January 1985

Methodology Report: Updating the Estimation of Water Surface Elevation Probabilities and Associated Damages for Great Salt Lake

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L. D. James

METHODOLOGY REPORT

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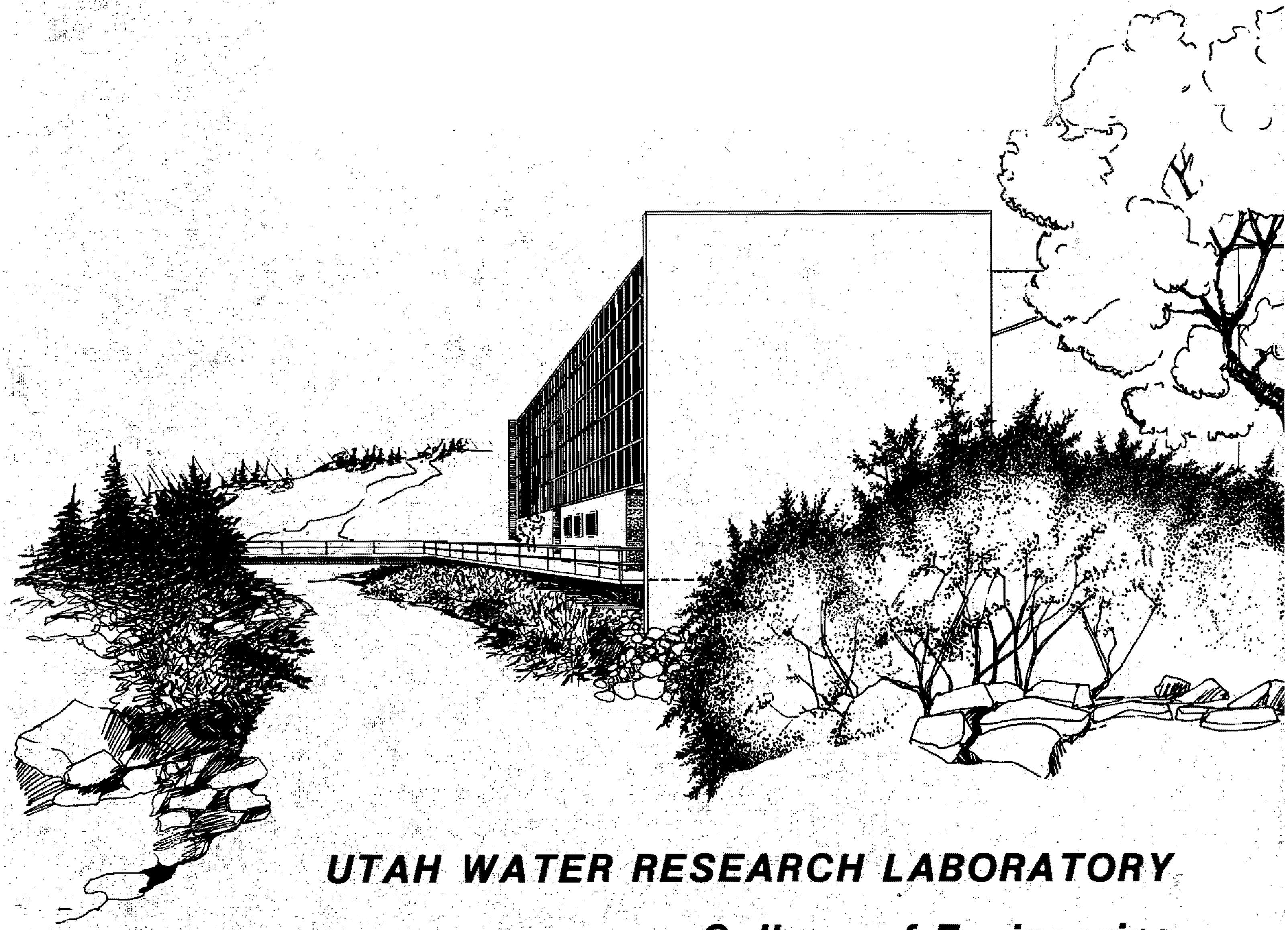

UTAH WATER RESEARCH LABORATORY

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Logan, Utah

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METHODOLOGY REPORT

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

by

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June 1985

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CHAPTER 1

INTRODUCTION

Problem Statement

Rising levels of the Great Salt Lake are severely impacting private and public property. In the private sector, the mineral industry, several railroads, and a number of recreation enterprises are suffering major damages. Other land uses are being seriously threatened. In the public sector, the State of Utah is experiencing large losses inflicted on roads and highways, waterfowl and related wildlife areas, and park and recreation facilities.

