRT(B(J,J))
      IF (J.EQ.N) GO TO 5
      DO 3 K2=J+1,N
      IF(B(J,J).NE.0.)GOTO 25
      B(K2,J)=0.
      GOTO 3
   25 B(K2,J)=B(J,K2)/B(J,J)
    3 B(J,K2)=0.
    4 CONTINUE
    5 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE MMULT(A,B,C,N1,N2,N3,NI)
      DOUBLE PRECISION A,B,C
      DIMENSION A(NI,NI),B(NI,NI),C(NI,NI)
      DO 1 I=1,N1
      DO 1 J=1,N2
      C(I,J)=0.
      DO 1 K=1,N3
    1 C(I,J)=C(I,J)+A(I,K)*B(K,J)
      RETURN
      END
```

```
      SUBROUTINE MINV(A,N1,N2,N3,NY,DET,TEST,NI)
C     SQUARE MATRIX INVERSION, GAUSSIAN ELIMINATION.
C     INVERSE BETWEEN N1 AND N2 WITH OPTIONAL SOLUTIONS STARTING AT N3 AND
C     GOING TO N3 + NY - 1.
C     DIAGONAL ELEMENTS  < #TEST# SET TO ZERO.
C     DETERMINANT RETURNED AS DET. NI IS THE NUMBER OF ROWS OF A IN CALLING
      DIMENSION A(NI,NI)
      NK=N3+NY-1
      DET=1.0
      DO 40 L=N1,N2
       IF (ABS(A(L,L)).GT.TEST) GO TO 5
       DET=0.0
       A(L,L)=0.0
       GO TO 10
 5     DET=DET*A(L,L)
       A(L,L)=1.0/A(L,L)
 10   DO 25 I=N1,N2
       IF (I.EQ.L) GO TO 25
        A(I,L)=A(I,L)*A(L,L)
       DO 15 J=N1,N2
        IF (J.EQ.L) GO TO 15
         A(I,J)=A(I,J)-A(I,L)*A(L,J)
 15     CONTINUE
       IF (NY.LE.0) GO TO 25
        DO 20 J=N3,NK
 25    CONTINUE
      DO 30 J=N1,N2
       IF (J.EQ.L) GO TO 30
        A(L,J)=-A(L,L)*A(L,J)
 30     CONTINUE
      IF (NY.LE.0) GO TO 40
      DO 35 J=N3,NK
 35     A(L,J)=-A(L,L)*A(L,J)
 40   CONTINUE
      IF (NY.LE.0) GO TO 50
       DO 45 I=N1,N2
        DO 45 J=N3,NK
 45     A(I,J)=-A(I,J)
 50   RETURN
      END
```

```
      SUBROUTINE READ3(Y,NS,NY)
      DIMENSION DUM(150),Y(150,10)
      DO 60 I=1,NS
      CALL READ(DUM,NY,STID)
      DO 50 J=1,NY
      Y(J,I)=DUM(J)
 50   CONTINUE
 60   CONTINUE
      RETURN
      END
      SUBROUTINE READ(A,NY,STID)
C**** TO READ SELECTED YEARS FROM HYDRO-MET DATA FILES

      DIMENSION DUM(8),A(1)
      DATA BLANK/6H      /
 9000 FORMAT(I1,A6,2I4,6F10.0)
 9002 FORMAT(8F10.0)
 9500 FORMAT(1H0,A6,2I10/(1H ,12F10.1))
      READ(5,9001)NR,JY1,JY2,JJY1
      NY=JY2-JY1+1
      JY=0
      STID=BLANK
      IF(JJY1.GT.0)GOTO 180
C***  OUR DATA FILES

 100  READ(NR,9000)ICDTP,STID,IY1,IY2,(DUM(I),I=1,6)
      IF(JY1.GT.IY2)GOTO 100
      I1=1
      IF(JY1.GT.IY1)I1=JY1-IY1+1
      I2=IY2-IY1+1
      IF(IY2.GT.JY2)I2=6-(IY2-JY2)
      DO 120 I=I1,I2
      JY=JY+1
      A(JY)=DUM(I)
 120  CONTINUE
      IF(IY2.LT.JY2)GOTO 100
 130  WRITE(6,9500)STID,JY1,JY2,(A(I),I=1,NY)
      RETURN
C***  WRD DATA FILES
 180  IY1=JJY1-8
      IY2=JJY1-1
 200  READ(NR,9002)(DUM(I),I=1,8)
      IY1=IY1+8
      IY2=IY2+8
      IF(JY1.GT.IY2) GOTO 200
      I1=1
      IF(JY1.GT.IY1)I1=JY1-IY1+1
      I2=8
      IF(IY2.GT.JY2)I2=8-(IY2-JY2)
      DO 220 I=I1,I2
      JY=JY+1
      A(JY)=DUM(I)
 220  CONTINUE
      IF(IY2.LT.JY2) GOTO 200
      GOTO 130
      END
```

Table D-2a. Input data and decision parameters for Data Preparation Model.

I. Main program input

1. (RHDG(I), I=1,N) - Format (13A6)

1-72	RHDG(I)	Row headings for each variable

2. (CHDG(I), I=1,N) - Format (13A6)

1-72	CHDG(I)	Column headings for each variable

3. N, NYR, NYG, NPC, IPC, MARKOV, NTRACE, ISKEW, NX, NAT, IONE, IW, II, MSI - Format (14I5)

1-5	N	Number of input variables i.e. 5
6-10	NYR	Number of years in the input time series i.e. 41
11-15	NYG	Number of years to be generated i.e. 125
16-20	NPC	Number of principal component time series i.e. 2
21-25	IPC	Option for doing principal components if = 1 do if = 0 don't use P.C.
26-30	MARKOV	Parameter for determining types multivariate stochastic model: if = 1, then ARIMA (1,0,1); if = 2, then ARIMA (1,0,0); if 3, then MARKOV
31-35	NTRACE	Number of intervals for multiple generations i.e. 7
36-40	ISKEW	Option to prevent log transformation regardless of skew: if = 1, then do; if = 0 determines log transformation based on skew <±SLN
41-45	NX	Number of time series remaining if doing principal components: if NPC = 2 and N = 5, then NX = 3
46-50	NAT	Option to convert natural flows generated to present modified flows if = 1
51-55	IONE	if = 1, then do only one generation.
56-60	IW	if = 1, then prints out various write statements; if = 0, then normal printout
61-65	II	Number of generations within each NTRACE i.e. 3
66-70	MSI	if = 1, option to read in previous sum of squares from file if continuing on in number of generations on another start.

4. NUP, NI, NN, NM, IADIAG - Format (5I5)

1-5	NUP	if = B, then assumes the B matrix to be lower triangular
6-10	NI	Dimension of matrices A, D, C, assuming square matrices
11-15	NN	Number of iterations desired
16-20	NM	Number of lines of convergence values desired written
21-25	IADIAG	if = 1, then A matrix is computed by equation A = $M2M_1^{-1}$: if = 0, then A is computed as a diagonal matrix where the diagonals = M2/M1

5. (SCALE(I), I = 1,N) = Format (8F10.0)

1-80	SCALE(I)	The conversion factor to maintain all variables in units of feet i.e., evap. and precip (inches) - 12, streamflow (acre-feet = 1079259 AC = Area GSL

6. LAM, CRITV, DELTA, SLN - Format (4F10.0)

1-10	LAM	Damping coefficient, 0.0 < λ < 1.0, to help oscillating iterations converge
11-20	CRITV	Significance level i.e. (5 percent for N years) to set nonsignificant elements of M0, M1, M2 matrices to zero

6.

21-30	DELTA	Convergence criteria i.e. .0063
31-40	SLN	In Skew S/R the criteria for determining normal distribution (0.1)

7. (A(I), I = 1,N) - Format (8F10.0)

1-80	A(I)	Half the lowest historic value of each variable time series except for exap. = 80% of lowest value.

IF NAT = 1 then read these parameters

1. (CU(I), I=3,5) - Format (3F10.0)

CU(I)	1-10	CU(I) Consumptive use for Bear, Weber, Jordan River Basins

2. (DV(I), I=3,5) - Format (3F10.0)

DV(I)	1-10	DV(I) Diversions into or out of Weber, Jordan River Basins

3. (CSNB(I), I=3,5) - Format (3F10.0)

CSNB(I)	1-10	CSNB(I) Constants for linear regression equations for three basins for change of storage = (natural - consumptive use ± diversion = natural')

4. (CSNM(I), I=3,5) - Format (3F10.0)

CSNM(I)	1-10	CSNM(I) Coefficient for linear regression for change of storage = $natural'_t$

5. (CSLAG(I), I=8,5) - Format (3F10.0)

CSLAG(I)	1-10	CSLAG(I) Coefficient for lag natural' term in linear regression equation for change of storage = NAT'

6. (STOR(I,1), I=3,5) - Format (3F10.0)

STOR(I)	1-10	Initial end of year storage for each river basin

IF IPC. = 1 then read in principal component time series coefficients

Principal component time series (Princ), called if IPC = 1

1. (PCA(J,I), J=1, NPC, I=1,N) - Format (8F10.0)

1-80	PCA(J,I)	Principal component coefficient for each variable (i) up to N, for the Jth principal component time series

2. Repeat above card for each principal component time series up to NPC

CALL Read 3 subroutine: reads input time series (sets of cards 1 and 2 or 3 for each time series)

1. NR, JY1, JY2, JJY1 - Format (4I10)

1-10	NR	File number time series is to be read from, 5 if cards
11-20	JY1	Beginning year of time series
21-30	JY2	Ending year of time series
31-40	JJY1	Beginning year of time series if data has no index years on data card and is in 8F10.0 format

2. ICDTP, STID, IY1, IY2, (DUM(I), I=1,6) - Format (I1, A6, 2I4, 6F10.0)

1	ICDTP	Not used
2-7	STID	Station identification

Table D-2a. Continued.

8-11	IY1	Beginning year for data on card/file sequence
12-15	IY2	Ending year for data on card/file sequence
16-75	DUM(I)	Data points
3. (DUM(I), I=1,8) - Format (8F10.0) If JJY1 is >0 then this format is called		
1-80	DUM(I)	Data points

Table D-2b. Input Data Preparation Program.

```
 EVAP  ESLPCP  BEAR WEBERJORDANRESIO
     5   41  125     2    1     1     7         5
     1   10  100     1    1
        12          12   1079259   1079259   1079259
   1.                  .0063      .12
       40.        3.1   202600.   30250.    65950.
 .22117965 .9318105  -.19098067.19960032 .080590102
 .84109744 -.13821509.49304633 .14755654 .092650269
-.06523656-.22546632-.22045803.94383114 -.07409562
-.05743973-.10101648-.12175517.020827238.98551421
 .43588015 -.22712637-.81055879-.21710777-.09051382
         5      1937      1977      1937
      59.2      56.1      59.4      63.2      50.1      53.9      55.7      52.8
      48.4      50.4      48.3      53.1      48.3      47.9      51.4      51.4
      50.3      55.1      49.9      50.3      48.2      55.4      49.4      58.
      56.3      52.4      49.9      49.1      44.6      54.6      45.8      49.9
      55.3      53.0      49.1      51.0      52.5      58.3      46.5      49.6
      48.7
         5      1937      1977      1875
       9.4      12.2       6.6       8.9       3.5       5.9       7.6       6.0
       5.3      12.0      10.6       8.8       6.5       5.2       6.1      12.6
      10.7       8.3       9.6       8.1       5.4       7.1       8.1       7.6
       6.9       6.4       9.5       7.1       7.6       9.4       8.3      13.0
      11.2      11.7      13.3       7.5       8.7      10.2       8.4      11.1
       9.4       7.6      12.4       6.6       7.0       8.1       9.1      10.3
      11.6       5.2      14.1      13.2       9.7       6.7      11.6      10.5
       5.9      10.9       7.3       5.2      10.5      10.6      11.6      11.3
      14.0       9.8      11.2      10.8      12.1      11.2       9.5       6.2
       9.4       9.1      11.7       9.0       9.0       6.4       7.8      12.1
       8.9      10.7      12.1       6.4      12.7      12.9      10.9      11.4
      13.8      10.8      15.7       9.7      15.0      12.2       9.9
         5      1937      1977      1901
   1204800    883300    773100   1595900    764900   1224700   2293500   1366300
   2233400   1960000   1487500   1414200   1416900   1770700    921500   1270500
   1771100   1249400   1052900   1306900   1696300   2112400   1808900   1297200
   1113900    904600    784800    760800    880600    776200    466600    781800
    646800    343200    470800    860800    767800    811800    600200    468600
    524800    707800    875400    697400    812000   1041400   1070600   1167800
   1020000   1741000   1630200   1686400   1043800    539200    611200    879800
    954400   1058800    602200    569800    405200    874800    629400    916400
   1091000   1154400   1054200   1059200   1215400    875800   2067800   2070600
   1485000   1505000   1457000   1827000    689300
         5      1937      1977      1901
    408000    274000    286000    814000    287000    556000   1100000    397000
    411000    360000    503000    466000    540000    233000    114500    412400
    679000    346000    301000    650000    959000    828000    745000    370000
   1100000    698000    506000    673000    450000    782000    291000    699000
    367300     89900    188400    429900    412200    438400    283100    166900
    180100    411500    436100    344600    370400    483600    322900    447200
    512600    633400    602000    659100    444300    151600    119200    301300
    327100    425600    112500    112100     60500    210400    145900    312300
    337700    116000    175100    211100    492400    233500    496800    522400
    451000    529900    560000    353546    770580
         5      1937      1977      1901
    263300    227900    210300    282300    214300    253700    340700    296000
    343800    363500    301700    278600    279800    507100    247700    284900
    303600    288100    262100    270600    312100    533900    322000    292700
    269000    243200    266700    240100    246000    217000    230100    212000
    229200    166500    140000    177900    219200    236200    239100    225500
    235200    280000    264000    263800    235100    282100    236500    284000
    270300    258100    252600    235200    280000    264500    191400    211700
    224000    252200    220800    180900    131900    168100    157900    199400
```

Table D-3. Output Data Preparation Program.

```
N=5, NYR=41, NYG=41, NPC=2, IPC=1, MARKOV=1, NTRACE=7, ISKEW=0, NX=5, NAT=0, ICNE=1, IW=2, II=3, MSI=0, INABC=0,
NUP=1, NI=10, NN=100, NM=1, IADIAG=1,
12,0, 12,0, 1079259,0, 1079259,0, 1079259,0,
LAM=1, CRITV=0,0, DELTA=0,0063, SLN=0,12,
40,0, 3,1, 202600,0 ,30250,0, 65950,0,
0,22117968, 0,9318105, =0,19098087, 0,19960032, 0,080590102,
0,84109744, =0,138215090001, 0,493046330001, 0,14755654, 0,092650269,
=0,06523656, =0,22546632, =0,22045803, 0,94383114, =0,07409562,
=0,05743973, =0,10101648, =0,12175517, 0,020827238, 0,98551421,
0,48588015, =0,22712637, =0,81055879, =0,21710777, =0,09051382,
            1937     1977
    59,2     56,1     59,4     63,2     50,1     53,9     55,7     52,8     48,4     50,4     48,3     53,1
    48,3     47,9     51,4     51,4     50,3     55,1     49,9     50,3     48,2     55,4     49,4     58,0
    56,3     52,4     49,9     49,1     44,6     54,6     45,2     49,9     55,3     53,0     49,1     51,0
    52,5     58,3     46,5     49,6     48,7
            1937     1977
    11,6     11,3     10,7      9,0     15,2     12,6      8,7     11,2     12,1     10,4     14,0      9,8
    11,2     10,8     12,1     11,2      9,5      6,2      9,4      9,1     11,7      9,0      9,0      6,4
     7,8     12,1      8,9     10,7     12,1      6,4     12,7     12,9     10,9     11,4     13,8     10,8
    15,7      9,7     15,0     12,2      9,9
            1937     1977
 767800,0  811800,0  600200,0  468600,0  524800,0  707800,0  875400,0  697400,0  812000,0 1041400,0 1070600,0 1167800,0
1020000,0 1741000,0 1630200,0 1686400,0 1043800,0  539200,0  611200,0  879800,0  954400,0 1058800,0  602200,0  569800,0
 405200,0  874800,0  629400,0  916400,0 1091000,0 1154400,0 1054200,0 1059200,0 1215400,0  875800,0 2067800,0 2070600,0
1485000,0 1505000,0 1457000,0 1827000,0  689300,0
            1937     1977
 412200,0  438400,0  283100,0  166900,0  180100,0  411500,0  436100,0  344600,0  370400,0  483600,0  322900,0  447200,0
 512600,0  633400,0  602000,0  659100,0  444300,0  151600,0  119200,0  301300,0  327100,0  425600,0  112500,0  112100,0
  60500,0  210400,0  145900,0  312300,0  337700,0  116000,0  175100,0  211100,0  492400,0  233500,0  496800,0  522400,0
 451000,0  529900,0  560000,0  353546,0  770580,0
            1937     1977
 219200,0  236200,0  239100,0  225500,0  235200,0  280000,0  264000,0  263800,0  235100,0  282100,0  236500,0  284000,0
 270300,0  258100,0  252600,0  235200,0  280000,0  264500,0  191400,0  211700,0  224000,0  252200,0  220800,0  180900,0
 131900,0  168100,0  157900,0  199400,0  239700,0  231200,0  240200,0  278100,0  373400,0  389200,0  378900,0  374400,0
 360000,0  430400,0  395000,0  496411,0  218600,0
PRINCIPAL COMPONENT TIME SERIES
 ,1949E+01 ,1867E+01 ,1890E+01 ,1829E+01 ,2062E+01 ,1944E+01 ,1648E+01 ,1803E+01 ,1774E+01 ,1663E+01 ,1865E+01 ,1637E+01
 ,1694E+01 ,1550E+01 ,1729E+01 ,1658E+01 ,1583E+01 ,1449E+01 ,1578E+01 ,1550E+01 ,1705E+01 ,1630E+01 ,1540E+01 ,1499E+01

 ,1593E+01 ,1802E+01 ,1538E+01 ,1646E+01 ,1649E+01 ,1338E+01 ,1683E+01 ,1794E+01 ,1770E+01 ,1779E+01 ,1731E+01 ,1537E+01
```

```
.2034E+01 .1692E+01 .1897E+01 .1641E+01 .1703E+01
.4442E+01 .4253E+01 .4374E+01 .4582E+01 .3621E+01 .4036E+01 .4286E+01 .3960E+01 .3695E+01 .3979E+01 .3778E+01 .4228E+01
.3816E+01 .4137E+01 .4312E+01 .4354E+01 .3978E+01 .4080E+01 .3701E+01 .3882E+01 .3744E+01 .4343E+01 .3662E+01 .4283E+01

.4061E+01 .3976E+01 .3716E+01 .3797E+01 .3552E+01 .4316E+01 .3548E+01 .3886E+01 .4405E+01 .4049E+01 .4328E+01 .4500E+01

.4270E+01 .4772E+01 .3863E+01 .4262E+01 .3738E+01
3PLN,A(J)
.66888651E+00 .17740072E+01

M0 MATRIX,

1.0, -2.487285378126E-5,

-2.487285378126E-5, 1.0,

M1 MATRIX,

0.308452147674, 0.439625190038,

0.470558393459, 0.0159100837102,

M2 MATRIX,

0.385935785822, 0.259248740897,

0.0456734348033, 0.299896962289,

M1-1 MATRIX,
 -.78778E-01  .21768E+01
  .23299E+01 -.15273E+01

A MATRIX
  .57363E+00  .44415E+00
  .69514E+00 -.35861E+00

Q=(M0-(AM1T)-M2T(M1-1T)M1+M2(M1-1)M0(M2T)(M1-1T)) MATRIX,
  0.78191   -0.09431
 -0.09431    0.96903

T=(AM0-M1) MATRIX,
  0.26517    0.00451
  0.22459   -0.37453
  0.00000    1.00000

XMAX=0.288419721446, DELTA=0.0063, SBSQ=0.203611555738, D=1.0,

XMAX=0.033504216115, DELTA=0.0063, SBSQ=0.0146411421733, D=0.530678847826,

XMAX=0.006464138379e, DELTA=0.0063, SBSQ=0.00414280070936, D=0.489223203973,

XMAX=0.00115613597336, DELTA=0.0063, SBSQ=6.3251693564E-4, D=0.480037556059,
```

```
NEG=0, <EXP>=0, <EXP>=0,
NO. ITERATIONS =     21 XMAX =    .1156136OE-02

BBT MATRIX,
  0.67145  -0.15339
 -0.15339   0.74761

B(I,1),

I=2, <EXP>=-0.187197015122,

B(J,K1),B(J,J),


J=2, K1=3, <EXP>=0.0, J=2, K=2, <EXP>=0.71257001484,
LOWER TRIANGULAR MATRIX
  0.81942   0.00000
 -0.18720   0.84414
THE OTHER MATRIX
  0.32360   0.07711
  0.27409  -0.38290
```

```
 VARIABLE FIERINGS F. UNCORR. SD.    CORR. SD.UNCORR SDO.  CORR. SDO
         1     1.00005  .25150E+01  .25151E+01  .20498E+00  .20499E+00
         2     1.10057  .27138E+01  .29868E+01  .23251E+00  .25589E+00
         3     1.00072  .37017E+06  .37044E+06  .47660E+00  .47694E+00
         4     1.02716  .12957E+06  .13309E+06  .44628E+00  .45840E+00
         5     1.02654  .53816E+05  .55244E+05  .29728E+00  .30517E+00