The lake is partitioned by a semipervious railroad causeway into a north and a south arm with the south arm having about twice the water surface area and usually being two or four feet higher because it receives nearly all the surface runoff from tributary rivers (see Figure 1-1). However, in the summer of 1984, a 300-ft long breach was constructed in the causeway in order to reduce this difference and thereby lower south arm stages.

In the last three years, the largest rainfall years of record (exceeded only by an approximation made for 1866), record inflows, and record low evaporation rates have brought the largest historical rise in the lake water surface. Over this period, the south arm lake level rose to 4200.25 (June 1981), dropped to 4198.20 (October 1981), rose to 4200.85 (June 1982), dropped to 4199.80 (September 1982), and then rose to 4205.00 (July 1983)*. The south arm level dropped to about 4204.6, on

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*Lake level measurements in 1981-3 have been adjusted downward by the USGS by up to 0.25 feet because of settlement of the gage.

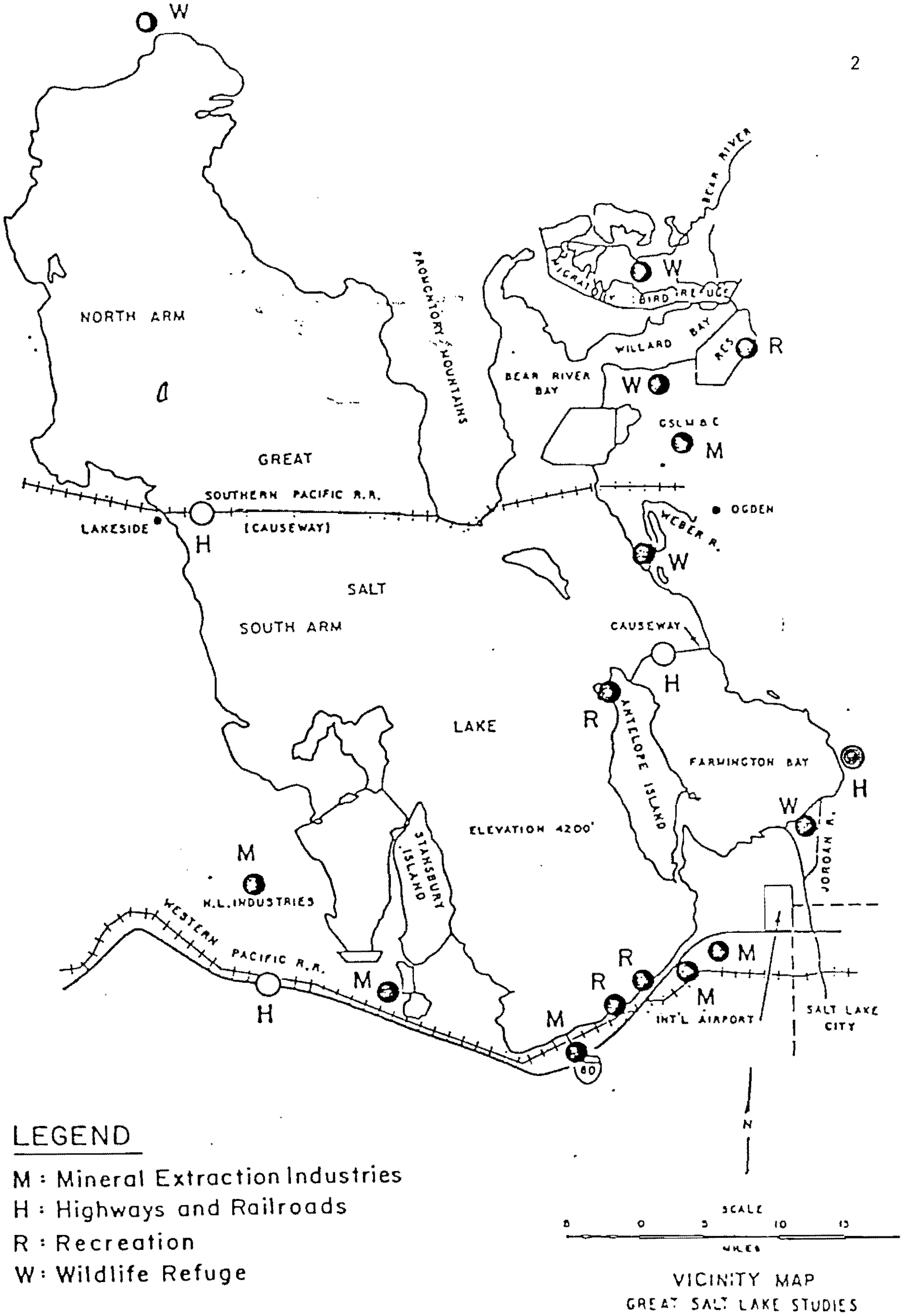

Figure 1-1. Site map showing damage centers near the Great Salt Lake.

August 15, and peaked in the summer of 1984 at an elevation of 4209.25. The lake level was the highest since 1878 when the lake was retreating from a high of 4211.6 in 1873. The gaged streamflow of 5.3 million acre feet (maf) during the water year ending September 1983, was the largest of record, surpassing estimated and more approximate values of 4.5 maf for 1872 and of 4.1 maf for 1909. The rise of 5.2 feet in 1983 surpassed the previously highest values of 3.4 feet in 1862 and 1907. In 1983, precipitation was 68 percent above normal, and evaporation was only 86 percent of normal.

Objective planning of a strategy for dealing with this problem requires defining technically workable control methods, estimating their effects on probable lake levels, translating effects on levels to effects on damages, and comparing the benefits of the damage reduction achieved with costs. A methodological framework for this type of planning was developed and tested by James et al. (1979). It comprised a lake water balance model for calculating lake levels from lake inflows, a multivariate stochastic model for generating lake inflows which resemble, statistically, historical inflow sequences, and a continuous simulation model for estimating damages and damage reductions or benefits associated with lake level control alternatives (breaching the causeway, pumping into the western desert, and constructing reservoirs for irrigation development in the tributary basin) (see Figure 1-2) based on generated lake level sequences. In a follow-up report James et al. (1981) reevaluated the selection of the stochastic model. However, both studies used only the more reliable period of historical data collected since 1937. This period of data does not include a period of unusually high

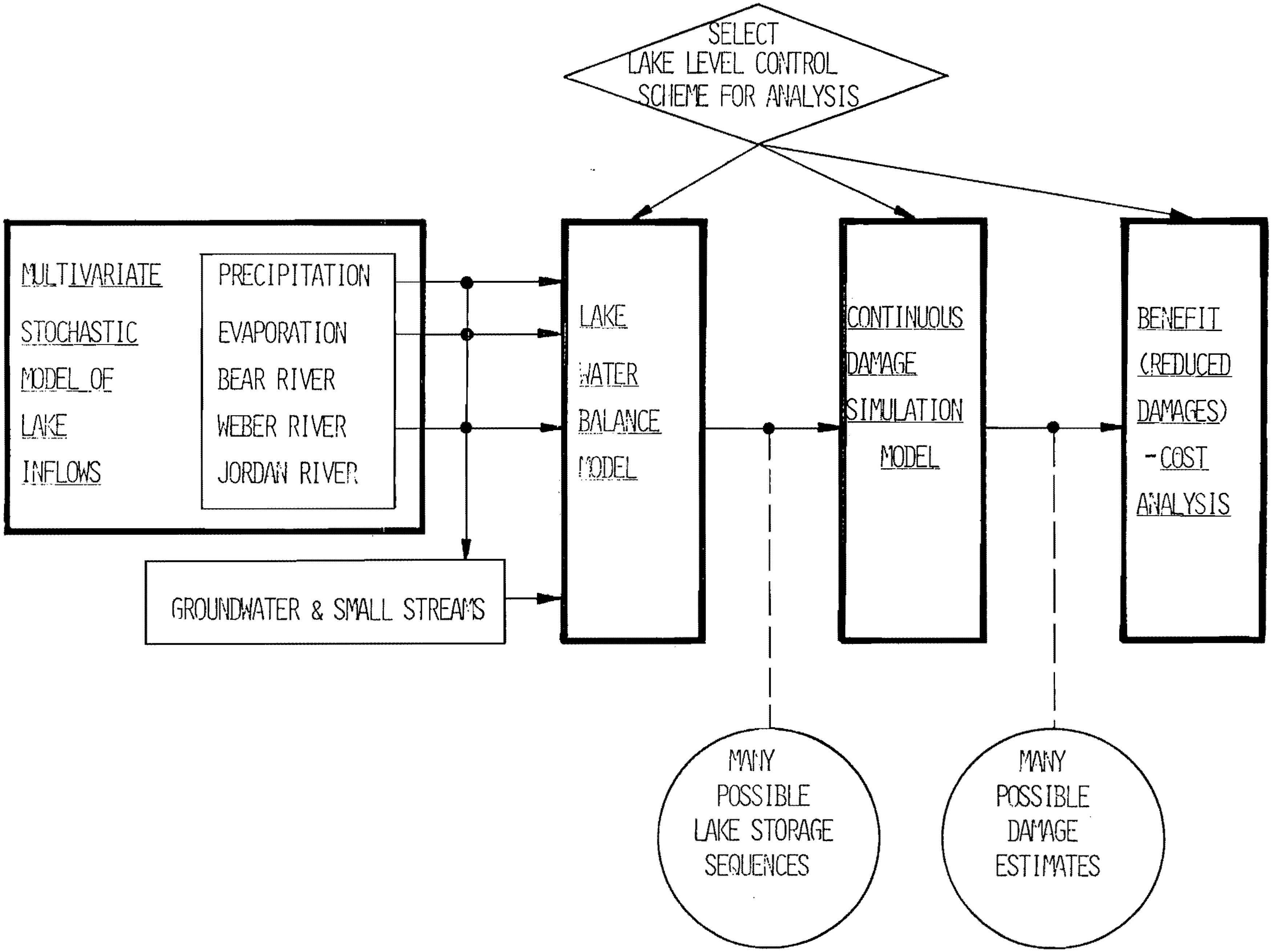

Figure 1-2. Outline of the use of the models to assess the alternative for lake level control.

inflows in the late 1800s and therefore generated sequences did not reproduce such a rare event, thus leading to an underestimation of lake level probabilities.

Objectives

In 1983, the Utah Division of Water Resources (hereafter referred to as the Division) requested the Utah Water Research Laboratory to conduct a new study with the following objectives:

1. To refine and update the climatologic and hydrologic data base and the model developed and used in the previous work for estimating water surface elevation probabilities for the Great Salt Lake.

2. To cooperate with the study underway at the Bureau of Business and Economic Research, University of Utah, in refining and updating the economic data base used to estimate damages in order to have the information needed for integration with the hydrologic models.

3. To incorporate the refined hydrologic and economic data into a model that can be used to estimate the damages associated with various lake level management alternatives.

4. To work with Division staff in the modeling and analyses so that the Division will be able to employ the model as needed in the future.

In particular, the hydrometeorological data base was to be extended forward to 1983 and backward to include the period of high lake inflows which occurred between 1861 and 1873. Also, the damage data base was to be updated, the integration of the hydrologic and economic data was to be refined, and such recent schemes as the Puddle Valley pumped storage alternative were to be added.

As a result of these modifications, it was expected that the generated lake stage sequences and damage estimates would better represent the full range of historic hydrologic events than did the earlier studies. The more representative hydrologic sequences were to be used to estimate lake level probabilities over various time periods.

Also they were to be integrated with the damage information and used to generate damage sequences providing the damage patterns and expected benefits from various management alternatives. Thus by employing these tools, the UWRL team in cooperation with the Division of Water Resources would formulate and justify recommendations to the Legislature of the State of Utah for adopting management alternatives that will reduce the damages associated with lake level fluctuations.

Outline of This and Related Reports

This report presents the improvements to the data base and methodology used in the study to update the estimation of water surface elevation probabilities and associated damages for the Great Salt Lake. For additional information on the theoretical aspects of the methodology or problems encountered with its development, the interested reader is directed to James et al. (1979) and James et al. (1981).

This report is divided into four chapters following the introduction. The updating of the data base is described in Chapter 2. Modifications and improvements to the Lake Water Balance, Stochastic Inflow Generation, and Damage Simulation Models are presented in Chapters 3, 4, and 5, respectively. Descriptions of input formats and examples of program input and output are included in Appendices A through D.