MEANS AND STANDARD DEVIATIONS OF  6 GENERATIONS ON  5 VARIABLES
ORIG. STATS      52.00      10.861030729.27 357973.80 265980.76      4.08       2.21 446688.08 176853.04  80739.18
AVER. MEANS      52.73      10.65 977126.00 343515.45 255086.72      2.94       4.53 383591.63 163831.61  74837.99
AVER. STDEV.       1.66       3.20 199193.01 110458.05  51758.22      1.14       1.03  46781.22  18683.43  15170.21
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
ORIG. CORR.   1.00000  -0.46261  -0.35913  -0.20492  -0.06455
AVER. CORR.   1.00000  -0.76633  -1.11914  -0.99618  -0.98557
STDEV. CORR.   0.00000   0.23397   0.07726   0.16490   0.17148
ORIG. CORR.  -0.46261   1.00000   0.40307   0.34822   0.38527
AVER. CORR.  -0.76633   1.00000   0.81784   0.98813   0.96470
STDEV. CORR.   0.23397   0.00000   0.11378   0.03419   0.01713
ORIG. CORR.  -0.35913   0.40307   1.00000   0.63922   0.69191
AVER. CORR.  -1.11914   0.81784   1.00000   0.93466   0.93475
STDEV. CORR.   0.07726   0.11378   0.00000   0.04961   0.04601
ORIG. CORR.  -0.20492   0.34822   0.63922   1.00000   0.44292
AVER. CORR.  -0.99618   0.98813   0.93466   1.00000   0.99593
STDEV. CORR.   0.16490   0.03419   0.04961   0.00000   0.00846
```

Table D-4a. Dictionary of variables for Data Preparation Program, main program.

Variable	IBO	Type	Dimension	Definition
A	I	R	10	3rd parameter in log normal dist. half lowest value historically
AB	I	R	10	3rd parameter in log normal dist. half lowest value historically
AZ	I	R	10	Same as above except for principal component time series
AVER	O	R	2,10	Average value over II generations of the first few moments of the time series
AVT	O	R	108	Average values over II generations of the correlation elements
BA	B	R	10	Same as A
B	B	R	1	Number of generated time series
BB	B	R	1	B minus one
CU	I	R	5	Consumptive use values for each river time series
CSNB	I	R	5	Linear regression constant for change in storage per basin
CSUM	I	R	5	Linear regression coefficient for change in storage per basin
CSLAG	I	R	5	Lag coefficient for change in storage regression
FMEAN	B	R	10	Original time series average values
FSIG	B	R	10	Original time series standard deviations
IONE	I	I	1	Option to do only one generation
IPC	I	I	1	Option to call principal components
MSI	I	I	1	Option to read sums from previous generations
N	I	I	1	Number of variables in time series
NCORE	B	I	1	Number of correlation elements in the three matrices
NPC	I	I	1	Number of principal component time series
NTRACE	I	I	1	Number of sets of II generations to compute
NTUT	I	I	1	When reading previous summations from previous generations NTUT is the number of generations in the sample
NTI	D	I	1	Number of generations done in current program run
NYR	I	I	1	Number of years in input time series
NYG	I	I	1	Number of years in generation time series
PCA	I	R	10,10	Principal component coefficients
SCALE	I	R	10	Scale factor for time series
SMT	B	R	108	Sum of the correlation elements
SMTV	B	R	108	Variance of the correlation elements
STDEV	D	R	2,10	Standard deviation of time series
STDC	D	R	108	Standard deviation of gen. correlation elements
SUM	B	R	2,10	Sum of gen. time series moments
T	B	R	2,10	First and second moments of time series
TT	B	R	2,10,150	First and second moments of all generated time series

Table D-4b. Variable definition MSTAT Subroutine.

Variable	IBO[a]	Type[b]	Dimension	Definition
A	I	R	10	Half the lowest historic value for each variable, scaled
AB	I	R	10	Half the lowest historic value for each variable - unscaled
CHDG	I	R	10	Column headings for matrix
ESDYI1	B	R	1	Exponential of the standard deviation squared minus one.
IW	I	I	1	Option for write subroutine
LAG	B	I	1	The lag factor
M	O	R	10,10	Correlation matrices at various lags
N	I	I	1	Number of input variables
NYR	B	I	1	Number of years in time series
NYR1	B	I	1	Number of years minus lag in time-series.
PX	B	R	1	Element in correlation matrix
RHDG	I	R	10	Row heading in matrix
RX	B	R	10,10	Correlation matrix
SCALE	I	R	10	Scale factor, to convert to common units and magnitude.
SD	B	R	10	Standard deviation
SDIJ	B	R	1	The "i" variable standard deviation.
SDO	B	R	10	Lagged standard deviation
SDY	B	R	10	Log transformed standard deviation
SDYO	B	R	10	Log transformed lagged standard deviation
TM	O	R	10,10	Transposed correlation matrix
V	B	I	10	Index for determining whether variable needs to be log trans.
VV	B	I	10,10	Index for determining combination of log transformed and normal
X	B	R	150,10	Input variables
XMN	B	R	10	Mean or input variable
XMNO	B	R	10	Lagged mean or input variable
XMNY	B	R	10	Log transformed mean
XMNYO	B	R	10	Lagged log transformed mean
Y	B	R	150,10	Input variables

[a] I = Input B = Body of Program O = Output

[b] R = Real I = Integer

Table D-4c. Variable definition for MODEL Subroutine.

Variable	IBO[a]	Type[b]	Dimension	Definition
A	O	R	10,10	Output matrix and temporary variable.
B	O	R	10,10	Output matrix and temporary variable.
BSQ	B	R	1	Absolute value of an element in the iterative matrix.
C	O	R	10,10	Output matrix.
CRITV	I	R	1	Significance value for setting element to zero
DELTA	I	R	1	Convergence criteria value
IDIAG	I	I	1	Option to compute only diagonal elements of "A"
IWRITE	I	I	1	Option to write out intermediate computations
LAM	I	I	1	Convergence factor - less than one
MARKOV	I	I	1	Option to use Markov vice ARIMA (1,0,1)
MO	I	R	10,10	Lag zero correlation matrix, temporary variable.
M1	I	R	10,10	Lag one correlation matrix, temporary variable.
M2	I	R	10,10	Lag two correlation matrix, temporary variable.
N	I	I	1	Number of variables
NEG	B	I	1	Negative values counter
NI	I	I	1	Dimension of matrix assumes square
NM	I	I	1	Number of lines written in convergence logs
NN	I	I	1	Number of iterations
NNN	B	I	10	Element in MX matrix
NR	I	I	1	Correlation file MO, M1, M2
NUP	I	I	1	Option to compute lower or upper B triangular matrix
NW	I	I	1	Output A, B, C file
S	B	R	10,10	Temporary variable
SBSQ	B	R	1	Sum of largest elements in MX matrix
T	I	R	1	Variable set to zero for matrix inversion subroutine
XMAX	B	R	1	Maximum value in MX matrix for convergence criteria

[a] I = Input B = Body of Program O = Output

[b] R = Real I = Integer

Table D-4d. Variable definition of MGEN Subroutine.

Variable	IBO[a]	Type[b]	Dimension	Definition
A	I	R	10,10	"A" matrix for generation equation
B	I	R	10,10	"B" matrix for generation equation
BETA	I	R	10,1	Third parameter in log-normal distribution.
C	I	R	10,10	"C" matrix for generation equation
CHDG	I	R	10	Column heading on matrix
DUMI	B	R	10,1	Temporary variable
DUMZ	B	R	10,1	Temporary variable
E	B	R	10,1	Error term
EE	B	R	10,150	Random normal number
EE1	B	R	1500	Random number normal: zero, one
E1	B	R	10,1	Previous error term
FSEED	B	R	1	Seed number
IDIAG	I	I	1	Option in Read matrix subroutines
IE	I	I	1	Option to print each computation for debugging
ISEED	B	I	1	Seed number
IOUT	I	I	1	Option for matrix write subroutine
IOPT	I	I	1	Option to write out random numbers
IOPT1	I	I	1	Option to write final output
IX	I	I	1	Option to write out computations.
MARKOV	I	I	1	Option to go Markov vice ARIMA (1,0,1)
MU	I	R	10,1	Mean for each variable
N	I	I	1	Number of variables.
NN	B	I	1	Total number of random numbers
NR	I	I	1	ABC matrix file
NR1	I	I	1	Statistics file
NW	I	I	1	Output file
NYR	I	I	1	Number of years for generation
RHDG	I	R	10	Row heading for matrix
SCALE	I	R	10,1	Scale factor
SIG	I	R	10,1	Standard deviation
SEED	B	I	1	Seed number from the clock
V	I	I	10	Log transformation indicator
XIC	I	R	10,1	Initial starting variable
XMIN	I	R	10,1	Minimum allowable generated value
YPC	O	R	10,150	Generated output variable
Y	B	R	1	Temporary variable
Z	O	R	10,1	Standardized variable
Z1	B	R	10,1	Standardized variable

[a] I = Input B = Body of Program O = Output

[b] R = Real I = Integer

APPENDIX E

STOCHASTIC GENERATION AND WATER BALANCE MODEL

Table E-1. Stochastic Generation and Water Balance Model, program listing.

```
C       GSL ONE-LAKE SIMULATION
        COMMON V(5,50),A(5,50),E(5,50),VV(50),AA(50),EE(50),RESID(150)
      *,H(50),VS(50),VN(50),NPNS,NP
        COMMON/MV/ VLOG(5),MU(5,1),SIG(5,1),XIC(5,1),BETA(5,1),YMIN(5,1),
      .SCALE(5,1),AM(5,5),B(5,5),C(5,5),IE,IW,IER,MARKOV
         COMMON/UNT/XMN(5),BETAX(5),XMINX(5),MI(5),PC(5,5),NX,SCALEX(5)
        COMMON/MW/CU(3),DV(3),CSNa(3),CSNM(3),CSLAG(3),S(3,150)
        REAL MU
        DOUBLE PRECISION RHDG,CHDG
        INTEGER TIME,VLOG
        REAL MUQ,MUP,JORDN(150)
        REAL QIN(5,150),QX(5,150),ELP(5,150),ELV(5,150)
        REAL POP(5),ACRE(5),BIRDS(5),DPOP(5),DACRE(5),QIMP(5)
        REAL VLL(5),ARI(5),SALT(5),SUM(10),QTI(150)
        REAL PPAF(5,150),EVAP(5,150),SAR(5,150),VOL(5,150),CON(5,150)
        REAL PPAFM(5),EVAPM(5),SARM(5),VOLM(5),CONM(5),ELPM(5),FLVM(5)
        REAL QBWJ(150),QTS(150),QSW(150),QTT(150),CCN(5),PPT(150)
        DIMENSION RNAME(20),IYEAR(150),VOUT(150),DUM(150),AREA(150),SALIN(
      .150),CC1(4),CC2(4),DUMP(150),RESIDP(150),SSP(150),SNP(150),SS(150)
      .,CP(3),CR(6),ER(150),EP(150),SN(150),EX(150),EVMP(150)
      .,RHDG(5),CHDG(5),BEAR(150),WEBER(150)
      .,BPMF(150),WPMF(150),PMFJ(150),SD(100),ACTUP(150)
      .,WNACL(7),EVRAT(7),SLAKE(5),ADJPT(5)
        DATA CC1/0.012761,0.,-0.012443,-0.013466/
        DATA CC2/-52.0591,0.975,52.7822,56.7659/
  100 FORMAT (16I5)
  102 FORMAT (8F10.0)
  105 FORMAT (20A4)
  107 FORMAT(5E15.9)
  108 FORMAT(7F10.0,I10)
  200 FORMAT (1H0,30X,'GREAT SALT LAKE SIMULATION INPUT DATA',///)
  202 FORMAT (10X,I3,5X,3F12.0,2F12.3,F12.0)
  902 FORMAT(1H ,5F10.2)
  907 FORMAT(1H ,5E15.9)
  203 FORMAT (///,10X,'POI,C1,C2,C3,EVRT,VTOP,VRATE,SALT(L)')
  204 FORMAT (10X,5F12.3,5F12.0)
  210 FORMAT (1H0,30X,20A4,///)
  211 FORMAT (6X,'YEAR',7X,'QBWJ',8X,'QTS',8X,'QGW',8X,'QTT',5X,'PRECIP'
     1,8X,'EVAP',7X,'AREA',5X,'VOLUME',6X,'CONT',3X,'PK ELEV',3X,'AN ELE
     2V',/)
  212 FORMAT (6X,I4,5F11.2,F12.2,2F11.2,3F10.2)
  213 FORMAT (/,6X,'MEAN',5F11.2,F12.2,2F11.2,3F10.2)
  220 FORMAT(1H1,15X,'YEAR     EXCESS')
  221 FORMAT(15X,15,F10.0)
  223 FORMAT(1H0,6X,4HYEAR,8X,3HSSP,8X,3HSNP,9X,2HSS,9x,2HSN)
 9000 FORMAT(1H ,8E10.5)
 9500 FORMAT(1H ,26I5)
 9501 FORMAT(1H ,2F6.4,5F13.4,I10)
 9502 FORMAT(1H ,2F5.3,5F6.3)
 9503 FORMAT(1H ,F10.4,2E11.5,3F10.0)
 9504 FORMAT(1H ,6E11.6,4F10.5)
 9505 FORMAT(1H ,2F10.9)
 9506 FORMAT(1H ,16I5)
C
C        READ INPUT DATA
C       IF MVOPT=1, THEN CALLS MULTIVARIATE GENERATION S/R FOR INPUTS
C        IF MVOPT=2, THEN GOES THRU UNIVARIATE SEQUENCE FOR INPUTS
C        IF MVOPT=3, THEN MODEL CALCULATES HISTORIC PERIOD, CALLS READ
C          5 TIMES (BEAR,WEBER,JORDAN,EVAP,PRECIP) IN THAT ORDER
         READ(5,100)MVOPT
         WRITE(6,9506)MVOPT
         GOTO(1111,998,1111),MVOPT
C       STREAMFLOW PARAMETERS FOR UNIVARIATE STOCHASTIC MODEL
  998    READ(5,108)THQ,PHIQ,XICQ,MUQ,SIGXQ,BETAQ,XMINQ,IOPT3
         WRITE(6,9501)THQ,PHIQ,XICQ,MUQ,SIGXQ,BETAQ,XMINQ,IOPT3
C      PRECIP PARAMETERS FOR UNIVARIATE STOCHASTIC MODEL
         IF(IOPT3.EQ.1)GOTO 1100
         READ(5,102)THP,PHIP,XICP,MUP,SIGXP,BETAP,XMINP
         WRITE(6,9502)THP,PHIP,XICP,MUP,SIGXP,BETP,XMINP
         WRITE(6,9502)THP,PHIP,XICP,MUP,SIGXP,BETAP,XMINP
         GOTO 1110
C     PRECIP PARAMETERS FOR LINEAR REGRESSION SEQUENCE WITH STREAMFLOW
C       AND LAKE AREA
 1100 READ(5,102)(CP(I),I=1,3),EPM,EPS,BETAP1
C        RESIDUAL PARAMETERS FOR LINEAR REGRESSION WITH STREAMFLOW,LAG1,
C        LAG2, AND AREA, WHERE RESIDUAL =(LAKE EVAP,SMALL STREAMS,GROUNDWAT
 1110 READ(5,102)(CR(I),I=1,6),ERM,ERS,BETAR,RESMIN
         WRITE(6,9504)(CR(I),I=1,6),ERM,ERS,BETAR,RESMIN
C      PERCENT EVAP OCCURRED BY PEAK STAGE,UNIT CONVERSION FACTOR FOR
C      TO CONVERT SLC PRECIP TO GSL PRECIP
 1111 READ(5,102)CE,CPP
         WRITE(6,9505)CE,CPP
         QTT1=XICQ
C     MAIN PROGRAM PARAMETERS
C         IOPT1=1, CALL S/R READ FOR UNIVARIATE INPUT( =2, READ CARDS'WRD,
C       =3, CALL UNI STOCHASTIC S/R
C       IOPT2=1, CALCULATE RESIDUAL TIME SERIES FROM HISTORIC DATA
C       ICWO''CAUSEWAY OPENING 1=PRESENT OPENING,2=100 FT,3=300 FT,4=600FT
C     NTRACE=NO. OF GENERATIONS OF TRACES OF LAKE STAGES NYR YEARS IN
C     LENGTH
C        NW8= FILE FOR SOUTH ARM PEAK STAGES
         READ (5,100) IYR,LYR,NLK,NRB,NQIN,NP,IPNCH,IOPT1,IOPT2,NW,NW1,NW2,
      .NW3,ICWO,NTRACE,NW4,NW5,NW6,NW7,NW8,NW9,NW10,NW11,IRAND,NPNS,IOPT4
         WRITE(6,9500)IYR,LYR,NLK,NRB,NQIN,NP,IPNCH,IOPT1,IOPT2,NW,NW1,NW2,
      .NW3,ICWO,NTRACE,NW4,NW5,NW6,NW7,NW8,NW9,NW10,NW11,IRAND,NPNS,IOPT4
C       IOPT10=1, IF NO OUTPUT IS PRINTED
         READ(5,100)IOPT5,IOPT6,IOPT7,IOPT8,IOPT9,IOPT10,IOPT11,MYBUP,NW12
      .          NW12
C     MULTIVARIATE GENERATED INPUTS FILE NO.SNW13-17=(EVAP,PRECIP,B,W,J)
C        NW18-20=NAT/PMF(B,W,J) NWSD=SEED FILE,KEPSED=1, USES PREVIOUS SEED
         READ(5,100)NW13,NW14,NW15,NW16,NW17,NW18,NW19,NW20,NWSD,KEPSED
         WRITE(6,9506)NW13,NW14,NW15,NW16,NW17,NW18,NW19,NW20,NWSD,KEPSED
C        CONTROL ELEVATION OF LAKE, UPSTREAM DEVELOPMENT ON BEAR,
C        BEAR RIVER MINIMUM FLOW TO SUSTAIN BIRD REFUGE
         READ(5,102)  CONELV,UPSTCI,ADJM,BRMIN
         WRITE(6,9000)CONELV,UPSTCI,ADJM,BRMIN
         GOTO(997,1501,1501),MVOPT
         WRITE(6,9500)NV,IDIAG,IOUT,MARKOV,IE,IW,IER,NX,NAT
C      INPUT PARAMETERS FOR MULTIVARIATE GENERATION,NV= NO.OF GEN.VAR.
C       NX=NO. OF PHYSICAL VAR.-OUTPUT FROM PRINCIPAL COMPONENTS VECTOTS
C       -1= LOG TRANSFORMATION 2= NORMAL
         READ(5,100)(VLOG(I),I=1,NV)
         WRITE(6,9500)(VLOG(I),I=1,NV)
         READ(5,106)(RHDG(I),I=1,NV)
         READ(5,106)(CHDG(I),I=1,NV)
         CALL MIN(AM,NV,NV,IDIAG,IOUT,RHDG,CHDG,5)
         CALL MIN(B,NV,NV,IDIAG,IOUT,RHDG,CHDG,5)
         IF(MARKOV.EQ.1)GOTO 51
         CALL MIN(C,NV,NV,IDIAG,IOUT,RHDG,CHDG,5)
C       INPUT PHYSICAL PARAMETERS AND PRINCIPAL COMPONENTS COEFFICIENTS
C       TO UNTRANSFORM ARIMA(1,0,1) GEN. P.C. SERIES
         READ(5,102)(XMN(I),I=1,NX)
         WRITE(6,902)(XMN(I),I=1,NX)
         READ(5,102)(BETAX(I),I=1,NX)
         WRITE(6,902)(BETAX(I),I=1,NX)
         READ(5,102)(XMINX(I),I=1,NX)
         WRITE(6,902)(XMINX(I),I=1,NX)
         READ(5,100)(MI(I),I=1,NX)
         WRITE(6,9506)(MI(I),I=1,NX)
         READ(5,102)(SCALEX(I),I=1,NX)
         WRITE(6,902)(SCALEX(I),I=1,NX)
         DO 999 I=1,NX
         READ(5,102)(PC(I,J),J=1,NX)
         WRITE(6,902)(PC(I,J),J=1,NX)
  999    CONTINUE
  51     CONTINUE
```

```
      READ(5,107)(MU(I,1),I=1,NV)
      WRITE(6,907)(MU(I,1),I=1,NV)
      READ(5,107)(SIG(I,1),I=1,NV)
      WRITE(6,907)(SIG(I,1),I=1,NV)
      READ(5,107)(BETA(I,1),I=1,NV)
      WRITE(6,907)(BETA(I,1),I=1,NV)
      READ(5,102)(XMIN(I,1),I=1,NV)
      WRITE(6,902)(XMIN(I,1),I=1,NV)
      READ(5,102)(XIC(I,1),I=1,NV)
      WRITE(6,902)(XIC(I,1),I=1,NV)
      READ(5,102)(SCALE(I,1),I=1,NV)
      WRITE(6,902)(SCALE(I,1),I=1,NV)
      IF(NAT.EQ.1)GOTO 1501
      READ(5,102)(CU(I),I=3,5)
      WRITE(6,902)(CU(I),I=3,5)
      READ(5,102)(DV(I),I=3,5)
      WRITE(6,902)(DV(I),I=3,5)
      READ(5,102)(CSNB(I),I=3,5)
      WRITE(6,902)(CSNB(I),I=3,5)
      READ(5,102)(CSNM(I),I=3,5)
      WRITE(6,902)(CSNM(I),I=3,5)
      WRITE(6,902)(CSLAG(I),I=3,5)
      READ(5,102)(S(I,1),I=3,5)
      WRITE(6,902)(S(I,1),I=3,5)
 1501 IR=0
      NYR=LYR-IYR+1
      NYR1=NYR+1
      DO 425 I=1,NRB
      READ (5,102) POP(I),ACRE(I),BIRDS(I),DPOP(I),DACRE(I),QIMP(I)
  425 CONTINUE
      READ (5,105) (RNAME(N),N=1,20)
      READ(5,102)VLLIC,ARI(1),SALT(1)
C    LAKE VOLUME-AREA-STAGE RELATIONSHIPS
C     SALT/FRESH EVAP RATIOS, PRECIP ADJUSTMENT -LAKE STAGE TABLES
      READ(5,102)(WNACL(J),J=1,7)
      READ(5,102)(EVRAT(J),J=1,7)
      READ(5,102)(SLAKE(I),I=1,5)
      READ(5,102)(ADJPT(I),I=1,5)
      READ (5,102) (V(1,N),N=1,NP)
      READ (5,102) (A(1,N),N=1,NP)
      READ (5,102) (E(1,N),N=1,NP)
C   H= SOUTH ARM LAKE STAGE,VN=CORRESPONDING NORTH ARM VOLUME PROPORTION
      READ(5,102)(H(J),J=1,NPNS)
      READ(5,102)(VN(J),J=1,NPNS)
      DO 450 N=1,NP
      VV(N)=V(1,N)
      AA(N)=A(1,N)
      EE(N)=E(1,N)
  450 CONTINUE
C     PARAMETERS,POI=SMALL STREAMS,C1,2,3=GROUNDWATER PRESENT,LAG1,LAG2
C     EVRT=ANNUAL LAKE EVAP IN FT
        FNYR=NYR
C
C**** LOOP FOR GENERATING STAGE TRACES
        NY=NV
         IF(KEPSED.EQ.1)READ(NWSD,9711)(SD(J),J=1,NTRACE)
        DO 500 KTRACE=1,NTRACE
        NV=NY
        GOTO(531,509,509),MVOPT
  509   GOTO (3,1,510),IOPT1
  1     DO 2 I=1,NQIN
        READ (5,102) (QIN(I,N),N=1,NYR)
      2 CONTINUE
        GOTO 6
  3     DO 5 I=1,NQIN
C     READ IN HISTORIC STREAMFLOW,PRECIP
        CALL READ(DUM,NYR,STID)
        DO 4 N=1,NYR
        QIN(I,N)=DUM(N)
  4     CONTINUE
```