A summary report by James et al. (1984) presented estimates of probable lake levels based on conditions existing on October 1, 1983 and the changes in these probabilities that could be expected with various lake level control alternatives (breaching the causeway, pumping into the western desert, and constructing reservoirs for irrigation development in the tributary basin). It also presented benefit estimates for these alternatives. An associated report by Utah Water Research Laboratory (1984) examines the Puddle Valley Reservoir alternative.

A method for updating the estimates of lake level probabilities during the winter and spring snow accumulation and runoff seasons was also presented in James et al. (1984). This method is also presented in Appendix E of this report together with the updated forecasts for November 1983 through June 1984.

CHAPTER 2

UPDATING THE DATA BASE

Introduction

Lake level modeling begins from a base of historical data. For the Great Salt Lake study, data were needed describing inflows to the lake (precipitation on the lake and surface (from three major rivers and numerous smaller streams) and subsurface runoff to the lake), outflows consisting of evaporation from the lake, and data on lake levels that integrate the two in nature's water balance. An annual water balance was chosen to match the natural cycle of rising winter and spring and falling summer lake levels and be able to deal directly with the entire hydrologic cycle from one annual peak to the next. Supplemental data on inflows, outflows, and levels within the year were needed to estimate the peak level (occurring between April and July) from the year end (September 30) level estimated from the annual water balance.

A long series of recorded annual values for each of the annual inflows, outflows, and storages would be ideal. A long record provides more reliable estimates of the statistical properties and interrelationships among these time series by increasing the range and variety of wet and dry events covered. However, the analyst has to work with the data that he has available. Individual items vary from long periods of record to no systematic measurements at all (small stream and groundwater inflow), exhibit inconsistencies within periods of record generally caused by changes in measurement method or location, and generally are less reliable in the earlier years. The job of establishing the best practical data base was thus one of compiling available measurements, filling in the gaps, and extrapolating estimates from indirect information. Also, none of the inflows or outflows are measured precisely at the lake, and the effect of the difference between measurement site and lake values had to be assessed and incorporated into the data series used for modeling.

The available records are charted on Figure 2-1. The first major task in data preparation was one of extending the hydrometeorological data base back to 1851 and filling in gaps in the records. Other important steps in data preparation included identifying and removing data inconsistencies; developing methods for using the available precipitation and evaporation records to make areal estimates for the lake surface; and making estimates of ungaged surface and subsurface inflows.

For the Great Salt Lake, much of this work had already been done in the James et al. (1979) study. However, several needs for improving that data base were identified at the beginning of the study. These were:

1) Add recently collected data for the period 1978 through 1983.
2) Reconstruct a data base for the largest historical lake rise which occurred between 1861 and 1873 prior to the time of records.
3) Identify and remove nonhomogeneities in precipitation, evaporation, and streamflow records.
4) Assess and refine, as necessary, the estimates of ungaged surface and subsurface inflows to the lake.

This chapter is divided into sections describing the preparation of each type of data used in the hydrologic study. The reader is referred to the James et al. (1979) report for background information as the

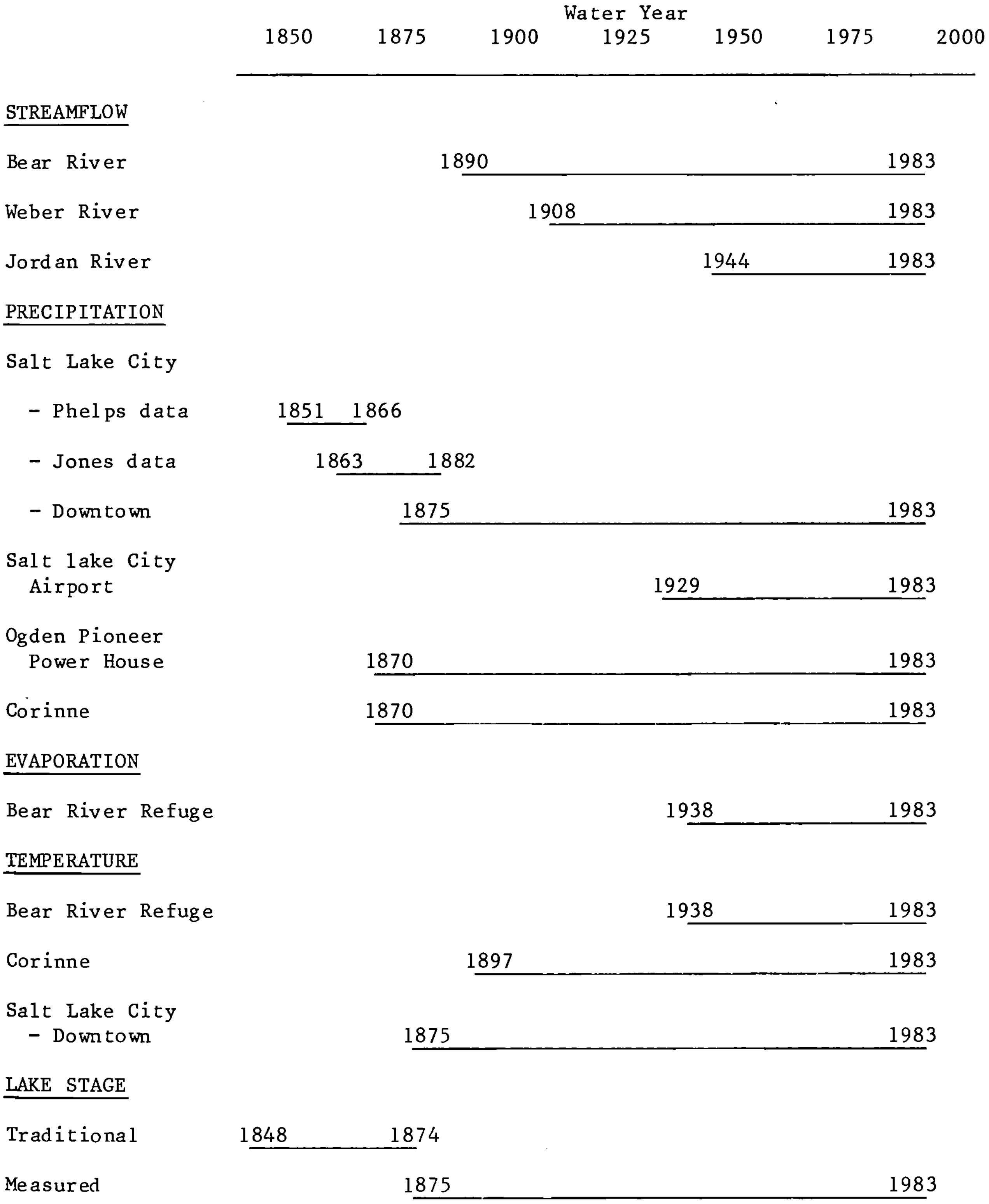

Figure 2-1. Period of historical records.

material which follows complements rather than duplicates the earlier report. The results are the sequences from water years 1851 through 1983 of river inflows (Bear, Weber and Jordan), precipitation on the lake, evaporation from the lake, and annual high stages given in Table 2-1.* Flows are adjusted to represent present land and water use conditions. Lake levels are historical readings or estimates of the south arm stages. Numbers given for the earlier years were not measured (except for two intermittent precipitation gages in the Salt Lake City area) but estimated through correlations and lake water balance computations by the Utah Division of Water Resources and the Utah Water Research Laboratory.

Recorded Lake Stages

Great Salt Lake stage data have been collected since 1876 at several sites. For the period 1848 through 1875, lake stages have been estimated from traditional data (Gilbert 1890). Recorded data on annual peaks and end-of-the-year lake levels, for the period 1978-1983, were added to the data base. Table 2-1 shows peak south arm lake stages used for calibration of the Lake Water Balance Model (see Chapter 3).

Precipitation on the Lake

Overview

Average areal estimates of annual precipitation totals on the lake are needed as a basis for the stochastic model of lake inflows. The

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*The values given provide general information on the magnitudes of the various events over time but cannot be taken as precise measurements. In the analyses presented in the following pages, the earlier data are used solely to bring information on earlier conditions into the estimates of the long term means and standard deviations of the data sequences. The definition of other relationships among them is based on actual measurements which began for the various items in underlined years.

Table 2-1. Historical hydrologic sequences[a].