```
  5     CONTINUE
        GOTO 6
C     UNIVARIATE  STOCHASTIC STREAMFLOW GENERATION BJ101=ARIMA(1,0,1,
C     BJ100=ARMA(1,0,0)
  510   IQ=TIME(0)
        IF(IQ.EQ.IR)GOTO 510
        SEEDQ=3.43597E10*FLOAT(IQ)/8.64E7
        IF(IOPT5.EQ.1)GOTO 515
        CALL BJ101(THQ,PHIQ,NYR1,XICQ,MUQ,SEEDQ,DUM,SIGXQ,BETAQ,XMINQ,
       .IOPT6,IOPT7)
        GOTO 516
  515   CALL BJ100(PHIQ,NYR1,XICQ,MUQ,SEEDQ,DUM,SIGXQ)
  516   DO 520 N=
        QIN(1,N1)=DUM(N)*ADJM-UPSTCI
        QIN(2,N1)=0.
        QIN(3,N1)=0.
  520   CONTINUE
C     UNIVARIATE STOCHASTIC PRECIP GEN. BJ101,BJ100
  525   IP=TIME(0)
        IF(IQ.EQ.IP)IP=IP+IRAND
        SEEDP=3.43597E10*FLOAT(IP)/8.64E7
        GOTO(6,526,527),IOPT3
  526   CALL BJ101(THP,PHIP,NYR1,XICP,MUP,SEEDP,DUMP,SIGXP,BETAP,XMINP,
       .IOPT8,IOPT9)
        GOTO 528
  527   CALL BJ100(PHIP,NYR1,XICP,MUP,SEEDP,DUMP,SIGXP)
  528   DO 530 N=2,NYR1
        N1=N-1
        QIN(NQIN,N1)=DUMP(N)
  530   CONTINUE
  6     CONTINUE
C    FOR RESIDUAL CALCULATION - READ IN ANN.AVER.LAKE STAGE AND PEAKS
        IF(IOPT2.EQ.0)GOTO 10
        CALL READ(DUM,NYR,STID)
        CALL READ(DUMP,NYR,STID)
        GOTO 10
  531   IP=TIME(0)
         IF(IP.EQ.IR)IP=IP+IRAND
        IF(KEPSED.EQ.1)GOTO 532
        SEED=3.43597E10*FLOAT(IP)/8.64E7
        SD(KTRACE)=SEED
  532   SEED=SD(KTRACE)
        IR=IP
        GOTO 111
C
C       INITIALIZATION
  10    DO 11 J=1,NYR
        IYEAR(J)=IYR+J-1
        PPT(J)=QIN(NQIN,J)
        QIN(NQIN,J)=0.
        EVMP(J)=QIN(4,J)
        QIN(4,J)=0.
  11    CONTINUE
        GOTO 110
C    MULTIVARIATE STOCHASTIC GEN. OF INPUTS (EVAP,PRECIP,BEAR,WEBER,AND
C   JORDAN RIVERS)
  111   CALL MVGEN(QIN,SEED,NV,NYR)
        DO 121 I=1,NV
        DO 120 J=1,NYR
        IF(I.NE.1)GOTO 1200
        IYEAR(J)=IYR+J-1
 1200   CONTINUE
        EVMP(J)=QIN(1,J)
        PPT(J)=QIN(2,J)
        IF(J.LE.NYBUP)GOTO 1205
        BEAR(J)=QIN(3,J)-UPSTCI
        IF(BEAR(J).LT.BRMIN)BEAR(J)=BRMIN
        GOTO 1210
 1205   BEAR(J)=QIN(3,J)
 1210   WEBER(J)=QIN(4,J)
```

```
      JORDN(J)=QIN(5,J)
  120 CONTINUE
  121 CONTINUE
      IF(NAT.EQ.1)GOTO 110
      CALL CNAT(QIN,NV,NYR)
      DO 131 I=3,NV
      DO 130 J=1,NYR
      IF(J.LE.NYBUP)GOTO 125
      BPMF(J)=QIN(3,J)-UPSTCI
      IF(BPMF(J).LT.BRMIN)BPMF(J)=BRMIN
      GOTO 126
  125 BPMF(J)=QIN(3,J)
  126 WPMF(J)=QIN(4,J)
      PMFJ(J)=QIN(5,J)
  130 CONTINUE
  131 CONTINUE
  110 SA1=ARI(1)
      CC= 20000./(62.4*4.3560)
      VLL(1)=VLLIC
      CCN(1)= CC*SALT(1)/VLL(1)
      IF (CCN(1).GT.27.5) CCN(1)=27.5
      IF(IOPT10.EQ.1)GOTO 20
C
C     PRINT OUT INPUT DATA
      WRITE (6,200)
      WRITE (6,201)
      DO 12 I=1,NRB
   12 CONTINUE
      WRITE (6,203)
      WRITE (6,204) POI,C1,C2,C3,EVRT,VTOP,VRATE, (SALT(N),N=1,NLK)
C     DETERMINE RIVER BASIN INFLOW
   20 DO 22 J=1,NYR
      GOTO(226,199,199),MVOPT
  199 DO 21 L=1,3
   21 QX(L,J)=QIN(L,J)+QIMP(L)-POP(L)*DPOP(L)-ACRE(L)*DACRE(L)-BIRDS(L)
      QTI(J)=QIN(1,J)+QIN(2,J)+QIN(3,J)
      GOTO 227
  226 IF(NAT.EQ.1)GOTO 2260
      QTI(J)=BPMF(J)+WPMF(J)+PMFJ(J)
      QBWJ(J)=BPMF(J)+WPMF(J)+PMFJ(J)
 2260 QTI(J)=BEAR(J)+WEBER(J)+JORDN(J)
      QBWJ(J)=BEAR(J)+WEBER(J)+JORDN(J)
      GOTO 228
  227 QBWJ(J)=QX(1,J)+QX(2,J)+QX(3,J)
  228 QX(4,J)=POI*QBWJ(J)
   22 QTS(J)=QBWJ(J)+QX(4,J)
C
C     START YEARLY SIMULATION
C
      GOTO(2315,229,2315),MVOPT
  229 EP(1)=SEEDP
      IF(IOPT3.EQ.1)CALL RANON(EP,NYR,EPM,EPS)
      IR=TIME(0)
      IF(IR.EQ.IP)IR=IP+IRAND
      SEEDR=3.43597E10*FLOAT(IR)/8.64E7
      ER(1)=SEEDR
      CALL RANON(ER,NYR,ERM,ERS)
      DO 23 I=1,NYR
      IF(IOPT3.NE.1)GOTO 231
      EP(I)=BETAP1+EXP(EP(I))
  231 ER(I)=BETAR+EXP(ER(I))
 2315 CALL INTERP(CONVOL,VV,CONELV,EE,NP)
      CALL INTERP(SM,EE,VLLIC,VV,NP)
      RE=SM
      IF(IOPT10.EQ.1)GOTO 24
      WRITE (6,210) (RNAME(N),N=1,20)
      WRITE (6,211)
      IYR1=IYR-1
      ZERO=0.
```

```
      WRITE(6,212)IYR1,XICQ,XICQ,ZERO,XICQ,XICP,ZERO,ARI(1),VLLIC,SALT(1
     .),ZERO,SM
   24 DO 50 J=1,NYR
C
C     SINGLE LAKE BODY  M=1
      IF (J.GT.2) GO TO 25
      QGW2=C2*QTI(J)
      QGW3=C3*QTI(J)
      GO TO 26
   25 QTT1=QTT(J-1)
      QGW2=C2*QTI(J-1)
      QGW3=C3*QTI(J-2)
   26 QGW(J)=C1*QTI(J)+QGW2+QGW3
      RV=VLL(1)
      QTT(J)=QTS(J)+QGW(J)
      CALL INTERP(ADJP,ADJPT,RE,SLAKE,5)
      PPF1=CPP*PPT(J)*ADJP
      GOTO(265,266,265),MVOPT
  265 EVRT=EVMP(J)*CPP
  266 IF(EVRT.GT.0)GOTO 2605
C2605 EVRT1=EVRT*(1.0-0.00833*CCN(1))
 2605 CALL INTERP(RATIO,EVRAT,CCN(1),WNACL,7)
      EVRT1=EVRT*RATIO
      GOTO 2650
 2610 EVRT1=CR(1)+CR(2)*QTT(J)+CR(3)*QTT1+ER(J)
      IF(RE.GT.4201.)EVRT1=CR(4)+CR(5)*QTT(J)+CR(6)*QTT1+ER(J)
      IF(EVRT1.LT.RESMIN)EVRT1=RESMIN
 2630 IF(IOPT3.NE.1)GOTO 2650
      PPF1=(CP(1)+CP(2)*QTT(J)+CP(3)*SA1+EP(J))/12.
      DUMP(J)=PPF1
 2650 RV=RV+0.75*QTT(J)+0.71*PPF1*SA1-CE*EVRT1*SA1
      VOUT(J)=0.0
      IF (RV.LE.VTOP) GO TO 27
      VOUT(J)=RV-VTOP
      IF (VOUT(J).GT.VRATE) VOUT(J)=VRATE
      RV=RV-VOUT(J)
   27 CONTINUE
      IF(IOPT2.EQ.0)GOTO 30
      CALL INTERP(VOLO,VV,DUMP(J),EE,NP)
      RESIDP(J)=RV-VOLO
      RV=VOLO
   30 CALL RESV(1,RV,RS,RE)
      SA2=RS
      SA=0.5*(SA1+SA2)
      ELP(1,J)=RE
      IF(IOPT4.EQ.0)GOTO 46
      WRITE(6,9000)RV,RS,RE,QTT(J),PPF1,SA1,CE,EVRT1
   46 CONTINUE
      CALL SNSTAG(RE,RV,SSP(J),SNP(J),CC1(ICWO),CC2(ICWO))
      EVAP(1,J)=EVRT1*SA
      PPAF(1,J)=PPF1*SA
      VLL(1)=VLL(1)+QTT(J)+PPAF(1,J)-EVAP(1,J) - VOUT(J)
      IF(IOPT2.EQ.0)GOTO 45
      RESID(J)=VLL(1)-VOLO
      VLL(1)=VOLO
   45 IF(IOPT11.EQ.0)GOTO 48
      EXC=0.
      IF(J.LE.NYBUP)GOTO 47
      IF(VLL(1).GT.CONVOL)EXC=VLL(1)-CONVOL
      IF(NAT.EQ.1)GOTO 471
      IF(EXC.GT.(BPMF(J)-BRMIN))EXC=BPMF(J)-BRMIN
      BPMF(J)=BPMF(J)-EXC
      ACTUP(J)=QIN(3,J)-BPMF(J)
      GOTO 472
  471 IF(EXC.GT.(BEAR(J)-BRMIN))EXC=BEAR(J)-BRMIN
      BEAR(J)=BEAR(J)-EXC
      ACTUP(J)=QIN(3,J)-BEAR(J)
  472 VLL(1)=VLL(1)-EXC
   47 EX(J)=EXC
```

```
 48    RV=VLL(1)
       VOL(1,J)=RV
       CCN(1)= CC*SALT(1)/RV
       IF (CCN(1).GT.27.5) CCN(1)=27.5
       CALL RESV (1,RV,RS,RE)
       SAR(1,J)=RS
       AREA(J)=RS
       SALIN(J)=CCN(1)
       ELV(1,J)=RE
       IF(IOPT4.EQ.0)GOTO 49
       WRITE(6,9000)VLL(1),PPAF(1,J),EVAP(1,J),SA,RV,RS,RE
       CALL SNSTAG(RE,RV,SS(J),SN(J),CC1(ICWO),CC2(ICWO))
       SA1=RS
   50  CONTINUE
C
C      DETERMINE MEAN VALUES
C
       DO 61 N=1,5
   61  SUM(N)=0.0
       DO 65 J=1,NYR
       SUM(1)=SUM(1)+QBWJ(J)
       SUM(2)=SUM(2)+QTS(J)
       SUM(3)=SUM(3)+QGW(J)
       SUM(5)=SUM(5)+VOUT(J)
   65  SUM(4)=SUM(4)+QTT(J)
       QBWJM=SUM(1)/FNYR
       QTSM=SUM(2)/FNYR
       QGWM=SUM(3)/FNYR
       QTTM=SUM(4)/FNYR
       VOUTM=SUM(5)/FNYR
       DO 70 L=1,NLK
       DO 67 N=1,7
   67  SUM(N)=0.0
       DO 68 J=1,NYR
       SUM(1)=SUM(1)+PPAF(L,J)
       SUM(2)=SUM(2)+EVAP(L,J)
       SUM(3)=SUM(3)+SAR(L,J)
       SUM(4)=SUM(4)+VOL(L,J)
       SUM(5)=SUM(5)+CON(L,J)
       SUM(6)=SUM(6)+ELP(L,J)
   68  SUM(7)=SUM(7)+ELV(L,J)
       PPAFM(L)=SUM(1)/FNYR
       EVAPM(L)=SUM(2)/FNYR
       SARM(L)=SUM(3)/FNYR
       VOLM(L)=SUM(4)/FNYR
       CONM(L)=SUM(5)/FNYR
       ELPM(L)=SUM(6)/FNYR
       ELVM(L)=SUM(7)/FNYR
   70  CONTINUE
       IF(IOPT10.EQ.1)GOTO 300
C
C      PRINT OUT RESULTS
C
       DO 80 L=1,NLK
       DO 78 J=1,NYR
       WRITE (6,212) IYEAR(J),QBWJ(J),QTS(J),QGW(J),QTT(J),PPAF(L,J),
      1EVAP(L,J),SAR(L,J),VOL(L,J),CON(L,J),ELP(L,J),ELV(L,J)
   78  CONTINUE
       WRITE (6,213) QBWJM,QTSM,QGWM,QTTM,PPAFM(L),EVAPM(L),SARM(L),
      1VOLM(L),CONM(L),ELPM(L),ELVM(L)
       IF (IPNCH.EQ.0) GO TO 80
       WRITE (7,105)  (RNAME(N),N=1,20)
       WRITE (7,102)  (ELP(L,J),J=1,NYR)
       WRITE (7,102)  (ELV(L,J),J=1,NYR)
   80  CONTINUE
       IF(IOPT11.EQ.0)GOTO 815
       WRITE(6,223)
       DO 81 J=1,NYR
       WRITE(6,212)IYEAR(J),SSP(J),SNP(J),SS(J),SN(J)
 81    CONTINUE
 815   CONTINUE
       IF(VRATE.LE.0.1E-10)GOTO 85
       WRITE(6,220)
       DO 82 J=1,NYR
   82  WRITE(6,221) IYEAR(J),VOUT(J)
       WRITE(6,222) VOUTM
 85    IF(IOPT2.EQ.0)GOTO 299
       CALL WRITE(RESID,IYEAR(1),IYEAR(NYR),NW)
       CALL WRITE(RESIDP,IYEAR(1),IYEAR(NYR),NW4)
       CALL WRITE(AREA,IYEAR(1),IYEAR(NYR),NW1)
       CALL WRITE(SALIN,IYEAR(1),IYEAR(NYR),NW3)
       DO 90 J=1,NYR
       RESID(J)=RESID(J)/SAR(1,J)
       RESIDP(J)=RESIDP(J)/SAR(1,J)
       CALL WRITE(RESID,IYEAR(1),IYEAR(NYR),NW2)
       CALL WRITE(RESIDP,IYEAR(1),IYEAR(NYR),NW5)
 299   WRITE(6,9657)
 9657  FORMAT(1H0,20HUPSTREAM DEVELOPMENT)
       WRITE(6,9658)
 9658  FORMAT(1H ,10HMVGEN/BEAR,2X,10HBEAR-UP/EX,2X,10HBPMF-UP/EX,2X,10HA
      .CTUPSTDEV,2X,9HEXCESSVOL)
 9659  FORMAT(1H ,5E12.5)
       DO 965 J=1,NYR
       WRITE(6,9659)QIN(3,J),BEAR(J),BPMF(J),ACTUP(J),EX(J)
 965   CONTINUE
 300   CONTINUE
       IF(NW6.EQ.0)GOTO 350
       CALL WRITE(DUM,IYEAR(1),IYEAR(NYR),NW6)
 350   IF(NW7.EQ.0)GOTO 360
       CALL WRITE(DUMP,IYEAR(1),IYEAR(NYR),NW7)
 360   IF(NW8.EQ.0)GOTO 370
       CALL WRITE(SSP,IYEAR(1),IYEAR(NYR),NW8)
 370   IF(NW9.EQ.0)GOTO 380
       CALL WRITE(SNP,IYEAR(1),IYEAR(NYR),NW9)
 380   IF(NW10.EQ.0)GOTO 390
       CALL WRITE(SS,IYEAR(1),IYEAR(NYR),NW10)
 390   IF(NW11.EQ.0)GOTO 400
       CALL WRITE(SN,IYEAR(1),IYEAR(NYR),NW11)
 400   IF(NW12.EQ.0)GOTO 403
       CALL WRITE(EX,IYEAR(1),IYEAR(NYR),NW12)
 403   IF(NW13.EQ.0)GOTO 405
       CALL WRITE(EVMP,IYEAR(1),IYEAR(NYR),NW13)
 405   IF(NW14.EQ.0)GOTO 410
       CALL WRITE(PPT,IYEAR(1),IYEAR(NYR),NW14)
 410   IF(NW15.EQ.0)GOTO 415
        CALL WRITE(BEAR,IYEAR(1),IYEAR(NYR),NW15)
 415   IF(NW16.EQ.0)GOTO 420
       CALL WRITE(WEBER,IYEAR(1),IYEAR(NYR),NW16)
 420   IF(NW17.EQ.0)GOTO 426
       CALL WRITE(JORDN,IYEAR(1),IYEAR(NYR),NW17)
 426   IF(NW18.EQ.0)GOTO 430
       CALL WRITE(BPMF,IYEAR(1),IYEAR(NYR),NW18)
 430   IF(NW19.EQ.0)GOTO 435
       CALL WRITE(WPMF,IYEAR(1),IYEAR(NYR),NW19)
 435   IF(NW20.EQ.0)GOTO 500
       CALL WRITE(PMFJ,IYEAR(1),IYEAR(NYR),NW20)
 500   CONTINUE
       WRITE(NWSD,9711)(SD(J),J=1,NTRACE)
       STOP
       END
@FOR,IS GSL*PROG10.SR78,GSL*PROG10.SR78
       SUBROUTINE RESV (L,VL,AR,EL)
       COMMON V(5,50),A(5,50),E(5,50),VV(50),AA(50),EE(50),RESID(150)
      .,H(50),VS(50),VN(50),NPNS,NP
       XX=VL
       DO 90 M=1,NP
       IF (XX-V(L,M)) 91,92,90
   90  CONTINUE
   91  XFACT=(XX-V(L,M-1))/(V(L,M)-V(L,M-1))
       EL = E(L,M-1) + (E(L,M)-E(L,M-1))*XFACT
```

```
      AR = A(L,M-1) + (A(L,M)-A(L,M-1))*XFACT
      GO TO 93
   92 EL = E(L,M)
      AR = A(L,M)
   93 CONTINUE
      RETURN
      END
@FOR,IS GSL*PROG10.SR79,GSL*PROG10.SR79
      SUBROUTINE INTERP(A,AA,B,BB,NTAB)
C**** TO INTERPRET A CORRESPONDING TO B IN TABLE OF AA VS BB
      IF(B.LT.BB(1))GOTO 150
      J=0
      DO 50 I=1,NTAB
      IF(B.GT.BB(I))GOTO 50
      J=I
      GOTO 70
 50   CONTINUE
      GOTO 150
 70   A=AA(J-1)+(AA(J)-AA(J-1))*(B-BB(J-1))/(BB(J)-BB(J-1))
      RETURN
 150  WRITE(6,9500)B,BB(I)
 9500 FORMAT(1H0,2E10.5,29HATTEMPT TO EXCEED TABLE RANGE)
      STOP
      END
@FOR,IS GSL*PROG10.SR82,GSL*PROG10.SR82
      SUBROUTINE SNSTAG(SM,VTOT,SS,SN,C1,C2)
      COMMON VVV(5,50),A(5,50),E(5,50),VV(50),AA(50),EE(50),RESID(150)
     *,H(50),VVS(50),VVN(50),NPNS,NP
      I=0
      DH=C1*SM+C2
      SS=SM
      SN=SM-DH
      RETURN
      D=10.
      SS=SM+DH/2.
      SN=SM-DH/2.
 50   CALL INTERP(VN,VVN,SS,H,NPNS)
      CALL INTERP(V,VV,SS,EE,NP)
      VS=V*(1.-VN/100.)
      CALL INTERP(VN,VVN,SN,H,NPNS)
      CALL INTERP(V,VV,SN,EE,NP)
      VN=V*VN/100.
      V=VS+VN
      VP=(VTOT-V)/VTOT
      VPA=ABS(VP)
      SIGN=VP/VPA
      IF(VPA.LT.0.003)RETURN
      DS=SIGN/D
      SS=SS+DS
      SN=SN+DS
      IF(I.EQ.1)GOTO 100
      I=1
      ISIGN1=IFIX(SIGN)
 100  ISIGN=IFIX(SIGN)
      IF(ISIGN.NE.ISIGN1)D=D*2.
      ISIGN1=ISIGN
      GOTO 50
      END
      SUBROUTINE BJ101(TH,PHI,N,XIC,MU,SEED,X,SIGX,BETA,XMIN,IOPT6,IOPT7
     *)
      REAL MU
      DIMENSION EE(2000),X(1)
      Z1=XIC-MU
      IF(IOPT6.EQ.1)Z1=ALOG(XIC-BETA)-MU
      X(1)=XIC
      EE(1)=SEED
      SIGE=SQRT((1.-PHI**2)/(1.+TH**2-2*PHI*TH))
      CALL RANDN(EE,N,0.,1.)
      E1=0.
      IF(IOPT7.EQ.1)E1=Z1/(SIGX*SIGE)-SQRT((1./SIGE)**2-1.)*EE(N)
      DO 50 J=2,N
      E=EE(J-1)
      Z=PHI*Z1+SIGE*SIGX*(E-TH*E1)
      X(J)=Z+MU
      IF(IOPT6.EQ.1)X(J)=BETA+EXP(X(J))
      IF(X(J).LT.XMIN)X(J)=XMIN
      Z1=Z
      E1=E
 50   CONTINUE
      RETURN
      END
      SUBROUTINE BJ100(PHI,N,XIC,MU,SEED,X,SIGX)
      REAL MU
      DIMENSION EE(2000),X(1)
      Z1=XIC-MU
      X(1)=XIC
      EE(1)=SEED
      SIGE=SQRT(1.-PHI**2)*SIGX
      DO 50 J=2,N
      E=EE(J-1)
      Z=PHI*Z1+E
      X(J)=Z+MU
      Z1=Z
 50   CONTINUE
      RETURN
      END
      SUBROUTINE MVGEN(XX,SEED,V,NYR)
      REAL MU
      INTEGER V
      COMMON/MV/ V(5),MU(5,1),SIG(5,1),XIC(5,1),BETA(5,1),XMIN(5,1),
     *SCALE(5,1),A(5,5),B(5,5),C(5,5),IE,IW,IER,MARKOV
       COMMON/UNT/XMN(5),BETAX(5),XMINX(5),MI(5),PC(5,5),NX,SCALEX(5)
      DIMENSION Z1(5,1),XX(5,150),EE(5,150),EE1(1500),E1(5,1),E(5,1),
     *DUM1(5,1),DUM2(5,1),Z(5,1),YY(5,150)
 900   FORMAT(1H ,16I5)
      NN=N*NYR
      EE1(1)=SEED
      CALL RANDN(EE1,NN,0.,1.)
      DO 100 I=1,N
      DO 50 J=1,NYR
      JJ=(I-1)*NYR+J
      EE(I,J)=EE1(JJ)
 50   CONTINUE
      IF(IER.EQ.1)WRITE(6,9520)(EE(I,J),J=1,NYR)
 100  CONTINUE
      DO 125 I=1,N
      IF(V(I).EQ.-1)Z1(I,1)=ALOG(XIC(I,1)-BETA(I,1))-MU(I,1)
      Z1(I,1)=Z1(I,1)/SIG(I,1)
      IF(IE.EQ.1)WRITE(6,9520)Z1(I,1)
      XX(I,1)=XIC(I,1)*SCALE(I,1)
      IF(V(I).EQ.-1)GOTO 110
      GOTO 115
 110  XX1=BETA(I,1)+EXP(XIC(I,1))
      XX(I,1)=XX1*SCALE(I,1)
 115  E(I,1)=0.
 125  CONTINUE
      DO 250 J=2,NYR
      E1(I,1)=E(I,1)
      E(I,1)=EE(I,J)
 150  CONTINUE
      CALL MMULT(A,Z1,DUM1,N,1,N,5,5,5,1,5,1)
      IF(IE.EQ.1)WRITE(6,9520)(DUM1(I,1),I=1,N)
      CALL MMULT(B,E,DUM2,N,1,N,5,5,5,1,5,1)
      IF(IE.EQ.1)WRITE(6,9520)(DUM2(I,1),I=1,N)
      CALL MADSUB(DUM1,DUM2,DUM1,N,1,1,5,1,5,1,5,1)
      IF(IE.EQ.1)WRITE(6,9520)(DUM1(I,1),I=1,N)
      IF(MARKOV.EQ.1)GOTO 180
      CALL MMULT(C,E1,DUM2,N,1,N,5,5,5,1,5,1)
      CALL MADSUB(DUM1,DUM2,Z,N,1,-1,5,1,5,1,5,1)
      GOTO 190
 180  DO 185 I=1,N
 185  CONTINUE
 190   CONTINUE
```

```
      DO 200 I=1,N
      Z1(I,1)=Z(I,1)
      XX1=(Z(I,1)*SIG(I,1))+MU(I,1)
      IF(V(I).EQ.-1)XX1=BETA(I,1)+EXP(XX1)
      XX1=XX1*SCALE(I,1)
      IF(XX1.LT.XMIN(I,1))XX1=XMIN(I,1)
      XX(I,J)=XX1
  200 CONTINUE
  250 CONTINUE
      IF(MARKOV.EQ.1)GOTO 258
      CALL UNTRAN(N,NYR,XX,YY)
      N=NX
      IF(IE.EQ.1)WRITE(6,900)N
      DO 257 I=1,N
      DO 255 J=1,NYR
      XX(I,J)=YY(I,J)
  255 CONTINUE
  257 CONTINUE
  258 DO 260 I=1,N
      IF(IE.EQ.1)WRITE(6,900)N
      IF(IW.EQ.1)WRITE(6,9520)(XX(I,J),J=1,NYR)
  260  CONTINUE
      RETURN
      END

      SUBROUTINE UNTRAN(N,NYR,Y,XX)
      COMMON/MV/ V(5),MU(5,1),SIG(5,1),XIC(5,1),BETA(5,1),XMIN(5,1),
     .SCALE(5,1),A(5,5),B(5,5),C(5,5),IE,IW,IER,MARKOV
       COMMON/UNT/XMN(5),BETAX(5),XMINX(5),MI(5),PC(5,5),NX,SCALEX(5)
      DIMENSION Y(5,150),X(5,150),PCT(5,5),XX(5,150),YB(5,150)
 9520 FORMAT(1H ,6E15.9)
      ND=N+1
      DO 50 I=1,NX
      YB(I,1)=0.
   50 CONTINUE
      DO 100 I=ND,NX
      DO 90 J=1,NX
      YB(I,1)=YB(I,1)+(PC(I,J)*XMN(J))
   90 CONTINUE
  100 CONTINUE
      IF(IE.EQ.1)WRITE(6,9520)(YB(I,1),I=ND,NX)
      IF(NX.EQ.NY)GOTO 155
      DO 150 K=1,NYR
      DO 125 I=ND,NX
      Y(I,K)=YB(I,1)
  125 CONTINUE
  150 CONTINUE
      DO 155 I=1,NX
      IF(IE.EQ.1)WRITE(6,9520)(Y(I,K),K=1,NYR)
  155 CONTINUE
C     TRANSPOSE PRINCIPAL COMPONENT COEFFICIENTS
      DO 160 I=1,NX
      DO 160 J=1,NX
      PCT(I,J)=PC(J,I)
      DO 170 I=1,NX
      IF(IE.EQ.1)WRITE(6,9520)(PCT(I,J),J=1,NX)
  170 CONTINUE
      CALL MMULT(PCT,Y,X,NX,NYR,NX,5,5,5,150,5,150)
      DO 250 K=1,NYR
      DO 200 I=1,NX
      XX1=X(I,K)
      IF(IE.EQ.1)WRITE(6,9520)XX1
      IF(MI(I).EQ.-1)XX1=BETAX(I)+EXP(X(I,K))
      XX1=XX1*SCALEX(I)
      IF(XX1.LT.XMINX(I))XX1=XMINX(I)
      XX(I,K)=XX1
  200 CONTINUE
  250 CONTINUE
      DO 260 I=1,NX
  260 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CNAT(XN,N,NYR)
      COMMON/MW/CU(3),DV(3),CSNB(3),CSNM(3),CSLAG(3),S(3,150)
      DIMENSION XN(5,150),CS(3,150)
      DO 50 I=3,N
      DO 25 J=1,NYR
      XN(I,J)=XN(I,J)-CU(I)+DV(I)
   25 CONTINUE
   50 CONTINUE
      DO 100 I=3,N
      DO 75 J=1,NYR
      CS(I,J)=CSNB(I)+CSNM(I)*XN(I,J)+CSLAG(I)*S(I,J-1)
      S(I,J)=CS(I,J)+S(I,J-1)
   75 CONTINUE
  100 CONTINUE
      RETURN
      END

      SUBROUTINE MADSUB(A,B,C,N1,N2,D,N3,N4,N5,N6,N7,N8)
      INTEGER D
      DIMENSION A(N3,N4),B(N5,N6),C(N7,N8)
      DO 10 I=1,N1
      DO 10 J=1,N2
      IF(D.LT.0)GOTO 5
       C(I,J)=A(I,J)+B(I,J)
      GOTO 10
    5  C(I,J)=A(I,J)-B(I,J)
   10 CONTINUE
      RETURN
      END
@FOR,USB SR78,SR78,SR78
      SUBROUTINE MOUT(AA,LL,MM,IOUT,RHDG,CHDG,NW)
C**** TO PRINT MATRIX AA(LL*MM)
C     IF IOUT=1  NO HEADINGS
C     IF IOUT=2 PRINT ROW HEADINGS
C     IF IOUT=3 PRINT ROW AND COLUMN HEADINGS
      DIMENSION AA(5,5),RHDG(5),CHDG(5)
      DOUBLE PRECISION RHDG,CHDG
 9002 FORMAT(1H ,10X,11(4X,A6))
 9003 FORMAT(1H ,A6,4X,10E12.5/1H,(1X,10E12.5/))
      IF(IOUT.GT.1)GOTO 20
      WRITE(NW,9000)(AA(I,J),J=1,MM)
   10 CONTINUE
      RETURN
   20 IF(IOUT.EQ.2)GOTO 25
      WRITE(NW,9002)(CHDG(J),J=1,MM)
   25 DO 30 I=1,LL
      WRITE(NW,9003)RHDG(I),(AA(I,J),J=1,MM)
      RETURN
      END
      SUBROUTINE WRITE(X,JY1,JY2,NW)
C*******  NW LT 0 USE FORMAT 9501
C******** NW GT 0 USE FORMAT 9500
      DIMENSION X(1)
      NY=JY2-JY1+1
      IY1=1
      IY2=6
      GOTO 20
   10 IY1=IY1+6
      IY2=IY2+6
   20 IF(IY2.GT.NY)IY2=NY
      KY1=IY1+JY1-1
      KY2=IY2+JY1-1
      IF(NW.LT.0) GOTO 30
      WRITE(NW,9500)KY1,KY2,(X(IY),IY=IY1,IY2)
 9500 FORMAT(7X,2I4,6E12.6)
      GOTO 40
      WRITE(NW,9501)KY1,KY2,(X(IY),IY=IY1,IY2)
      NW=-NW
 9501 FORMAT(7X,2I4,6E12.6)
   40 IF(IY2.EQ.NY)RETURN
      GOTO 10
      END
```

Table E-2a. Input data and decision parameters for Great Salt Lake Water Balance Model.

I. Main program input

1. MVOPT - Format (I5)

1-5	MVOPT	Multivariate option: if = 1, then multivariate stochastic generation. if = 2, then univariate stochastic generation, if = 3, then multivariate input for historic peaks

II. Univariate stochastic ARIMA (1, 0, 1) input parameters

2. THQ, PHIQ, XICQ, MUQ, SIGXQ, BETAQ, XMINQ, IΘPT3 - Format (7F10.0, I10)

1-10	THQ	Streamflow theta, Θ, parameter for O'Connell's ARIMA(1, 0, 1) model
11-20	PHIQ	Streamflow phi, ϕ, parameter for O'Connell's ARIMA(1, 0, 1) model
21-30	XICQ	Initial conditions for generating streamflow input series
31-40	MUQ	Mean of historical streamflow input (sum of annual Bear, Weber, Jordan Rivers)
41-50	SIGXQ	Standard deviation of historical sum of streamflow input series
51-60	BETAQ	Third parameter in log normal distribution of streamflow
61-70	XMINQ	Lower value for generated series, u 1/2 the lowest historical value
71-80	IΘPT3	Precip option: if = 1, then lake precip is estimated from Linear Regression. Equation parameters, if = 2, then precip is estimated from ARIMA (1, 0, 1), if = 3 then precip is estimated from ARIMA (1, 0, 0)

3. THP, PHIP, XICP, MUP, SIGXP, BETAP, XMINP - Format (7F10.0)

1-10	THP	Precip theta, Θ, value for ARIMA(1, 0, 1) model
11-20	PHIP	Precip phi, ϕ, value for ARIMA(1, 0, 1) model
21-30	XICP	Initial conditions for synthetic precip series
31-40	MUP	Historical precip mean
41-50	SIGXP	Historical precip standard deviation
51-60	BETAP	Third parameter in log normal distribution of precip
61-70	XMINP	Lower boundary for generated precip series

4. (CR(I), I=1, 6), ERM, ERS, BETAR, RESMIN - Format (10F10.0)

1-10	CR(1)	Constant term in linear equation for residuals (EVAP, small streams, groundwater)
11-20	CR(2)	Coefficient for historic computed streamflow variable
21-30	CR(3)	Coefficient for lag one historic computed streamflow variable
31-40	CR(4)	Coefficient for area variable
41-50	CR(5)	
51-60	CR(6)	
61-70	ERM	Mean for error term = zero
71-80	ERS	Standard deviation for error time
1-10	BETAR	Third parameter in log normal distribution for residuals
11-20	RESMIN	Minimum value for residual series equal to 1/2 the lowest historic value

Table E-2a. Continued.

III. Precip on the lake estimated from linear regression with streamflow.

3. (CP(I), I=1,3), EPM, EPS, BETAP1 - Format (6F10.0)

1-10	CP(1)	Constant term in precip linear regression equation with streamflow
11-20	CP(2)	Coefficient for historic computed streamflow variable
21-30	CP(3)	Coefficient for area of the lake variable
31-40	EPM	Mean of the error term = zero
41-50	EPS	Standard deviation of the error term
51-60	BETAP1	Lower boundary of the error term

I. Main program inputs

5. CE, CPP - Format (2F10.0)

1-10	CE	Percent of evaporation that has occurred during the year at peak stage
11-20	CPP	Conversion coefficient for evap/precip inches (0.0833) feet; or if using Salt Lake City precip vice lake precip use (0.06)

6. IYR, LYR, NLK, NRB, NQIN, NP, IPNCH, IØPT1, IØPT2, NW, NW1, NW2, NW3, ICWØ, NTRACE, NW4, NW5, NW6, NW7, NW9, NW10, NW11, IRAND, NPNS, IØPT4 - Format (25I5)

1-5	IYR	First year of time series to be generated or input
6-10	LYR	Last year of time series to be generated or input
11-15	NLK	Number of lakes = 1
16-20	NRB	Number of basins = 3
21-25	NQIN	Number of rivers = 2
26-30	NP	Number of values in stage-volume-area tables = 30
31-35	IPNCH	If = 0, don't punch cards, if = 1, then punch cards
36-40	IØPT1	If = 1, then call subroutine read for input, if = 2, read input from cards, if = 3, call stochastic generation subroutines as input
41-45	IØPT2	If = 0, don't calculate residual time series, = 1 do
46-50	NW	File number for residual time series to be written to
51-55	NW1	File number for area time series to be written to
56-60	NW2	File number for residual/area time series to be written to use negative number in order to get two decimal places
61-65	NW3	File number for SALIN time series to be written to
66-70	ICWØ	If = 1, then causeway widths present opening; if = 2, then = 100 feet, if = 3, then = 300 feet; if = 4, then = 600 feet
71-75	NTRACE	Number of times the water balance model generates a sequence of stage time series, up to 100 by 125 years
76-80	NW4	File number peak residual time series is written to
1-5	NW5	File number peak residual/area is written to, negative number = 2 decimals
6-10	NW6	File number for DUM = streamflow generated, if = 0, then skips
11-15	NW7	File number for DUMP = precip generated, if = 0, then skips
16-20	NW8	File number for SSP = south arm peak stage, if = 0, then skips
21-25	NW9	File number for SNP = north arm peak stage, if = 0, then skips
26-30	NW10	File number for SS = south arm stage, if = 0, then skips
31-35	NW11	File number for SN = north arm stage, if = 0, then skips
36-40	IRAND	Random number for seed in the generation subroutine
41-45	NPNS	Number of values in table of north arm percentage of volume-stage

Table E-2a. Continued.

46-50	IΘPT4	If = 0, don't write out arguments in program = debugging

7. IΘPT5, IΘPT6, IΘPO7, IΘPT8, IΘPT9, IΘPT10, IΘPT11, NYBUB, NW12 - Format (9I5)

1-5	IΘPT5	If = 0, calls subroutine BJ101 for streamflow; if = 1, calls BJ100
6-10	IΘPT6	If = 0, untransformed time series generated, if = 1, log transformed time series for streamflow
11-15	IΘPT7	If = 0, initial error term is zero in BJ101, if = 1, initial error is random number IRAND for streamflow
16-20	IΘPT8	If = 0, untransformed precip time series, if =1, generates log transformed precip
21-25	IΘPT9	If = 0, initial error term = 0, if = 1, initial error is = IRAND in precip generation
26-30	IΘPT10	If = 0, write to line printer output, if = 1, nothing written to line printer
31-35	IΘPT11	If = 0, don't calculate excess inflow, if = 1, do
36-40	NYBUB	Number of years before upstream development commences
41-45	NW12	File number for excess inflows to be written to

8. NW13, NW14, NW15, NW17, NW18, NW19, NW20 - Format (8I5)

1-5	NW13	File for multivariate generated evap	1
6-10	NW14	File for multi-generated precip	2
11-15	NW15	File for multi-generated Bear River	3
16-20	NW16	File for multi-generated Weber River	4
21-25	NW17	File for multi-generated Jordan River	8
26-30	NW18	File for NAT-PMF Bear River	
31-35	NW19	File for NAT-PMF Weber River	
36-40	NW20	File for NAT-PMF Jordan River	

9. CONELV, UPSTCI, ADJM - Format (3F10.0)

1-10	CONELV	Control elevation above which lake will not go into upstream development in feet
11-20	UPSTCI	Firm base (100 percent of time), upstream development acre-feet, annually
21-30	ADJM	Adjusts stochastic generation of streamflows mean to historic mean
31-40	BRMIN	Minimum flow allowable Bear River

IV. <u>Multivariate stochastic generation input parameters</u>

1. NV, IDIAG, IΘUT, MARKOV, IE, IW, IER, NX, NAT - Format (9I5)

1-5	NV	Number of input variables to be generated (i.e. 5)
6-10	IDIAG	Parameter for matrix read subroutine if = 1, then reads only a diagonal matrix, if = 0, reads entire matrix
11-15	IΘUT	Parameter in matrix write subroutine, if = 1 no headings are written, if = 2, row headings are written, if = 3, row and column headings are written
16-20	MARKOV	If = 1, then performs multivariate Markov generation otherwise performs ARIMA(1, 0, 1) generation and a "C" matrix must be read in
21-25	IE	If = 1, writes out steps in multivariate generation subroutine
26-30	IW	If = 1, writes out generated input
31-35	IER	If = 1, then writes out error terms in generation subroutine

Table E-2a. Continued.

36-40	NX	Number of physical variables in principal component vector
41-45	NAT	Option if NAT = 0 changes natural generated to present modified flows

2. (VLOG(I), I=1, NV) - Format (NVI5)

1-5	VLOG(I)	If = 1, then data is to be log transformed, if = 2, then not
etc.		

3. (RHDG(I), I=1,NV) - Format 13A6)

1-6	RHDG(I)	Row heading for matrix
etc.		

4. (CHDG(I), I=1,NV) - Format (13A6)

1-6	CHDG(I)	Column heading for matrix

5. Subroutine MIN (AM, NV, NV, ID, AG, IOUT, RHDG, CHDG, 6)
   Reads input AM matrix
   (AM(I,J), J=1,NV), (I=1,NV) - Format (8F10.0)

1-20	AM(I,J)	"A" matrix for Markov or ARIMA(1, 0, 1) multivariate matrix

6. Repeat above for "B" matrix

   If ARIMA option, then read:

IVa. ARIMA (1,0,1) Stochastic multivariate generation parameters

6a. Subroutine MIN (C, NV, NV, IDIAG, IOUT, RHDG, CHDG, 6)
    Reads input "C" matrix
    (C(I,J), J = 1, NV) (I=1,NV) - Format (8F10.0)

1-10	C(I,J)	"C" matrix

7a. (XMN(I), I=1,NX) - Format (8F10.0)

1-10	XMN(I)	Physical means of principal component elements

8a. (BETAX(I), I=1, NX) - Format (8F10.0)

1-10	BETAX(I)	Third parameter of physical series

9a. (XMINX(I), I=1, NX) - Format (8F10.0)

1-10	XMINX(I)	Minimum value for transform physical series

10a. (MI(I), I=1, NX) - Format (16I5)

1-5	MI(I)	If = 1 log transform, if = 2 normal physical variable

11a. (SCALEX(I), I = 1, NX) - Format (16I5)

1-5	SCALE X(I)	Scale factor for each physical variable

12a. PC(I,J), J=1, NX, I = 1, NX - Format (8F10.0)

1-10	PC(I,J)	Principal component coefficients for each vector and physical element

7. (MV(I,1), I=1,NV) - Format (5E15.9)

1-15 etc.	MU(I,1)	Mean of input physical variable i.e. (Evap, Precip, etc) If log transformed then, mean log transformed

8. (SIG(I,1), I=1,NV) - Format (5E15.9)

1-15 etc.	SIG(I,1)	Standard deviation of input physical variable, if log transformed then standard deviation log transformed

9. (BETA(I,1), I=1,NV) - Format (5E15.9)

1-15 etc.	BETA(I,1)	Third parameter of log normal transformation

Table E-2a. Continued.

10. (XMIN(I,1), I=1,NV) - Format (5F10.0)

1-10	XMIN(I,1)	Minimum value allowable in generation of values

11. (XIC(I,1, I=1,NV) - Format (5F10.0)

1-10 etc.	XIC(I,1)	Initial condition of each variable to be generated

12. (SCALE(I,1), I=1,NV) - Format (5F10.0)

1-10	Scale(I,1)	Scale factor of each variable 12 for evap and precip; 1079259 for each river

13. (CU(I), I=3,5) - Format (3F10.0)

CU(I)	1-10	CU(I) Consumptive use for Bear, Weber, Jordan River Basins

14. (DV(I), I=3,5) - Format (3F10.0)

DV(I)	1-10	DV(I) Diversions into or out of Weber, Jordan River Basins

15. (CSNB(I), I=3,5) - Format (3F10.0)

CSNB(I)	1-10	CSNB(I) Constants for linear regression equations for three basins for change of storage = (natural - consumptive use ± diversion) = natural'

16. (CSNM(I), I=3,5) - Format (3F10.0)

CSNM(I)	1-10	CSNM(I) Coefficient for linear regression for change of storage = $\text{natural}'_t$

17. (CSLAG(I), I=8,5) - Format (3F10.0)

CSLAG(I)	1-10	CSLAG(I) Coefficient for log natural' term in linear regression equation for change of storage = NAT'_{t-1}

18. (S(I,1) 1-10 Initial end of your storage for each river basin

2. (RNAME(N), N=1,20) - Format (20A4)

1-80	RNAME(N)	Title of lake

3. VLLIC, ARI(1), SALT(1) - Format (3F10.0)

1-10	VLLIC	Initial lake volume - acre feet
11-20	ARI(1)	Initial lake area - acre
21-30	SALT(1)	Total salt loading in tons

4. (WNACL(J), J=1,7) - Format (7F10.0)

1-10 etc.	WNACL (1)	Sodium chloride concentration data points corresponding to the percent evaporation EVRAT

5. (EVRAT(J), J=1,7) - Format (7F10.0)

1-10 etc.	EVRAT (1)	Evaporation ratio corresponding to the lake salt concentration WNACL(J)

6. (SLAKE(I), I=1,5) - Format (5F10.0)

1-10 etc.	SLAKE (1)	Lake stage corresponding to the Thiessen precip. adjustment factor ADJPT(J)

7. (ADJPT(J), J=1,5) - Format (5F10.0)

1-10 etc.	ADJPT(1)	Thiessen precip. adjustment factor corresponding to lake stage SLAKE(J)

8. (V(1,N), N=1, NP) - Format (8F10.0) NP=30

1-10 etc.	V(1,1)	Volume table of the lake

9. (A(1,N), N=1,NP) - Format (8F10.0) NP=30

1-10 etc.	A(1,1)	Area table correspondence to the volume table

Table E-2a. Continued.

10. (E(1,N), N=1,NP) - Format (8F10.0) NP=30

1-10 etc.	E(1,1)	Stage table correspondence to the area table

11. (H(J), J=1,NPNS) - format (8F10.0) NPNS=37

1-10 etc.	H(1)	Stage table for south arm of the lake - not used

12. (VN(I), J=1, NPNS) - Format (8F10.0) NPSN=37

1-10 etc.	VN(1)	Proportion of volume for north arm of lake

13. PΘI, C1, C2, C3, EVRT, VTΘT, VRATE - Format (7F10.0)

1-10	PΘI	Small streams percentage of combined streamflow i.e. .08
11-20	C1	Groundwater component as a percentage of present years' inflow i.e. .07
21-30	C2	Groundwater component as a percentage of previous years' inflow i.e. .04
31-40	C3	Groundwater component as a percentage of lag two year's inflow i.e. .02
41-50	EVRT	Amount in feet of annual average lake evaporation
51-60	VTΘP	Maximum volume of lake set to some large number i.e. 999999999
61-70	VRATE	Set = to zero not used

V. Input flows and precip for QIN(I,N) Option 1 = 2 Read input from cards for residual computation
Do (NQIN)=2 Two sets of input

1. (QIN(I,N), N=1, NYR) - Format (8F10.0)

1-10 etc.	QIN(1,1)	Total annual streamflows into lake
1-10	QIN(2,1)	Total annual precip on the lake

VI. Call subroutine read if option 1=1 for inflows and precip
Do (NQIN)=2 First input = streamflow, and = precip

1. NR, JY1, JY2, JJY1 - Format (4I10)

1-10	NR	File number streamflow record is on
11-20	JY1	First year of streamflow series
21-30	JY2	Last year of series
31-40	JJY1	Beginning year if series is in 8F10.0 format or 6F10.0

2. ICDTP, STID, IY1, IY2, (DUM(I), I=1,6) - Format (I1, A6, 2I4, 6F10.0)

1	ICDTP	Not used
2-7	STID	Station identification
8-11	IY1	First year of data on card
12-15	IY2	Last year of data on card
16-75	DUM(I)	Data streamflow or precip

VII. If option 2 is called residual is computed by inputing known annual streamflow, lake stage peak and average

1. Subroutine read is called for average annual lake stage
See section VI above for format and card arrangement
2. Subroutine read called for peak stage
See section VI for format and card arrangement

Table E-2b. Input: Water Balance Model.