Water Year	River Flow in Acre-Feet[c]	Precipitation on Lake in Inches[f]	Equivalent Fresh Water Lake Evaporation in Inches[g]	Annual Peak Lake Level in Feet[e] (msl)
1851	1403000	8.27	51.31	4202.10
1852	3474000	6.56	54.37	4203.00
1853	2083000	12.60	46.15	4204.00
1854	2269000	9.80	49.17	4204.20
1855	1351000	8.67	50.71	4204.60
1856	1349000	12.13	46.60	4204.20
1857	396000	14.66	44.41	4204.00
1858	871000	10.60	48.21	4203.00
1859	605000	14.10	44.85	4201.80
1860	1157000	9.50	49.55	4201.30
1861	1311000	10.51	48.31	4201.00
1862	3187000	12.54	46.21	4203.00
1863	3453000	7.33	52.88	4204.00
1864	2209000	10.28	48.58	4204.50
1865	3021000	13.28	45.54	4205.40
1866	1907000	19.30	41.40	4207.00
1867	3051000	13.68	45.20	4208.40
1868	2984000	16.24	43.27	4210.00
1869	2935000	11.50	47.23	4211.00
1870	1243000	13.84	45.06	4210.60
1871	3891000	8.18	51.45	4210.50
1872	4536000	9.85	49.11	4211.40
1873	1862000	13.01	45.78	4211.60
1874	1948000	9.28[h]	49.85	4211.30
1875	1278000	12.27	46.82	4211.00[h]
1876	2907000	15.38	43.48	4210.90
1877	2181000	8.55	50.81	4210.40
1878	1331000	11.35	48.00	4209.40
1879	1358000	5.99	54.64	4208.10
1880	2128000	8.16	48.95	4206.50
1881	2528000	10.50	49.56	4206.50
1882	1930000	8.49	49.44	4206.00
1883	1686000	7.53	51.97	4205.00
1884	2658000	15.35	41.83	4205.90
1885	2877000	13.76	45.04	4207.30
1886	2717000	11.61	48.80	4207.70
1887	2179000	8.21	51.75	4207.20
1888	1762000	7.16	53.53	4206.10
1889	895000[h]	7.83	53.34	4204.80
1890	1855000	14.79	44.07	4204.10
1891	1361000	12.55	44.95	4203.50
1892	988000	10.48	48.29	4202.90
1893	1641000	11.51	45.67	4203.00

See explanations in footnotes at the bottom of the last page in the table.

Table 2-1. Continued.

Water Year	River Flow in Acre-Feet[c]	Precipitation on Lake in Inches[f]	Equivalent Fresh Water Lake Evaporation in Inches[g]	Annual Peak Lake Level in Feet[e] (msl)
1894	3144000	9.84	48.46	4203.00
1895	1460000	7.05	51.47	4202.20
1896	2258000	8.78	49.43	4201.80
1897	2117000	9.92	49.09	4202.30
1898	1841000	9.12	49.90	4201.90
1899	2029000	8.74	48.10	4201.20
1900	1543000	7.18	55.08	4201.00
1901	1507000	10.02	51.90	4200.00
1902	1110000	7.73	52.20	4199.00
1903	1255000	8.37	50.63	4197.70
1904	2141000	10.03	49.85	4198.30
1905	1082000	8.87	51.87	4197.60
1906	1809000	13.25	45.39	4198.30
1907	3831000	11.54	49.14	4200.50
1908	1873000	12.06	48.69	4201.00
1909	4058000	13.41	48.99	4202.60
1910	3008000	9.11	53.24	4203.90
1911	1928000	9.95	50.06	4203.20
1912	2073000	11.31	44.39	4202.70
1913	2461000	9.93	47.61	4202.90
1914	2603000	12.27	47.00	4203.60
1915	1399000	10.79	46.76	4203.20
1916	2115000	8.92	47.25	4202.90
1917	2735000	14.12	41.75	4203.40
1918	2630000	8.09	51.99	4203.50
1919	1647000	8.28	53.37	4202.70
1920	1910000	11.22	46.04	4202.00
1921	3498000	11.65	47.77	4203.30
1922	3978000	11.36	50.82	4204.40
1923	2771000	11.50	44.18	4204.90
1924	2681000	6.86	51.50	4205.10
1925	1944000	14.87	44.81	4204.30
1926	1740000	10.38	48.96	4204.30
1927	1765000	10.00	46.63	4203.50
1928	1894000	6.77	51.79	4202.60
1929	1140000	11.45	45.79	4202.00
1930	3214000	10.76	48.79	4201.20
1931	811200	6.23	54.07	4200.45
1932	1406200	11.02	46.85	4199.40
1933	1243300	7.25	50.61	4198.85
1934	599600	5.50	60.99	4197.20
1935	799200	9.98	49.44	4196.05
1936	1468600	10.20	50.25[h]	4195.80

Table 2-1. Continued.