```
  1
 .280000.083333333
 1979 2103     1     3     2    30     0     3     0     6     6    -6     6     1   100     6
   -0     0     0    25     0    24    038469    37
    0     1     0     0     0     1     1   126
                                  3     4     8    19     1
   4219. 61614.                       140000
    3           1     1                          1
   -1     2    -1    -1    -1
EVAP  PRECIPBEAR  WEBER JORDAN
EVAP  PRECIPBEAR  WEBER JORDAN
.77592      .53492      -.19969     .05173      -.20224
.71746      .04067      .22778      -.01436     .14441
-.25144     .11241      .29831      .14169      .16566
-.04835     .24762      .16119      .28373      .21855
.02092      .36915      -.08541     .19622      .55666
.55729
-.54391     .73866
-.25011     .24732      .56912
-.19462     .14004      .09406      .66808
-.0961      .19476      .23094      -.28204     .37908
     -.53479-01      .904876+00      -.383194+00     -.1312747+01     -.175266+01
.33035696       .183768796       .507813135       .507370541       .390169816
       .3333+01  .258333         .15772139        .0280284899      .06110674
40.         3.1         202600.     30250.      65950.
 3.58899    1.093       .875693     .311372     .212326
   12.      12.         1079259.    1079259.    1079259.
          0           0           0          .16          1.6          0
          0           0           0          .11          1.6          0
          0           0           0          .20          1.5          0
GREAT SALT LAKE WATER BALANCE MODEL STOCHASTIC STAGES 1978-2102
13978840. 937988.2  4700000.
0.          5.          10.         15.         20.         25.         28.33
1.          .975        .933        .883        .842        .808        .795
4170.       4191.       4200.       4211.       4219.
1.014       1.014       .999        .989        .989
    160000   2950500   4732990   5724620   6768670   7311200   7868300   8440400
   9030560   9645950  10301090  11002040  11749730  12556430  13421890  14350140
  15370180  16481450  17640700  18828700  20040700  21276000  22542000  23808000
  25075000  26341000  27607000  29800000  30700000  43200000
    161000    407000    482000    509034    535056    550000    564196    580000
    601861    632676    677888    719964    772964    839809    890047    969949
   1079259   1140000   1175000   1201000   1223000   1250500   1330000   1375000
   1410000   1450000   1490000   1530000   1570000   2000000
      4170      4180      4184      4186      4188      4189      4190      4191
      4192      4193      4194      4195      4196      4197      4198      4199
      4200      4201      4202      4203      4204      4205      4206      4207
      4208      4209      4210      4211      4212      4219
      4170      4171      4172      4173      4174      4175      4176      4177
      4178      4179      4180      4181      4182      4183      4184      4185
      4156      4157      4188      4189      4190      4191      4192      4193
      4194      4195      4196      4197      4198      4199      4200      4201
      4202      4203      4204      4205      4212
      48.1      27.5      25.1      25.5      26.6      27.4      28.2      29.5
      30.3      31.1      31.6      32.3      32.8      33.3      33.5      33.6
      33.6      33.9      34.2      34.4      34.7      34.8      35.0      35.2
      35.4      35.6      35.7      35.9      36.1      36.3      36.4      36.5
      36.5      36.6      36.6      37.3      36.5
       .08      .070      .040      .020    4.3333 17640700. 310000.
```

Table E-3. Water Balance Model Output.

```
    1
.280000001.083333333
 1979 2103    1    3    2   30    0    3    0    6    6   -6    6    1    1    6   -6    0    0   25    0    0   038469   37
    0    1    0    0    0    0    1  126    0
    1    2    3    4    8    0    0    0   19    0
 .42190+04 .61614+05 .00000    .14000+06
    5    0    1    1    0    0    0    0    1
   -1    2   -1   -1   -1
   .37892+00    .53492+00  -.19969+00    .51730-01  -.20224+00
   .31746+00    .40670-01    .22778+00  -.14360-01    .14441+00
  -.29144+00    .11241+00    .29831+00    .14169+00    .15568+00
  -.48350-01    .24762+00    .16119+00    .28373+00    .21855+00
   .20920-01    .36915+00  -.85410-01    .19622+00    .55666+00
   .85729+00    .00000       .00000       .00000       .00000
  -.54391+00    .73866+00    .00000       .00000       .00000
  -.26311+00    .24732+00    .56912+00    .00000       .00000
  -.19462+00    .14004+00    .94060-01    .63808+00    .00000
  -.96100-01    .19476+00    .23094+00  -.28204+00    .37908+00
 -.534790000-01   .904877998+00 -.383194000+00 -.131274700+01 -.175266001+01
  .330356959+00   .183768796+00   .507813133+00   .507370539+00   .390169814+00
  .333300000+01   .258333001+00   .187721390+00   .260284898-01   .611067400-01
     40.00       3.10 202600.00   30250.00   65950.00
      3.69       1.09       .88        .31        .21
```

GREAT SALT LAKE SIMULATION INPUT DATA

BASIN	POP, ACRE, BIRDS, DPOP, DACRE, QIMP					
1	0.	0.	0.	.160	1.600	0.
2	0.	0.	0.	.110	1.600	0.
3	0.	0.	0.	.200	1.500	0.

POI, C1, C2, C3, EVRT, VTOP, VRATE, SALT(L)							
.080	.070	.040	.020	4.333	17640700.	310000.	4700000.

GREAT SALT LAKE WATER BALANCE MODEL STOCHASTIC STAGES 1978-2102

YEAR	QBWJ	QTS	QGW	QTT	PRECIP	EVAP	AREA	VOLUME	CONT	PK ELEV	AN ELEV
1978	.00	.00	.00	.00	.00	.00	937988.20	13978840.00	4700000.00	.00	4198.60
1979	2411436.78	2604351.72	313486.78	2917836.47	807656.66	3289317.12	976901.45	14415017.75	23.99	4200.43	4199.06
1980	1636612.56	1767541.55	212759.63	1980301.19	806437.56	3573500.16	907810.61	13628256.25	25.38	4200.11	4198.22
1981	1370447.66	1480083.47	209624.57	1689708.03	840716.15	3112470.31	868239.62	13046210.12	26.51	4199.28	4197.57
1982	1082640.39	1169251.61	163334.98	1332586.59	818372.68	2880031.62	819980.69	12317137.62	27.50	4198.44	4196.70
1983	1261602.89	1364151.11	160426.77	1544557.87	835006.07	3100662.97	762066.30	11596020.62	27.50	4197.75	4195.79

Table E-4. Variable definition, Water Balance Model.

Variable	IBO[a]	Type[b]	Dimension	Definition
A	I	R	5, 50	Area table of up to five lakes in acres
AA	B	R	50	Area table of Great Salt Lake in acres
ACRE	I	R	5	Area of each basin-not used
ACTUP	0	R	150	Actual upstream development on the Bear River
ADJM	I	R	1	Constant to adjust the streamflow input
ADJPT	I	R	5	Adjustment factor to precip to allow for Thiessen weighting factor biased by lake stage
AM	I	R	5, 5	"A" matrix for Markov or ARIMA (1, 0, 1) Multi-variate generation model
AREA	0	R	150	Area of the lake at end of year
ARI	I	R	5	Initial area of the lake
B	I	R	5, 5	"B" matrix for Markov or ARIMA (1,0,1) Multi-variate generation model
BEAR	B	R	150	Bear River generated by multivariate model
BETA	I	R	5, 1	Third parameter of Log normal distribution for log transformed variable generated by Markov model.
BETAP	I	R	1	Third parameter of log normal precipitation distribution
BETAP1	I	R	1	Lower boundary of error term in precip linear regression
BETAQ	I	R	1	Third parameter in log normal streamflow distribution
BETAR	I	R	1	Lower boundary if error term in residuals linear regression
BETAX	I	R	5	Third parameter for log normal distribution for physical variable to untransform principle component ARIMA (1,0,1) generated variables.
BIRDS	I	R	5	Not Used
BPMF	B	R	150	Bear River natural flow adjusted to present modified flows
BRMIN	I	R	1	Minimum allowable flow for Bear River Bird Refuge in upstream development mode
C	I	R	5, 5	"C" matrix for ARIMA (1,0,1) generation model
CC	B	R	1	Salinity conversion factor
CCN	B	R	5	Concentration of Great Salt Lake salinity
CC1	I	R	4	Slope of the line representing relationship between north-south lake stage depending on causeway opening present, 100 ft. 300 ft. 600 ft.
CC2	I	R	4	Intercept of the line representing the north-south lake stage relationship
CE	I	R	1	Proportion of lake evap. that has occurred by the time of peak stage
CHDG	I	R	5	Column headings for matrix
CON	0	R	5, 150	Concentration of the lake same as CCN
CONELV	I	R	1	Lake stage desired to maintain below by upstream development
CONM	0	R	5	Mean concentration of the lake over a period of years

[a] I = Input B = Body of program 0 - Output

[b] R = Real I = Integer

Table E-4. Continued.

Variable	IBO	Type	Dimension	Definition
CONVOL	B	R	1	The volume corresponding to the control lake elevation
CP	I	R	3	Linear regression coefficients for precipitation relationship with streamflow and lake area
CPP	I	R	1	Conversion coefficient for precip. from inches to feet
CR	I	R	6	Linear regression coefficients for model residual (made up of evaporation, small streams, groundwater, error) based on streamflow and lake area.
CSLAG	I	R	3	Linear regression coefficients for change in storage relationship with natural flows (less consumptive uses and interbasin diversion) logged one year.
CSNB	I	R	3	Same as CSLAG except being the intercept
CSNM	I	R	3	Same as CSLAG except not lagged
CU	I	R	3	Consumptive use constant for each river basin (Bear, Weber, Jordan)
C1	I	R	1	Groundwater component for present year streamflow
C2	I	R	1	Groundwater component for last year's streamflow
C3	I	R	1	Groundwater component for lag two years streamflow
DACRE	I	R	5	Not used
DPOP	I	R	5	Not used
DUM	B	R	150	Input temporary variable Rivers stage
DUMP	B	R	150	Peak stage input variable
DV	I	R	3	Diversion from river basins
E	I	R	5, 50	Lake stage table in feet msl
EE	B	R	50	Same as E
ELP	0	R	5, 150	Peak stage in feet
ELPM	0	R	5	Mean peak stage over the years
ELV	0	R	5, 150	End of the year stage in feet
ELVM	0	R	5	Mean end of the year stage in feet
EP	B	R	150	Error/noise term for linear regression precipitation function
EPM	I	R	1	Error mean for precip. linear regression = zero
EPS	I	R	1	Error term standard deviation for precip. linear regression
ER	B	R	150	Error/noise term for residual linear regression function
ERM	I	R	1	Error term mean for residual linear regression = zero
ERS	I	R	1	Error term standard deviation for residual linear regression
EVAP	0	R	5, 150	Lake evaporation in acre-feet
EVAPM	0	R	5	Mean lake evap. in ac-ft over years
EVMP	B	R	150	Input evaporation from multi-variable generation model
EVRT	I	R	1	Amount of annual average lake evaporation fresh water in feet
EVRAT	I	R	7	Evap. ratio of fresh water to salt water by salinity concentration
EVRTI	B	R	1	Lake evaporation derived by linear regression
EX	0	R	150	Excess volume from control lake stage to actual lake stage
EXC	B	R	1	Excess volume from upstream development
FNYR	B	R	1	Number of years during lake simulation loop

Table E-4. Continued.

Variable	IBO	Type	Dimension	Definition
H	I	R	50	South arm lake stage table
ICWO	I	I	1	Causeway opening index : 1 = present, 2 = 100 ft.. 3 = 300 ft., 4 = 600 ft.
IDIAG	I	I	1	Option in matrix real subroutine if = 1 read diagonal only, if = 0 reads entire matrix
IE	I	I	1	Option in multivariate subroutine if = 1 writes out computations
IER	I	I	1	Option in multivariate subroutine if = 1 write out error terms
IθPT1	I	I	1	Option for input of lake variables if 3 = multivariate generation subroutine
IθPT10	I	I	1	Option to write output in main program
IθPT11	I	I	1	Excess inflow option
IθPT2	I	I	1	Residual option
IθPT3	I	I	1	Precip. option if linear regression, stochastic generation
IθPT4	I	I	1	Debug write statement option
IθPT5	I	I	1	Univariate streamflow generation option
IθPT6	I	I	1	Log transformation streamflow option
IθPT7	I	I	1	Streamflow initial error term option
IθPT8	I	I	1	Log transformation precip. option
IθPT9	I	I	1	Precip. initial error term option
IθUT	I	I	1	Option in matrix write subroutine
IP	B	I	1	Precip. seed number
IPNCH	I	I	1	Punch cards option
IQ	I	I	1	Streamflow seed number
IR	I	I	1	Residual seed number
IRAND	I	I	1	Random number
IW	I	I	1	Write option in multivariate subroutine
I YEAR	B	I	150	Year time series used in write subroutine
IYR	I	I	1	Beginning year of simulation
IYR1	B	I	1	Previous year to beginning year
JORDN	B	R	150	Input Jordan River from multi-variation
KEPSED	I	I	1	Read seed option
LYR	I	I	1	Last year of simulation
MARKOV	I	I	1	Markov generation option
MI	I	I	5	Log transformation index if = -1 then variable is log transformed if = 2 then normal
MU	I	R	5, 1	Mean of the input variables for multivariate
MUP	I	I	1	Mean precip. for univariate generation
MUQ	I	I	1	Mean streamflow for univariate generation
MVθPT	I	I	1	Multivariate generation option
NAT	I	I	1	Natural streamflow option
NLK	I	I	1	Number of lakes
NP	I	I	1	Number of values in stage-volume area tables
NPNS	I	I	1	Number of values in north arm volume - south stage table
NQIN	I	I	1	Number of univariate generation inputs = 2
NRB	I	I	1	Number of basins
NTRACE	I	I	1	Number of traces
NV	I	I	1	Number of multivariate input variables
NW	I	I	1	Residual file
NWSD	I	I	1	Seed file
NW1	I	I	1	Area file
NW10	I	I	1	South lake stage file

Table E-4. Continued.

Variable	IBO	Type	Dimension	Definition
NW11	I	I	1	North lake stage file
NW12	I	I	1	Excess inflows file
NW13	I	I	1	Evaporation file
NW14	I	I	I	Precipitation file
NW15	I	I	1	Bear River file
NW16	I	I	1	Weber River file
NW17	I	I	1	Jordon River file
NW18	I	I	1	NAT-PMF Bear file
NW19	I	I	1	NAT-PMT Weber file
NW2	I	I	1	Residual/area file
NW20	I	I	1	NAT-PMF-Jordan file
NW3	I	I	1	SALIN file
NW4	I	I	1	Peak Residual file
NW5	I	I	1	Peak residual/area file
NW6	I	I	1	Streamflow file
NW7	I	I	1	Precipitation file
NW8	I	I	1	South peak stage file
NW9	I	I	1	North peak stage file
NX	I	I	1	Number of physical variables in principal components
NY	I	I	1	Same as NV
NYBUP	I	I	1	Number of year before upstream development starts
NYR	B	I	1	Number of years of simulation
NYR1	B	I	1	Number of years plus one for simulation
PC	I	R	5, 5	Principal component coefficients for ARIMA (1,0,1)
PHIP	I	R	1	Phi value for univariate generation of precipitation
PHIQ	I	R	1	Phi value for univariate generation of streamflow
PMFJ	B	R	150	Jordan River natural flow adjusted to present modified flows
POI	I	R	1	Small streams component of streamflow
POP	I	R	5	Not used
PPAF	O	R	5, 150	Precipitation on the lake for the year in acre-feet
PPAFM	O	R	5	Mean lake precip. for over the years in Ac.-ft.
PPFI	B	R	1	Precip. derived by linear regression
PPT	B	R	150	Precipitation in inches generated by multivariate model
QBWJ	B	R	150	Bear, Weber, Jordan Rivers combined
QBWJM	O	R	1	Mean combined streamflow
QGW	B	R	150	Total groundwater into the lake
QGWM	O	R	1	Mean ground water
QGWZ	B	R	1	Groundwater component
QGW3	B	R	1	Groundwater component
QIMP	I	R	5	Not used
QIN	B	R	5, 150	Multivariate generated input variables
QTI	B	R	150	Total inflow in the lake (Bear, Weber, Jordan)
QTS	B	R	150	Total surface inflow into the lake (Includes small streams)
QTSM	O	R	1	Mean total surface inflow
QTT	B	R	150	Total inflow into the lake included groundwater and surface inflow
QTTM	O	R	1	Mean total inflow
QTT1	B	R	1	Initial combined streamflow
QX		R	5, 150	Surface inflows QX14,J is small streams
RE	B	R	1	Lake stage, temporary variable
RESID	O	R	150	Residual difference in lake volume from actual to model end of year volume
RESIDP	O	R	150	Residual difference in peak lake volume from actual to model

Table E-4. Continued.

Variable	IBO	Type	Dimension	Definition
RESMIN	I	R	1	Residual minimum value
RHDG	I	R	5	Row headings for matrix
RNAME	I	R	20	Name of lake, title for water budget table
RS	B	R	1	Lake area, temporary variable
RV	B	R	1	Lake volume, temporary variable
SA	B	R	1	Mean lake area, temporary variable
SALIN	O	R	150	Salinity of the lake time series
SALT	I	R	5	Total salt load in the lake in tons
SAR	O	R	5, 150	Lake area in acres
SARM	O	R	5	Mean lake area in Ac. over the years
SA1	B	R	1	End of the year lake area
SAZ	B	R	1	Peak lake area
SCALE	I	R	5.1	Scale factor for input variables to convert inches to feet and acre-feet to feet
SCALEX	I	R	5	Same scale applied in untrans subroutine
SD	B	R	100	Seed for generation model
SEED	B	R	1	Seed number
SEEDP	B	R	1	Seed nunber of precipitation
SEEDA	B	R	1	Seed number for streamflow
SEEDR	B	R	1	Seed number for residual
SIG	I	R	5, 1	Standard deviation of input variables for multivariate generation
SLAKE	I	R	5	Lake stage for precip. adjustment factor ADJPT
SIGXP	I	R	1	Precipitation standard deviation
SIGXQ	I	R	1	Streamflow standard deviation
SM	B	R	1	Lake Stage
SN	B	R	150	North Lake Stage
SNP	B	R	150	North peak lake stage
SS	B	R	150	South Lake Stage
SSP	B	R	150	South peak lake stage
STID	I	R	1	Station, indentification
SLIM	O	R	10	Summation variable for water budget
THP	I	R	1	Theta value for univariate precip. generation
THQ	I	R	1	Theta value for univariate streamflow generation
TIME	I	I	1	Clock function for seed
UPSTCI	I	R	1	Amount of constant upstream development
V	I	R	5, 50	Lake volume tables
VLL	B	R	5	Computed lake volume
VLLIC	I	R	1	Initial lake volume
VLOG	I	I	5	Log transformation index same as MI
VN	I	R	50	Proportion of north arm volume of the lake at corresponding south arm stage H
VOL	O	R	5, 150	Final volume of the lake for each year
VOLM	O	R	5	Mean year end lake volume
VOLO	B	R	1	Computed lake volume, temporary variable
VOWT	B	R	150	Volume in excess to maximum lake volume
VOWTM	O	R	1	Mean excess volume
VRATE	I	R	1	Not Used - zero
VS	I	R	50	Not used
VTθP	I	R	1	Max. lake volume
VV	I	R	50	Lake volume table
WEBER	B	R	150	Weber river input variable from multivariate generation model
WPMR	B	R	150	Weber River natural flow adjusted to present modified flows

Table E4. Continued

Variable	IBO	Type	Dimension	Definition
WNACL	I	R	7	Salinity concentration for determining percent lake evap. EVRAT
XIC	I	R	5, 1	Initial starting condition for each input
XICP	I	R	1	Initial precipitation for univariate generation
XICQ	I	R	1	Initial streamflow for univariate generation
XMIN	I	R	5, 1	Lowest allowable value for each generated input variable
XMINP	I	R	1	Lower precipitation boundary
XMINQ	I	R	1	Lower streamflow boundary
XMINX	I	R	5	Lowest allowable value for each input variable in untrans subroutine
XMN	I	R	5	Mean for each input variable in untrans subroutine
ZERO	B	R	1	Zero value

APPENDIX F

DAMAGE SIMULATION MODEL

Table F-1. Damage Simulation Model program listing.

```
C****CONTINUOUS DAMAGE SIMULATION MODEL FOR GREAT SALT LAKE
      COMPILER(XM=1)
      DIMENSION FX(100),XPP(100),NSSTAG(25),NSSALT(25),TSGS1(10),
     *          TSGS(10,4),TSGN1(10),TSGN(10,4),TSGE(10),TT(10),
     *          TSGT(10)
      DIMENSION PWF(150),USF(150),A(158),IMAG4(5151),XJ(100),YP(100)
      DIMENSION NR(10,2),NSI(150),
     .DRM(25,30),DCI(25,30),DRLS(25,30),DRLL(25,30),CC1(4),CC2(4),
     .TITLE1(20),TITLE2(20),B(158),AREA(10),C(158),F(158)
      COMMON/COM1/DRM1(25,30),DCI1(25,30),IE(30),NP,DRLS1(25,30),DRLL1(2
     .5,30),IUCS(25),AREA1(10),DASUM(10),SCALE,IWD(25),REIN(25),DRLI1(25
     .,30)
      COMMON DAM(150,100),UNFS(100,10),PW(100,10),XB(100,10),Y1P(100,10)
     .,RLT(150,100),OMAR(150,100),CIRE(150,100),DRLI(25,30),APNTE(10),
     .0),XUSO(100),XUSR(100),YY(150,100),Y(150,100),YZ(150,100)
     .,DWIC(10),DWOC(10),DWSC(10),DWIA(10),DWOA(10),DWSA(10),TWE(10)
      COMMON/COM2/XND,IND
      DATA CC1/0.012761,0.,-0.012443,-0.013466/
      DATA CC2/-52.0591,0.975,52.7822,56.7659/
 9000 FORMAT(2A5,7F10.0/(10X,7F10.0))
 9001 FORMAT(16I5)
 9002 FORMAT(2I5,7F10.0)
 9003 FORMAT(13A6)
 9004 FORMAT(3I5,6F10.0)
 9005 FORMAT(8I10)
 9006 FORMAT(2A5,7I10/(10X,7I10))
 9007 FORMAT(80A1)
 9008 FORMAT(4F20.0)
 9009 FORMAT(8F10.0)
 9012 FORMAT(2I5,F10.0,I10,4F10.0,I10)
 9500 FORMAT(1H ,2A5,7F10.0/(1H ,10X,7F10.0))
 9505 FORMAT(1H ,I5,20F5.2/(5X,20F5.2))
 9506 FORMAT(1H ,4E14.9)
 9510 FORMAT(1H ,20A6)
 9511 FORMAT(1H ,16I5)
 9512 FORMAT(1H ,3I5,2F10.2)
 9513 FORMAT(1H ,2I5,7F10.0)
 9514 FORMAT(1H ,8I10)
 9517 FORMAT(1H ,13A6)
 9520 FORMAT(1H0,4HIER=)
 9521 FORMAT(1H ,8F10.2)
 9523 FORMAT(1H ,2I5,F10.0,I10,4F10.0,I10)
 9524 FORMAT(1H0,32HCAPITAL INVESTMENT/REINSTATEMENT)
 9525 FORMAT(1H0,29HOPERATIONS/MAINTENANCE/REPAIR)
 9526 FORMAT(1H0,5HTOTAL)
 9527 FORMAT(1H0,10E12.6)
 9528 FORMAT(1H0,12HREVENUE LOSS)
 9553 FORMAT(1H ,15HUNIFORM SERIES=,7E14.9)
 9554 FORMAT(1H ,14HPRESENT WORTH=,7E14.9)
C *** INPUT GENERAL
C *** INPUT
      READ(5,9007)(A(I),I=1,72)
      READ(5,9007)(A(I),I=73,108)
      READ(5,9007)(A(I),I=109,144)
      READ(5,9008)(A(I),I=145,148)
      READ(5,9007)(A(I),I=149,158)
      READ(5,9007)(B(I),I=1,72)
      READ(5,9007)(B(I),I=109,144)
      READ(5,9008)(B(I),I=145,148)
      READ(5,9007)(B(I),I=149,158)
      READ(5,9007)(C(I),I=1,72)
      READ(5,9007)(C(I),I=73,108)
      READ(5,9007)(C(I),I=109,144)
      READ(5,9008)(C(I),I=145,148)
      READ(5,9007)(C(I),I=149,158)
      READ(5,9007)(F(I),I=1,72)
      READ(5,9007)(F(I),I=109,144)
      READ(5,9008)(F(I),I=145,148)
      READ(5,9007)(F(I),I=149,158)
      READ(5,9001)IYR1,IYR2,ICWD,NPSG,NPT,IW,NYRIN,ISALT,IUCSF,ISGLE,IWR
     .D,IOPT1,IOPT2
      WRITE(6,9511)IYR1,IYR2,ICWD,NPSG,NPT,IW,NYRIN,ISALT,IUCSB,ISGLE,IW
      NYR=IYR2-IYR1+1
      READ(5,9004)NP,NS10,NI,R,SCALE
      WRITE(6,9512)NP,NS10,NI,R,SCALE
      READ(5,9001)NRR,NHW,NSC,NRC,NBR,NR1,NPA,NIND
      WRITE(6,9511)NRR,NHW,NSC,NRC,NBR,NR1,NPA,NIND
      NTE=NRR+NHW+NSC+NRC+NBR+NIND
      READ(5,9001)(NSI(M),M=1,NI)
      WRITE(6,9511)(NSI(M),M=1,NI)
      READ(5,9001)(NR(K,K1),K=1,NS10)
      WRITE(6,9511)(NR(K,K1),K=1,NS10)
      READ(5,9012)NG,IND,XND,NSTEP,XMIN,XMAX,YMIN,YMAX,NYSTEP
      WRITE(6,9523)NG,IND,XND,NSTEP,XMIN,XMAX,YMIN,YMAX,NYSTEP
      NSTEP=NG
      NYSTEP=NG
      READ(5,9003)(TITLE1(I),I=1,20)
      WRITE(6,9517)(TITLE1(I),I=1,20)
      READ(5,9003)(TITLE2(I),I=1,20)
      READ(5,9005)(IUCS(L),L=1,NTE)
      WRITE(6,9514)(IUCS(L),L=1,NTE)
      READ(5,9009)(REIN(L),L=1,NTE)
      DO 10 L=1,NTE
      REIN(L)=REIN(L)*1000./SCALE
 10   CONTINUE
      READ(5,9001) (NSSTAG(L),L=1,NTE)
      WRITE(6,9511)(NSSTAG(L),L=1,NTE)
      READ(5,9001) (NSSALT(L),L=1,NSC)
      READ(5,9009) (AREA(L),L=1,NSC)
      WRITE(6,9521)(AREA(L),L=1,NSC)
      READ(5,9009)(TSGE(J),J=1,NPSG)
      WRITE(6,9521)(TSGE(J),J=1,NPSG)
      DO 20 I=1,4
      READ(5,9009)(TSGN(J,I),J=1,NPSG)
      WRITE(6,9521)(TSGN(J,I),J=1,NPSG)
 20   CONTINUE
      DO 30 I=1,4
      READ(5,9009) (TSGS(J,I),J=1,NPSG)
      WRITE(6,9521)(TSGS(J,I),J=1,NPSG)
 30   CONTINUE
      READ(5,9009) (TSGT(J),J=1,NPT)
      WRITE(6,9521)(TSGT(J),J=1,NPT)
      READ(5,9009) (TT(J),J=1,NPT)
      WRITE(6,9521)(TT(J),J=1,NPT)
      READ(5,9009) (APNTE(J),J=1,NPA)
      WRITE(6,9521)(APNTE(J),J=1,NPA)
      READ(5,9009) (APNT(J),J=1,NPA)
      WRITE(6,9521)(APNT(J),J=1,NPA)
C *** CALCULATE HISTOGRAM INTERVALS
      STEP=(XMAX-XMIN)/FLOAT(NSTEP)
      YSTEP=(YMAX-YMIN)/FLOAT(NYSTEP)
C *** CALCULATE PLOTTING POSITIONS
      NS=NS10*10
      IF(ISGLE.EQ.1)NS=1
      DO 60 I=1,NS
      XPP(I)=FLOAT(I)/FLOAT(NS+1)
 60   CONTINUE
C*** READ STAGE - DAMAGE TABLES
      READ(NR1,9006)D,E,(IE(J),J=1,NP)
      IF(IW.EQ.1)WRITE(6,9501)D,E,(IE(J),J=1,NP)
      DO 100 L=1,NTE
      READ(NR1,9000)D,E,(DCI(L,J),J=1,NP)
      READ(NR1,9000)D,E,(DRM(L,J),J=1,NP)
      READ(NR1,9000)D,E,(DRLS(L,J),J=1,NP)
      READ(NR1,9000)D,E,(DRLL(L,J),J=1,NP)
      READ(NR1,9000)D,E,(DRLI(L,J),J=1,NP)
      IF(IW.EQ.0)GOTO 80
      WRITE(6,9500)D,E,(DCI(L,J),J=1,NP)
```

```
      WRITE(6,9500)D,E,(DRM(L,J),J=1,NP)
      WRITE(6,9500)D,E,(DRLS(L,J),J=1,NP)
      WRITE(6,9500)D,E,(DRLL(L,J),J=1,NP)
      WRITE(6,9500)D,E,(DRLI(L,J),J=1,NP)
 80   DO 90 J=1,NP
      DCI(L,J)=DCI(L,J)*1000./SCALE
      DRM(L,J)=DRM(L,J)*1000./SCALE
      DRLS(L,J)=DRLS(L,J)*1000./SCALE
      DRLL(L,J)=DRLL(L,J)*1000./SCALE
      DRLI(L,J)=DRLI(L,J)*1000./SCALE
 90   CONTINUE
 100  CONTINUE
C*** READ WRD DATA
      IF(IWRD.EQ.0)GOTO 103
      READ(5,9009)(DWIC(J),J=1,8)
      READ(5,9009)(DWOC(J),J=1,8)
      READ(5,9009)(DWSC(J),J=1,8)
      READ(5,9009)(DWIA(J),J=1,8)
      READ(5,9009)(DWOA(J),J=1,8)
      READ(5,9009)(DWSA(J),J=1,8)
      IF(IW.EQ.0)GOTO 101
      WRITE(6,9521)(DWIC(J),J=1,8)
      WRITE(6,9521)(DWOC(J),J=1,8)
      WRITE(6,9521)(DWSC(J),J=1,8)
      WRITE(6,9521)(DWIA(J),J=1,8)
      WRITE(6,9521)(DWOA(J),J=1,8)
      WRITE(6,9521)(DWSA(J),J=1,8)
 101  DO 102 J=1,10
      DWIC(J)=DWIC(J)*1000./SCALE
      DWOC(J)=DWOC(J)*1000./SCALE
      DWSC(J)=DWSC(J)*1000./SCALE
      DWIA(J)=DWIA(J)*1000./SCALE
      DWOA(J)=DWOA(J)*1000./SCALE
      DWSA(J)=DWSA(J)*1000./SCALE
 102  CONTINUE
C *** READ SYNTHETIC STAGE TRACES
 103  DO 125 K1=1,2
      DO 120 K=1,NS10
      NSEQ=10
      IF(ISGLE.EQ.1)NSEQ=1
      CALL READ2(Y,NR(K,K1),NSEQ,IYR1,IYR2,NYR)
      JJ=(K-1)*10+J
      DO 105 I=1,NYR
      IF(K1.EQ.2)GOTO 104
      YY(I,JJ)=Y(I,J)
 104  YZ(I,JJ)=Y(I,J)
 105  CONTINUE
 110  CONTINUE
 120  CONTINUE
 125  CONTINUE
      DO 130 K=1,NS10
      DO 128 J=1,10
      JJ=(K-1)*10+J
      DO 126 I=1,NYR
      IF(YY(I,JJ).LT.4196.)YY(I,JJ)=YZ(I,JJ)
 126  CONTINUE
 128  CONTINUE
 130  CONTINUE
C  ** INITIALISATION
      C1=CC1(ICWO)
      C2=CC2(ICWO)

C******    TRACE LOOP
      DO 500 K=1,NS
      IF(IOPT2.EQ.1)WRITE(6,9710)K
 9710 FORMAT(1H ,9HTRACE NO=,I3)
      DO 140 L=1,NSC
      DASUM(L)=0.
      AREA1(L)=AREA(L)
 140  CONTINUE
      DO 150 J=1,NPSG
      TSGS1(J)=TSGS(J,ICWO)
      TSGN1(J)=TSGN(J,ICWO)
 150  CONTINUE
      DO 200 L=1,NTE
      IWD(L)=0
      DO 190 J=1,NP
      DRM1(L,J)=DRM(L,J)
      DRLS1(L,J)=DRLS(L,J)
      DRLL1(L,J)=DRLL(L,J)
      DRLI1(L,J)=DRLI(L,J)
 190  CONTINUE
 200  CONTINUE
      SIC=0.
      SOC=0.
      SSC=0.
      SIA=0.
      SOA=0.
      SSA=0.
      DS=0.
      SIC1P=0.
      SOC1P=0.
      SSC1P=0.

C**** YEAR LOOP
      DO 400 I=1,NYR
      S=YY(I,K)
C    * ESTIMATE NORTH ARM STAGE AND SOUTH ARM STAGE GIVEN CAUSEWAY
C      OPENING
      DH=C1*S+C2
      DCF=1.
      DS=S-S1
      S1=YY(I,K)
      IF(DS.GT.-.5.AND.DS.LT..5)GOTO 208
      IF(DS.GT.1.)GOTO 202
      IF(DS.LT.-1.)GOTO 203
      IF(DS.GT..5.AND.DS.LT.1.)GOTO 204
      DCF=1.5+DS
      GOTO 208
 202  DCF=1.5
      GOTO 208
 203  DCF=0.5
      GOTO 208
 204  DCF=0.5+DS
 208  CALL INTERP(APN,APNT,S,APNTE,NPA)
      S=S+APN/100.*DH*DCF
      SN=S-DH*DCF
      IF(IWRD.EQ.1)GOTO 300
C    0.5 ADDED TO MAKE IFIX TRUNCATION EQUIVALENT TO ROUNDOFF
      IS=IFIX(S+0.5)
      IN=IFIX(SN+0.5)
      IF(I.NE.1)GOTO 209
      ISP=IS
      INP=IN
 209  FIS=FLOAT(IS)
      FIN=FLOAT(IN)
      IF(IOPT1.EQ.0)GOTO 2095
      WRITE(6,9600)(I,YY(I,K),S,DH,DS,S1,DCF,SN,IS,IN,FIS,FIN)
 2095 IF(I.NE.1)GOTO 210
      CALL INTERP(SGSI,TSGS1,FIS,TSGE,NPSG)
      CALL INTERP(SGNI,TSGN1,FIN,TSGE,NPSG)
      CALL INTERP(TSI,TT,SGSI,TSGT,NPT)
      CALL INTERP(TNI,TT,SGNI,TSGT,NPT)
C*** CAPITAL INVESTMENT
 210  DAM(I,K)=0.
      DMAR(I,K)=0.
      CIRE(I,K)=0.
       RLT(I,K)=0.
      DO 228 L=1,NTE
      IS1=IS
      IF(NSSTAG(L).EQ.0)IS1=IN
      IF(I.NE.1)GOTO 214
```

```
      DO 211 J=1,NP
      IF(IOPT1.EQ.0)GOTO 2105
      WRITE(6,9850)J,JJ,IS1,IE(J)
 9850 FORMAT(1H ,2HJ=,I2,3HJJ=,I2,4HIS1=,I5,6HIE(J)=,I5)
 2105 IF(IS1.GT.IE(J))GOTO 211
      JJ=J
      GOTO 212
  211 CONTINUE
      WRITE(6,9700)IS1
 9700 FORMAT(1H ,37HLOWER DAMAGE STAGE EXCEED TABLE RANGE,I4)
      STOP
  212 IF(JJ.LT.5)GOTO 214
      DO 213 J=5,JJ
      DCI1(L,J)=0.
  213 CONTINUE
      IF(IOPT1.EQ.0)GOTO 214
      WRITE(6,9800)(DCI1(L,J),J=1,NP)
 9800 FORMAT(1H ,5HDCI1=,E14.9)
  214 ISP1=ISP
      IF(NSSTAG(L).EQ.0)ISP1=INP
C****ENTITY WIPED OUT/REINSTATED
      IF(IS1.LT.IUCS(L))GOTO 215
      IWO(L)=1
      GOTO 220
  215 IF(IWO(L).EQ.0)GOTO 218
      IF(IS1.LE.(IUCS(L)-IUCSB))GOTO 216
      IWO(L)=1
      GOTO 228
  216 IF(IWO(L).GT.NYRIN)GOTO 217
      GOTO 228
  217 IWO(L)=0
      CIE1=REIN(L)
      GOTO 219
  218 CALL CI(L,IS1,CIE1)
  219 DAM(I,K)=DAM(I,K)+CIE1
      CIRE(I,K)=CIRE(I,K)+CIE1
  220 IDIS=IS1-ISP1
      IF(ABS(IDIS).LE.1)GOTO 228
      IF(IDIS.LT.0)GOTO 222
      IDIS1=IDIS-1
      DO 224 II=1,IDIS1
      ISI=ISP1+II
      CALL CI(L,ISI,CIE1)
      DAM(I,K)=DAM(I,K)+CIE1
      CIRE(I,K)=CIRE(I,K)+CIE1
  224 CONTINUE
      GOTO 228
  222 IF(ISP.GT.4196)GOTO 228
      IDIS=-IDIS
      IDIS1=IDIS-1
      DO 226 II=1,IDIS1
      ISI=ISP1-II
      CALL CI(L,ISI,CIE1)
      DAM(I,K)=DAM(I,K)+CIE1
      CIRE(I,K)=CIRE(I,K)+CIE1
  226 CONTINUE
  228 CONTINUE
      ISP=IS
      INP=IN
      IF(IOPT1.EQ.0)GOTO 229
      WRITE(6,9610)(IWO(L),L=1,NTE),DAM(I,K),CIRE(I,K)
 9610 FORMAT(1H ,6HWP/CAP,18I2,2E14.9)
C****OMR
  229 DO 240 L=1,NTE
      IF(IWO(L).NE.0)GOTO 240
      IS1=IS
      CALL OMR(L,IS1,OMRE1)
      DAM(I,K)=DAM(I,K)+OMRE1
      OMAR(I,K)=OMAR(I,K)+OMRE1
  240 CONTINUE
      IF(IOPT1.EQ.0)GOTO 250
```



```
      WRITE(6,9620)DAM(I,K),OMAR(I,K)
 9620 FORMAT(1H ,3HOMR,3E14.9)
  250 DO 260 L=1,NTE
C *** REVENUE LOSSES/ LOST BENEFITS
      IS1=IS
      IF(NSSTAG(L).EQ.0)IS1=IN
      CALL RL(L,IS1,RLSE1,RLLE1,RLIE1)
      DAM(I,K)=DAM(I,K)+RLSE1+RLLE1+RLIE1
      RLT(I,K)=RLT(I,K)+RLIE1+RLSE1+RLLE1
  260 CONTINUE
      IF(IOPT1.EQ.0)GOTO 265
      WRITE(6,9630)DAM(I,K),RLT(I,K)
  265 IF(IOPT2.EQ.0)GOTO 268
      WRITE(6,9750)I,IS,IN,(IWO(L),L=1,NTE),DAM(I,K),CIRE(I,K),OMAR(I,K)
     *,RLT(I,K)
 9750 FORMAT(1H ,5HSTAGE,I4,4H IS=,I5,4H IN=,I5,4HWIPE,21I2,6HTOTAL=,E8.
     *3,8HCAPITAL=,E8.3,4HOMR=,E8.3,5HREVL=,E8.3)
C *** SALINITY LOSSES
  268 IF(ISALT.EQ.0)GOTO 400
      CALL INTERP(SGS,TSGS1,FIS,TSGE,NPSG)
      CALL INTERP(SGN,TSGN1,FIN,TSGE,NPSG)
      CALL INTERP(TS,TT,SGS,TSGT,NPT)
      CALL INTERP(TN,TT,SGN,TSGT,NPT)
      WRITE(6,9513)K,I,DAM(I,K)
      DO 280 L=1,NSC
      IF(IWO(L).NE.0)GOTO 280
      IF(NSSALT(L).EQ.1)GOTO 270
      T1=TNI
      T2=TN
      GOTO 275
  270 T1=TSI
      T2=TS
  275 CALL SALT(L,T1,T2,SCI,SRM)
      DAM(I,K)=DAM(I,K)+SCI+SRM
  280 CONTINUE
      IF(TS.LT.TSI)TSI=TS
      IF(TN.LT.TNI)TNI=TN
      GOTO 400
C *** WRD DAMAGE ALGORTHM
C   * ANNUAL DAMAGES
  300 CALL INTERP(SIA1,DWIA,S,TWE,8)
      CALL INTERP(SOA1,DWOA,S,TWE,8)
      CALL INTERP(SSA1,DWSA,S,TWE,8)
      SIA=SIA+SIA1
      SOA=SOA+SOA1
      SSA=SSA+SSA1
C   * CAPITAL DAMAGES
      CALL INTERP(SIC1,DWIC,S,TWE,8)
      CALL INTERP(SOC1,DOIC,S,TWE,8)
      CALL INTERP(SSC1,DSIC,S,TWE,8)
      IF(DS.LE.0.)GOTO 380
      Y(I,K)=S
      II=5
      IF(I.EQ.1)GOTO 360
      IF(I.LT.5)II=I
      DO 340 I1=1,II
      I2=I-1
      IF(S.GT.YY(I2,K))GOTO 360
  340 CONTINUE
      GOTO 380
  360 SIC=SIC+SIC1-SIC1P
      SOC=SOC+SOC1-SOC1P
      SSC=SSC+SSC1-SSC1P
  380 SIC1P=SIC1
      SOC1P=SIC1
      SSC1P=SSC1
  400 CONTINUE
      IF(ISALT.EQ.0)GOTO 500
      WRITE(6,9513)K,I,(AREA1(L),L=1,NSC)
      WRITE(6,9513)K,I,(DASUM(L),L=1,NSC)
  500 CONTINUE
```

```
      IF(IWRO.EQ.1)GOTO 970

      PWF(1)=1.
      USF(1)=1.
      R1=1.+R
      RI=R1
C *** CALCULATE PRESENT WORTH AND CR FACTORS
      DO 600 I=2,NYR
      I1=I-1
      PWF(I)=PWF(I1)/R1
      RI=RI*R1
      IF(R.LT.0.000001)GOTO 580
      USF(I)=R*RI/(RI-1.)
      GOTO 600
  580 USF(I)=1./I
  600 CONTINUE
      IF(IOPT1.EQ.0)GOTO 700
      WRITE(6,9640)(PWF(I),I=1,NYR)
      WRITE(6,9650)(USF(I),I=1,NYR)
 9640 FORMAT(1H ,3HPWF,F7.4)
 9650 FORMAT(1H ,3HUSF,F7.4)
  700 DO 880 M=1,NI
      NSIM=NSI(M)
      WRITE(6,9660)NSIM
 9660 FORMAT(1H ,18HINTERVAL IN YEARS=,I3)
      DO 740 K=1,NS
      PWDAM=0.
      PWRLT=0.
      PWCIRE=0.
      PWOMAR=0.
      PWDAM=PWDAM+DAM(I,K)*PWF(I)
      PWCIRE=PWCIRE+CIRE(I,K)*PWF(I)
      PWOMAR=PWOMAR+OMAR(I,K)*PWF(I)
      PWRLT=PWRLT+RLT(I,K)*PWF(I)
  720 CONTINUE
      YPWT(K)=PWDAM
      YPWC(K)=PWCIRE
      YPWO(K)=PWOMAR
      YPWR(K)=PWRLT
      XUST(K)=PWDAM*USF(NSIM)
      XUSC(K)=PWCIRE*USF(NSIM)
      XUSO(K)=PWOMAR*USF(NSIM)
      XUSR(K)=PWRLT*USF(NSIM)
  740 CONTINUE
      WRITE(6,9524)
      WRITE(6,9553)(XUSC(K),K=1,NS)
      IF(ISGLE.EQ.1)GOTO 742
      CALL HISTAT(XUSC,NS,STEP,-NG,XMIN,XMAX,FX,XMN,XSD,XSK,XKURT)
      WRITE(6,9506)XMN,XSD,XSK,XKURT
  742 WRITE(6,9525)
      WRITE(6,9553)(XUSO(K),K=1,NS)
      CALL HISTAT(XUSO,NS,STEP,-NG,XMIN,XMAX,FX,XMN,XSD,XSK,XKURT)
      WRITE(6,9506)XMN,XSD,XSK,XKURT
  744 WRITE(6,9528)
      WRITE(6,9553)(XUSR(K),K=1,NS)
      IF(ISGLE.EQ.1)GOTO 745
      CALL HISTAT(XUSR,NS,STEP,-NG,XMIN,XMAX,FX,XMN,XSD,XSK,XKURT)
      WRITE(6,9506)XMN,XSD,XSK,XKURT
  745 WRITE(6,9526)
      WRITE(6,9553)(XUST(K),K=1,NS)
      IF(ISGLE.EQ.1)GOTO 762
      CALL HISTAT(XUST,NS,STEP,NG,XMIN,XMAX,FX,XMN,XSD,XSK,XKURT)
      WRITE(6,9510)(TITLE1(I),I=1,20)
      DO 750 K=1,NS
      XB(K,M)=XUST(K)
  750 CONTINUE
      DO 760 K=1,NG
      UNFS(K,M)=FX(K)
      WRITE(6,9505)NSI(M),(FX(K),K=1,NG)
      WRITE(6,9506)XMN,XSD,XSK,XKURT
```

```
  762 WRITE(6,9524)
      WRITE(6,9554)(YPWC(K),K=1,NS)
      IF(ISGLE.EQ.1)GOTO 764
      WRITE(6,9506)YMN,YSD,YSK,YKURT
  764 WRITE(6,9525)
      WRITE(6,9554)(YPWO(K),K=1,NS)
      CALL HISTAT(YPWO,NS,YSTEP,-NG,YMIN,YMAX,FX,YMN,YSD,YSK,YKURT)
      WRITE(6,9506)YMN,YSD,YSK,YKURT
  765 WRITE(6,9528)
      WRITE(6,9554)(YPWR(K),K=1,NS)
      IF(ISGLE.EQ.1)GOTO 767
      CALL HISTAT(YPWR,NS,YSTEP,-NG,YMIN,YMAX,FX,YMN,YSD,YSK,YKURT)
  767 WRITE(6,9526)
      WRITE(6,9554)(YPWT(K),K=1,NS)
      IF(ISGLE.EQ.1)GOTO 880
      CALL HISTAT(YPWT,NS,YSTEP,NG,YMIN,YMAX,FX,YMN,YSD,YSK,YKURT)
      WRITE(6,9510)(TITLE2(I),I=1,20)
      DO 770 K=1,NS
      Y1P(K,M)=YPWT(K)
  770 CONTINUE
      DO 780 K=1,NG
      PW(K,M)=FX(K)
  780 CONTINUE
      WRITE(6,9505)NSI(M),(FX(K),K=1,NG)
      WRITE(6,9506)YMN,YSD,YSK,YKURT
  880 CONTINUE
      IF(ISGLE.EQ.1)STOP
      XUMID=XMIN+STEP/2.
      XPMID=YMIN+YSTEP/2.
      DO 900 I=1,NG
      XU(I)=XUMID
      XUMID=XUMID+STEP
      XP(I)=XPMID
      XPMID=XPMID+YSTEP
  900 CONTINUE
      CALL USPLX(XU,UNFS,NG,NI,1,100,A,IMAG4,IER)
      IF(IER.NE.0)WRITE(6,9520)IER
      CALL USPLX(XP,PW,NG,NI,1,100,B,IMAG4,IER)
      IF(IER.NE.0)WRITE(6,9520)IER
      CALL USPLX(XPP,XB,NS,NI,1,100,C,IMAG4,IER)
      IF(IER.NE.0)WRITE(6,9520)IER
      CALL USPLX(XPP,Y1P,NS,NI,1,100,F,IMAG4,IER)
      IF(IER.NE.0)WRITE(6,9520)IER
      DO 960 K=1,NS
      DO 950 M=1,NI
      XB(K,M)=ALOG10(XB(K,M))
      Y1P(K,M)=ALOG10(Y1P(K,M))
  950 CONTINUE
  960 CONTINUE
      CALL USPLX(XPP,XB,NS,NI,1,100,C,IMAG4,IER)
      IF(IER.NE.0)WRITE(6,9520)IER
      CALL USPLX(XPP,Y1P,NS,NI,1,100,F,IMAG4,IER)
      IF(IER.NE.0)WRITE(6,9520)IER
      GOTO 1000
  970 SIA=SIA/NYR
      SOA=SOA/NYR
      SSA=SSA/NYR
      SIC=SIC/NYR
      SOC=SOC/NYR
      SSC=SSC/NYR
      SST=SSA+SSC
      SIT=SIA+SIC
      SOT=SOA+SOC
      ST=SST+SIT+SOT
      WRITE(6,9527)SSA,SSC,SST,SIA,SIC,SIT,SOA,SOC,SOT,ST
 1000 STOP
      END
```

```
@FOR,ISB GSL*PROG20.SR89,GSL*PROG20.SR89
      SUBROUTINE OMR(L,IS,OMRE)
      COMMON/COM1/DRM1(25,30),DCI1(25,30),IE(30),NP,DRLS1(25,30),DRLL1(2
     .5,30),IUCS(25),AREA1(10),DASUM(10),SCALE,IWO(25),REIN(25),DRLI1(25
     .,30)
      IF(L.NE.20)GOTO 40
      IF(IS.NE.4193)GOTO 40
      DRM1(20,4)=15000.
      DRM1(20,5)=15000.
 40   DO 50 J=1,NP
      IF(IS.GE.IE(J))GOTO 50
      JJ=J-1
      IF(JJ.EQ.0)JJ=1
      GOTO 60
 50   CONTINUE
      WRITE(6,9500)IS,IE(NP)
 9500 FORMAT(1H0,2I10,29HATTEMPT TO EXCEED TABLE RANGE)
      STOP
 60   OMRE=DRM1(L,JJ)
      RETURN
      END
@FOR,ISB GSL*PROG20.SR90,GSL*PROG20.SR90
      SUBROUTINE CI(L,IS,CIE)
      COMMON/COM1/DRM1(25,30),DCI1(25,30),IE(30),NP,DRLS1(25,30),DRLL1(2
     .5,30),IUCS(25),AREA1(10),DASUM(10),SCALE,IWO(25),REIN(25),DRLI1(25
     .,30)
      DO 50 J=1,NP
      IF(IS.NE.IE(J))GOTO 50
      JJ=J
      GOTO 60
 50   CONTINUE
      CIE=0.
      GOTO 100
 60   CIE=DCI1(L,JJ)
      DCI1(L,JJ)=0.
 100  RETURN
      END
@FOR,ISB GSL*PROG20.SR91,GSL*PROG20.SR91
      SUBROUTINE RL(L,IS,RLSE,RLLE,RLIE)
      COMMON/COM1/DRM1(25,30),DCI1(25,30),IE(30),NP,DRLS1(25,30),DRLL1(2
     .5,30),IUCS(25),AREA1(10),DASUM(10),SCALE,IWO(25),REIN(25),DRLI1(25
     .,30)
      IF(IWO(L).EQ.0)GOTO 40
C *** WHEN ENTITY WIPED OUT
 80   IUCSL=IUCS(L)
      DO 30 J=1,NP
      IF(IUCSL.NE.IE(J))GOTO 30
      JJ=J
      GOTO 60
 30   CONTINUE
C *** WHEN ENTITY NOT WIPED OUT
 40    DO 50 J=1,NP
      IF(IS.EQ.IE(NP))GOTO 55
      IF(IS.GE.IE(J))GOTO 50
      JJ=J-1
      IF(JJ.EQ.0)JJ=1
      GOTO 60
 50   CONTINUE
 52   WRITE(6,9500)IS,IE(NP)
 9500 FORMAT(1H0,2I10,29HATTEMPT TO EXCEED TABLE RANGE)
      STOP
 55   JJ=NP
 60   CONTINUE
C *** RLSE=DRLS1(L,JJ)
C     RLLE=DRLL1(L,JJ)
      RLIE=DRLI1(L,JJ)
      RETURN
      END
@FOR,ISB GSL*PROG20.SR93,GSL*PROG20.SR93
      SUBROUTINE SALT(L,T1,T2,SCI,SRM)
      COMMON/COM1/DRM1(25,30),DCI1(25,30),IE(30),NP,DRLS1(25,30),DRLL1(2
     .5,30),IUCS(25),AREA1(10),DASUM(10),SCALE,IWO(25),REIN(25),DRLI1(25
     .,30)
      IF(T1.LT.T2)GOTO 200
      DA=AREA1(L)*(T1/T2-1.)
      AREA1(L)=AREA1(L)+DA
      DASUM(L)=DASUM(L)+DA
      SCI=DA*200./SCALE
      SRM=DASUM(L)*10./SCALE
      RETURN
 200  SRM=DASUM(L)*10./SCALE
      SCI=0.
      RETURN
      END
```

Table F-2a. Input data and decision parameters for Continuous Simulation Model of the Great Salt Lake.

I. Graph subroutine inputs

1. (A(I), I=1,72) - Format (72A1)

1-72	A(I)	Title of graph Uniform series histogram

2. (A(I), I=73,108) - Format (36A1)

1-36	A(I)	X-axis, damages in dollars

3. (A(I), I=109,144) - Format (36A1)

1-36	A(I)	Y-axis, relative frequency

4. (A(I), I=145,148) - Format (4F20.0)

1-20	A(1)	X-axis minimum if zero automatically computer range
21-40	A(2)	X-axis maximum if zero automatically computer range
41-60	A(3)	Y-axis mininum = 0
61-80	A(4)	Y-axis maximum = 1

5. (A(I), I=149,158) - Format (10A1)

1-10	A(I)	Up to 10 different plot symbols

Repeat above sequence of cards for graph arrays, B, C, F

6-10	B = Present worth histograms
11-15	C = Cumulative frequency distribution of uniform series damages
16-20	F = Cumulative frequency distribution of present worth damages

II. Main program parameters

1. IYR1, IYR2, ICWΘ, NPSG, NPT, IW, NYRIN, ISALT, IUCSB, ISGLE, IWRD, IΘPT1, IΘPT2 - Format (13I5)

1-5	IYR1	First year of time series
6-10	IRY2	Last year of time series
11-15	ICWT	Causeway opening 1 = present opening, 2 = 100 ft, 3 = 300 feet, 4 = 600 ft
16-20	NPSG	Number of points in salt table, = 8
21-25	NPT	Number of points in TSGT Table = 10
26-30	IW	If = 1, debugging write statement, if = 0, does not write out input damage tables
31-35	NYRIN	Number of years after a wipeout that stage must remain down before reinstatement of entity
36-40	ISALT	If = 1, computer damages due to decrease of salinity, must set = 0 to skip
41-45	IUCSB	Number of feet below wipeout stage that the lake level must remain below before reinstatement of the entity i.e., 3'
46-50	ISGLE	If = 1, does not compute nor plot HISTOGRAMs, also reads in only one time series
51-55	IWRD	If = 1, uses Water Resource Division of Utah damages, if = 0, skips
56-60	IΘPT1	If = 0, does not write out discount factors, nor individual damages - for debugging

61-65	IØPT2	If = 1, writes out wipeout damages	

2. NP, NS10, NI, R, SCALE - Format (3I5,2F10.0)

1-5	NP	Number of points in table of lake stages and damages
6-10	NS10	Number of stage files with 10 sets of time series of length N4R each
11-15	NI	Number of intervals time series are segmented into
16-25	R	Discount rate
26-35	SCALE	Use 1

3. NRR, NHW, NSC, NRC, NBR, NR1, NPA, NIND - Format (8I5)

1-5	NRR	Number of railroads around the lake considered for damages	4
6-10	NHW	Number of highways considered for damage	3
11-15	NSC	Number of mineral and salt companies considered	6
16-20	NRC	Number of recreational areas	4
21-25	NBR	Number of bird refuges	2
26-30	NR1	File number for damage file input	30
31-35	NPA	Number of points in APNTE/APNT tables	10
36-40	NIND	#Industry, not mining lakes	1

4. (NSI(M), M=1, NI) - Format (10I5)

1-5	NSI(M)	Interval length of period i.e. (10, 25, 50, 75, 100, 125 years) limit 10
etc.		

5. (NR(K), K=1,NS10) - Format 10I5)

1-5	NR(K)	File number from which the lake stage traces are read each file has 10 separate traces of NYR years each

6. NG, IND, XND, NSTEP, XMIN, XMAX, YMIN, YMAX, NYSTEP - Format (2I5, F10.0, I10, 4F10.0, I10)

1-5	NG	Number of groups in histogram (100)
6-10	IND	Parameter for subroutine KVRSK (Skewness, kurtosis, statistics) if = 1, then skewness and kurtosis are estimated by moments; if = 2, then skew and kurtosis are estimated by Fisber's K statistic
11-20	XND	Parameter in subroutine STDEV if = 1.0, then maximum likelihood estimate is used for computation of statistics; if = -1.0, then an unbiased estimate is performed (use -1.0)
21-30	NSTEP	Interval in histogram subroutine i.e. (100,000) for uniform series
31-40	XMIN	First interval i.e. (50,000) for uniform series histogram
41-50	XMAX	Last interval i.e. (1,950,000) for uniform series histogram
51-60	YMIN	First interval i.e. (2,500,000) for present worth histogram
61-70	YMAX	Last interval i.e. (9,750,000) for present worth histogram
71-80	NYSTEP	Length of interval in present worth histogram

7. (TITLE1(I), I=1,20) - Format (13A6)

1-6	TITLE1(I)	Title heading for uniform series histogram

8. (TITLE2(I), I=1,20) - Format (13A6)

1-6	TITLE2(I)	Title heading for present worth histograms

9. (IVSC(L), L=1, NTE) - Format (8I10)

1-10	IVSC(L)	Critical stage upon which an entity wipeout occurs, one stage for each entity = NTE (in feet)

10. (REIN(L), L=1,NTE) - Format (8F10.0)

1-10	REIN(L)	Reinstatement damages incurred after wipeout of an entity (in thousands of dollars)

11. (NSSTAG(L), L=1,NTE) - Format (16I5)

1-5	NSSTAG(L)	Indicator of whether the entity is located in the north or south arm of the lake if = 1, then south arm; if = 0, then north

12. (NSSALT(L), L=1,NSC) - Format (16I5)

1-5	NSSALT(L)	Indicator of whether salt company is located in north or south arm of lake

13. (AREA(L), L=1,NSC) - Format (8F10.0)

1-10	AREA(L)	

Table F-2b. Damage input.

PVML DCI 1							
PVML DCI 2							
PVML DCI 3	0	0	0	40			
PVML DCI 5							
PVML DRM 1							
PVML DRM 2							
PVML DRM 3							
PVML DRM 4							
PVML DRM 5							
PVML DRLS1							
PVML DRLS2							
PVML DRLS3							
PVML DRLS4							
PVML DRLS5							
PVML DRLL1							
PVML DRLL2							
PVML DRLL3							
PVML DRLL4							
PVML DRLL5							
PVML DRLI1	0	0	0	0	0	0	0
PVML DRLI2	0	14	28	42	56	70	84
PVML DRLI4	196	210	224	238	252	252	252
PVML DRLI5	252						

Table F-2b. Continued.

```
UNIFORM SERIES HISTOGRAMS - CONTINUOUS DAMAGE SIMULATION MODEL OF GSL
DAMAGES IN DOLLARS
RELATIVE FREQUENCY
                                                                    0                  1

1234567890
PRESENT WORTH  HISTOGRAMS - CONTINUOUS DAMAGE SIMULATION MODEL OF GSL
DAMAGES IN DOLLARS
RELATIVE FREQUENCY
                                                                    0                  1

1234567890
CUMULATIVE FREQUENCY DISTRIBUTION OF UNIFORM SERIES DAMAGES
RELATIVE FREQUENCY
DAMAGES IN DOLLARS
                         0                   1
1234567890
CUMULATIVE FREQUENCY DISTRIBUTION OF PRESENT WORTH DAMAGES
RELATIVE FREQUENCY
DAMAGES IN DOLLARS
                         0                   1
1234567890
 1979 2103     1     8    10     0     0     0     3
   29    2     8    .06875            1.
    4    3     6     4     3    30    10     1
    2    5    10    25    50    75   100   125
   25   25    25    25    25    25    25    25    25    25
   24   24    24    24    24    24    24    24    24    24
  100    1          -1.0          20           0  20000000            0 200000000          20
GROUPSX  1     2     3     4     5     6     7     8     9    10    11    12    13    14
15   16    17    18    19    20
GROUPSY1 1     2     3     4     5     6     7     8     9    10    11    12    13    14
15   16    17    18    19    20
    4207        4210        4216        4220        4220        4207        4220        4220
    4220        4220        4220        4208        4220        4208        4211        4213
    4207        4205        4220        4193        4208
   70000        5500        5500           0           0         700           0           0
       0           0           0        5000           0        6800        2200         210
     100         250           0         300         100
    1    1     1     1     1     0     1     1     1     1     1     1     1     1     1     1
    1    1     1     1     1
    0    1     1     1     1     0
   17000.       4800.       1620.      35000.       1100.        300.
    4170        4192        4195        4197        4200        4204        4208        4220
   1.250       1.244       1.240       1.236       1.223       1.195       1.154       1.050
   1.250       1.244       1.237       1.226       1.205       1.168       1.124       1.050
   1.250       1.243       1.229       1.213       1.183       1.145       1.160       1.050
   1.250       1.242       1.226       1.206       1.177       1.136       1.095       1.050
   1.120       1.112       1.110       1.106       1.097       1.083       1.065       1.050
   1.160       1.145       1.140       1.135       1.123       1.101       1.072       1.050
   1.250       1.184       1.165       1.153       1.134       1.109       1.080       1.050
   1.250       1.210       1.186       1.171       1.146       1.118       1.088       1.050
   1.050       1.080       1.110       1.130       1.150       1.170       1.190       1.200
   1.22        1.25
     36.         61.         98.        125.        157.        194.        235.        257.
    319.        420.
    4170        4175        4180        4185        4190        4195        4200        4205
    4212        4220
      40          40          40          40          40          40          40          40
      40          40          4
```

Table F-3. Damage output.

```
1979 2103    1    8    10    0    0    0    3    0    0    0    0
  29    2    8       .07      1.00
   4    3    6    4    3   30   10    1
   2    5   10   25   50   75  100  125
  25   25
  24   24
 100    1      -1.       20        0. 20000000.        0.200000000.       20
GROUPSX  1    2    3    4    5    6    7    8    9   10   11   12   13   14
15   16   17   18   19   20
      4207      4210      4216      4220      4220      4207      4220      4220
      4220      4220      4220      4208      4220      4208      4211      4213
      4207      4205      4220      4193      4208
  70000.00   5500.00   5500.00       .00       .00    700.00       .00       .00
       .00       .00       .00    000.00       .00   5800.00   2200.00    210.00
    100.00    250.00       .00    300.00    100.00
   1    1    1    1    1    0    1    1    1    1    1    1    1    1    1    1
   1    1    1    1    1
   0    1    1    1    1    0
  17000.00   4800.00   1620.00  35 00.00   1100.00    300.00
   4170.00   4192.00   4195.00  4 97.00   4200.00   4204.00   4208.00   4220.00
      1.25      1.24      1.24      1.24      1.22      1.19      1.15      1.05
      1.25      1.24      1.24      1.23      1.20      1.17      1.12      1.05
      1.25      1.24      1.23      1.21      1.18      1.14      1.16      1.05
      1.25      1.24      1.23      1.21      1.16      1.14      1.09      1.05
      1.12      1.11      1.11      1.11      1.10      1.08      1.06      1.05
      1.16      1.14      1.14      1.14      1.12      1.10      1.07      1.05
      1.25      1.18      1.17      1.15      1.13      1.11      1.08      1.05
      1.25      1.21      1.19      1.17      1.15      1.12      1.09      1.05
      1.05      1.08      1.11      1.13      1.15      1.17      1.19      1.20
      1.22      1.25
     36.00     61.00     98.00    125.00    157.00    194.00    235.00    257.00
    319.00    420.00
   4170.00   4175.00   4180.00   4185.00   4190.00   4195.00   4200.00   4205.00
   4212.00   4220.00
     40.00     40.00     40.00     40.00     40.00     40.00     40.00     40.00
     40.00     40.00
INTERVAL IN YEARS=  2

CAPITAL INVESTMENT/REINSTATEMENT
UNIFORM SERIES= .000000000    .000000000    .000000000    .000000000    .000000000    .266057422+06 .113655597+06
UNIFORM SERIES= .000000000    .300412406+07 .000000000    .000000000    .000000000    .000000000    .000000000
UNIFORM SERIES= .000000000    .000000000    .000000000    .000000000    .000000000    .000000000
 .169191852+06 .670266898+06 .000000000    .000000000

OPERATIONS/MAINTENANCE/REPAIR
UNIFORM SERIES= .668230336+06 .786600062+06 .876010203+06 .755603070+06 .786600062+06 .870327422+06 .753472039+06
UNIFORM SERIES= .786600062+06 .101343016+07 .755603070+06 .786600062+06 .786600062+06 .786600062+06 .668230336+06
UNIFORM SERIES= .787668812+06 .701358359+06 .668230336+06 .755603070+06 .755603070+06 .668230336+06
 .770860000+06 .605465537+05 .112604326+01 .193000811+01

REVENUE LOSS
UNIFORM SERIES= .176682793+05 .694687549+05 .414000199+06 .524204150+05 .694687549+05 .391837359+06 .512483423+05
UNIFORM SERIES= .694687549+05 .105822078+07 .524204150+05 .694687549+05 .694687549+05 .694687549+05 .176682793+05
UNIFORM SERIES= .694687549+05 .358886924+05 .176682793+05 .524204150+05 .524204150+05 .176682793+05
 .135891562+06 .237209764+06 .303541684+01 .861053979+01
```

```
TOTAL
UNIFORM SERIES= .685898617+06 .856068812+06 .129001041+07 .808023484+06 .856068812+06 .152822220+07 .918375969+06
UNIFORM SERIES= .856068812+06 .507577500+07 .808023484+06 .856068812+06 .856068812+06 .856068812+06 .685898617+06
UNIFORM SERIES= .857137562+06 .737247055+06 .685898617+06 .808023484+06 .808023484+06 .685898617+06
GROUPSX  1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19   20
    2  .00  .00  .00  .25  .60  .00  .05  .05  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .05  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .107594344+07 .938674203+06 .384868196+01 .134966147+02

CAPITAL INVESTMENT/REINSTATEMENT
PRESENT WORTH= .000000000    .000000000    .000000000    .000000000    .000000000    .481871344+06 .205847951+06
PRESENT WORTH= .000000000    .544093562+07 .000000000    .000000000    .000000000    .000000000    .000000000
PRESENT WORTH= .000000000    .000000000    .000000000    .000000000    .000000000    .000000000
 .306432742+06 .118322294+07 .000000000    .000000000

OPERATIONS/MAINTENANCE/REPAIR
PRESENT WORTH= .121026900+07 .142465497+07 .158659064+07 .136851461+07 .142465497+07 .157629823+07 .136465497+07
PRESENT WORTH= .142465497+07 .183547953+07 .136851461+07 .142465497+07 .142465497+07 .142465497+07 .121026900+07
PRESENT WORTH= .142659064+07 .127026900+07 .121026900+07 .136851461+07 .136851461+07 .121026900+07
 .139614730+07 .145882326+06 .112604274+01 .193000704+01

REVENUE LOSS
PRESENT WORTH= .320000000+05 .125818713+06 .749818711+06 .949415195+05 .125818713+06 .709678359+06 .928187129+05
PRESENT WORTH= .125818713+06 .191660233+07 .949415195+05 .125818713+06 .125818713+06 .125818713+06 .320000000+05
PRESENT WORTH= .125818713+06 .650000000+05 .320000000+05 .949415195+05 .949415195+05 .320000000+05
 .246120746+06 .429623766+06 .303541705+01 .861054015+01

TOTAL
PRESENT WORTH= .124226900+07 .155047367+07 .233640934+07 .146345612+07 .155047367+07 .276784794+07 .166332162+07
PRESENT WORTH= .155047367+07 .919301750+07 .146345612+07 .155047367+07 .155047367+07 .155047367+07 .124226900+07
PRESENT WORTH= .155240934+07 .133526900+07 .124226900+07 .146345612+07 .146345612+07 .124226900+07
GROUPSY1 1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19   20
    2  .85  .10  .00  .00  .05  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
      .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00
 .194870080+07 .170008489+07 .384868208+01 .134966154+02
```

Table F-4. Damage Simulation Model.

Variable	I Input B Body O Output	Real Integer Type	Dimension	Definition
A	I	R	158	Plotting array for uniform series damages
APN	B	R	1	Proportion of north lake stage from linear interpolation
APNT	I	R	10	Proportion of north lake stage corresponding to APNTE
APNTE	I	R	10	Lake stage table
AREA	I	R	10	Area of each mineral salt company's holding pond
AREA1	B	R	10	Same as AREA
B	I	R	158	Plotting array for present worth damages
C	I	R	158	Plotting array for cumulative frequency distribution of uniform series
CC1		R	4	The four causeway opening coefficients
CC2		R	4	The four causeway opening intercepts
CIE1	B	R	1	Capital investment damages
CIRE	O	R	150,100	Capital investment damages
C1	B	R	1	Causeway opening coefficient for linear function
C2	B	R	1	Causeway opening intercept for linear function
D	I	R	1	Title of entity in damage file
DAM	O	R	150,100	Total damages
DASUM*	B	R	10	Total area added to evaporation ponds to maintain production levels
DCF	B	R	1	Slope of linear function in north-south stage function
DCI	I	R	20,30	Capital investment damages
DCI1	B	R	20,30	Same as above, DCI
DH	B	R	1	The difference in lake stage between north-south arm
DOIC		R	1	Table of other capital damages by WRD algorithm
DRLI	I	R	20,30	Revenue loss to the industry
DRLI1	B	R	20,30	Same as above, DRLI
DRLL	I	R	20,30	Revenue loss to the local government
DRLL1	B	R	20,30	Same as above, DRLL
DRLS	I	R	20,30	Revenue loss to the state government
DRLS1	B	R	20,30	Same as above, DRLS
DRM	I	R	20,30	Operations, repair and maintenance damages
DRM1	B	R	20,30	Same as above, DRM
DS	B	R	1	Difference between two succeeding stages
DSIC	I	R	1	Initial difference between two succeeding stages
DWIA	I	R	10	Annual damages to industry estimated by WRD algorithm
DWIC	I	R	10	Capital damages to industry estimated by WRD algorithm
DWOA	I	R	10	Annual damages to other entities estimated by WRD algorithm
DWOC	I	R	10	Capital damages to other entities estimated by WRD algorithm
DWSA	I	R	10	Annual damages to State of Utah estimated by WRD algorithm
DWSC	I	R	10	Capital damages to State of Utah estimated by WRD algorithm
E	I	R	1	Title of type damage in damage file
F	I	R	158	Plotting array for cumulative frequency distribution present worth
FIN	B	R	1	North lake stage
FIS	B	R	1	South lake stage
FX	O	R	100	Frequency output from Histogram Subroutine
ICWO	I	I	1	Causeway opening
IDIS	B	I	1	Difference in stages in feet
IDIS1	B	I	1	Difference in stage less one foot
IE	I	I	30	Lake stage table
IER	O	I	1	Error message option for Plot Subroutine
IMAG4	O	I	5151	Working space for Plot Subroutine
IN	B	I	1	North lake stage
IND	I	I	1	Skewness, Kurtosis option
INP	B	I	1	Present year north lake stage
IOPT1	I	I	1	Option to write out discount factors, damages
IOPT2	I	I	1	Option to write out wipeout damages
IS	B	I	1	South lake stage
ISALT	I	I	1	Index for salinity damages

Table F-4. Continued.

Variable	I Input B Body O Output	Real Integer Type	Dimension	Definition
ISGLE	I	I	1	Option to do only simulation
ISI	B	I	1	Incremental stage in feet when difference in stage
ISP	B	I	1	Present year south lake stage
ISP1	B	I	1	Present year lake stage
IS1	B	I	1	South lake stage
IUCS	I	I	20	Wipeout stage for each entity in analysis
IUCSB	I	I	1	Number of feet stage must be below wipeout before re-instatement
IW	I	I	1	Option for debugging write statements
IWO	B	I	20	Wipeout of entity indicator
IWRD	I	I	1	Option to use Utah Water Resources Division damages
IYR1	I	I	1	First year in simulation
IYR2	I	I	1	Last year in simulation
NBR	I	I	1	Number of bird refuges in analysis
NG	I	I	1	Number of groups for histogram
NHW	I	I	1	Number of highways in analysis
NI	I	I	1	Number of interval time periods to run analysis on
NIND	I	I	1	Number of non-lake mining industries in analysis
NP	I	I	1	Number of points in damage-stage table
NPA	I	I	1	Number of points in APNTE and APNT table
NPSG	I	I	1	Number of values in salt table
NPT	I	I	1	Number of values in TSGT table
NR	I	I	10	Lake stage file
NRC	I	I	1	Number of recreational areas in analysis
NRR	I	I	1	Number of railroads in analysis
NR1	I	I	1	Damage file
NS	B	I	1	Number of lake stage sequences read in
NSC	I	I	1	Number of mineral and salt companies in analysis
NSEQ	B	I	1	Number of sequences of lake stage files to read in sets of 10
NSI	I	I	150	Interval length of time for each analysis
NSIM	B	I	1	Same as NSI
NSSALT	I	I	20	Indicator of salt-mineral entity location - north-south
NSSTAG	I	I	20	Indicator of entity location in south-north lake
NSTEP	I	I	1	Interval size in histogram for uniform series
NS10	I	I	1	Number of simulations to run in sets of 10
NTE	B	I	1	Number of entities around the lake
NYR	B	I	1	Number of years in stage file sequence
NYRIN	I	I	1	Number of years after a wipeout before reinstatement
NYSTEP	I	I	1	Present worth histogram interval size
OMAR	O	R	150,100	Operation, repair and maintenance damages
OMRE1	B	R	1	Same as OMAR
PW	O	R	100,10	Frequency for present worth histogram
PWCIRE	B	R	1	Present worth of capital investment damages
PWDAM	B	R	1	Present worth of total damages
PWF	B	R	150	Present worth factor
PWOMAR	B	R	1	Present worth of operations, repair, and maintenance damages
PWRLT	B	R	1	Present worth of revenue loss
R	I	R	1	Discount rate
REIN	I	R	20	Reinstatement damages for each entity
RI	B	R	1	One plus discount factor
RLIE1	B	R	1	Revenue loss to industry
RLLE1	B	R	1	Revenue loss to local
RLSE1	B	R	1	Revenue loss to state
RLT	O	R	150,100	Revenue loss damages
R1	B	R	1	One plus discount factor
S	B	R	1	Lake stage for a particular year
SCALE	I	R	1	Scale factor = 1
SCI*	B	R	1	Capital investments by industry to increase pond area by DA
SGN	B	R	1	Specific gravity in north arm in current year
SGN1	B	R	1	Specific gravity in north arm in previous high year

Table F-4. Continued.

Variable	I Input B Body O Output	Real Integer Type	Dimension	Definition
SGS	B	R	1	Specific gravity in south arm in current year
SGSI	B	R	1	Specific gravity in south arm in previous high year
SIA	B	R	1	Cumulated annual industrial damages from WRD algorithm
SIA1	B	R	1	Current year's annual industrial damages from WRD algorithm
SIC	B	R	1	Cumulated capital industrial damages from WRD algorithm
SIC1	B	R	1	Current year's capital industrial damages from WRD algorithm
SIC1P	B	R	1	Previous year's capital industrial damages from WRD algorithm
SIT	B	R	1	Total cumulated industrial damages from WRD algorithm
SN	B	R	1	North arm stage
SOA	B	R	1	Cumulated annual other damages from WRD algorithm
SOA1	B	R	1	Current year's annual other damages from WRD algorithm
SOC	B	R	1	Cumulated capital other damages from WRD algorithm
SOC1	B	R	1	Current year's capital other damages from WRD algorithm
SOC1P	B	R	1	Previous year's capital other damages from WRD algorithm
SOT	O	R	1	Total cumulated other damages from WRD algorithm
SRM*	B	R	1	Repair and maintenance
SSA	B	R	1	Cumulated annual state damages from WRD algorithm
SSA1	B	R	1	Current year's annual state damages from WRD algorithm
SSC	B	R	1	Cumulated capital state damages from WRD algorithm
SSC1	B	R	1	Current year's capital state damages from WRD algorithm
SSC1P	B	R	1	Previous year's capital state damages from WRD algorithm
SST	O	R	1	Total cumulated state damages from WRD algorithm
ST	O	R	1	Total damages from WRD algorithm
STEP	B	R	1	Interval size in histogram for uniform series
S1	B	R	1	Present year's stage
TITLE1	I	R	20	Uniform series histogram frequency heading
TITLE2	I	R	20	Present worth histogram frequency heading
TN	B	R	1	Specific gravity of north arm
TNI	B	R	1	Initial specific gravity of north arm
TS	B	R	1	Specific gravity of south arm
TSGE	I	R	10	Specific gravity vs. evaporation table
TSGN	I	R	10,4	Specific gravity of evaporation ponds in north arm
TSGN1	B	R	10	Specific gravity of evaporation ponds in north arm
TSGS	I	R	10,4	Specific gravity of evaporation ponds in south arm
TSGS1	B	R	10	Specific gravity of evaporation ponds in south arm
TSGT	I	R	10	Tons of salt vs. specific gravity table
TSI	B	R	1	Initial specific gravity of south arm
TT	I	R	10	Tons of salt per acre from evaporation ponds corresponding to TSGT
TWE	I	R	10	Lake stages for tables of lake damages in WRD algorithm
T1	B	R	1	Tons of salt per acre from evaporation ponds at previous high stage
T2	B	R	1	Tons of salt per acre from evaporation ponds at new high stage
UNFS	O	R	100,10	Frequency for uniform series histogram
USF	B	R	150	Uniform series factor
XB	O	R	100,10	Uniform series total damages frequency
XKURT	O	R	1	Kurtosis of uniform series damages
XMAX	I	R	1	Uniform series histogram final interval
XMIN	I	R	1	Uniform series histogram initial interval
XMN	O	R	1	Mean of uniform series damages
XND	I	R	1	Statistic estimation option
XP	O	R	100	Present worth frequency
XPMID	B	R	1	Midpoint of beginning interval for present worth frequency
XPP	B	R	100	Frequency of each stage or year
XSD	O	R	1	Standard deviation of uniform series damages
XSK	O	R	1	Skew of uniform series damages
XU	O	R	100	Uniform series frequency

Table F-4. Continued.

Variable	I Input B Body O Output	Real Integer Type	Dimension	Definition
XUMID	B	R	1	Midpoint of beginning interval for uniform series frequency
XUSC	B	R	100	Uniform series of capital investment damages
XUSO	B	R	100	Uniform series of operations, repair and maintenance damages
XUSR	B	R	100	Uniform series of revenue loss
XUST	B	R	100	Uniform series of total damages
Y	B	R	150,100	Lake stage per year per trace
YKURT	O	R	1	Kurtosis of present worth damages
YMAX	I	R	1	Present worth histogram final interval
YMIN	I	R	1	Present worth histogram initial interval
YMN	O	R	1	Mean of present worth damages
YPWC	B	R	100	Present worth of capital investment damages
YPWO	B	R	100	Present worth of operations, repair and maintenance damages
YPWR	B	R	100	Present worth of revenue loss
YPWT	B	R	100	Present worth of total damages
YSD	O	R	1	Standard deviation of present worth damages
YSK	O	R	1	Skew of present worth damages
YSTEP	B	R	1	Interval size in histogram for present worth
YY	B	R	150,100	Lake stages for a particular year
Y1P	O	R	100,10	Present worth total damages frequency

*This variable is part of a procedure for estimating costs of expanding evaporation pond area to maintain mineral production during periods of rising lake levels. The procedure was used on a trial basis and is not part of the final damage algorithm which considers only flooding-related damages.