Water Year	River Flow in Acre-Feet[c]	Precipitation on Lake in Inches[f]	Equivalent Fresh Water Lake Evaporation in Inches[g]	Annual Peak Lake Level in Feet[e] (msl)
1937	1399200	11.12	47.63	4196.45
1938	1486400	10.76	54.18	4196.55
1939	1122400	10.08	55.16	4196.55
1940	861000	8.21	58.91	4195.75
1941	940100	14.11	48.33	4195.65
1942	1399300	11.47	47.76	4196.55
1943	1575500	8.42	53.57	4196.20
1944	1305800	10.82	50.08	4196.45
1945	1417500	11.35	47.22	4196.40
1946	1807100	10.14	49.50	4197.15
1947	1630000	12.43	46.60	4197.20
1948	1899000	9.49	49.68	4197.75
1949	1802900	10.82	46.47	4198.25
1950	2632500	10.43	45.82	4198.80
1951	2484800	11.38	49.55	4199.90
1952	2580700	10.80	47.83	4200.95
1953	1768100	8.91	48.17	4200.55
1954	955300	6.65	52.65	4199.35
1955	921800	9.31	46.36	4198.05
1956	1392800	9.01	48.13	4197.85
1957	1505500	11.73	46.02	4197.45
1958	1736600	8.82	51.63	4197.40
1959	935500	8.83	49.00	4196.05
1960	862800	6.56	53.93	4195.30
1961	597600	7.97	53.58	4193.80
1962	1253300	11.93	48.75	4193.85
1963	921800	8.59	47.08	4192.95
1964	1392800	10.46	46.03	4194.15
1965	1505500	12.04	43.85	4194.25
1966	1584200	6.57	51.19	4195.60
1967	1620500	11.73	44.50	4195.15
1968	1652300	12.42	47.82	4195.60
1969	2182700	10.73	51.35	4197.10
1970	1593500	10.89	50.06	4196.40
1971	3009700	13.15	47.42	4198.00
1972	3071700	10.32	48.32	4199.60
1973	2364000	14.81	48.94	4200.45
1974	2545300	9.19	53.93	4201.30
1975	2337200	13.45	44.91	4201.55
1976	2535700	10.81	45.51	4202.25
1977	1068900	9.74	47.18	4200.70
1978	1637700	12.56	43.75	4200.25
1979	1453700	9.36	44.42	4199.90

Table 2-1. Continued.

Water Year	River Flow in Acre-Feet[c]	Precipitation on Lake in Inches[f]	Equivalent Fresh Water Lake Evaporation in Inches[g]	Annual Peak Lake Level in Feet[e] (msl)
1980	2493400	13.25	44.24	4200.55
1981	1496600	9.31	46.73	4200.25[d]
1982	2440000	17.23	44.00	4200.85[d]
1983	5304300	17.79	41.85	4205.00[d]
Average	1953072	10.59	48.64	

[a] Data estimated from available surface runoff and lake stage (U.S. Geological Survey) and climatological (National Weather Service) records by the Utah Water Research Laboratory and the Utah Division of Water Resources.

[b] South arm levels are presented after construction of the causeway in 1959.

[c] River flows are combined totals for the Bear, Weber, and Jordan Rivers. River flows through 1889 are estimated from the water balance model. Stream gaging began on the Bear River in 1890, and the annual flow totals are highly correlated with the records beginning later on the Weber and Jordan. Historical flows are modified to represent current tributary land and water use conditions (James et al. 1979). Includes water released from Willard Bay beginning in 1965.

[d] The USGS has adjusted the 1981-3 stages to correct for a gradual settlement of the gage in the lake muds. The corrected stages are 4200.15, 4200.70 and 4204.70, respectively.

[e] Lake levels before 1876 are approximate and disputed.

[f] The precipitation and evaporation amounts over the entire lake surface should be considered reliable to no more than the nearest inch. Precipitation estimates are based on Thiessen polygons for weighting precipitation records since 1875 at Salt Lake City, Ogden, and Corinne; adjusted to reflect relatively smaller amounts of precipitation over the lake as estimated from a Thiessen network encompassing Kelton, Corinne, Farmington, Lakepoint, and Midlake for the period of 1920 through 1929; and correlations of older gages with these records for earlier years.

[g] Fresh water evaporation estimates are based on the data collected at the Bear River Bird Refuge beginning in 1937 and correlations of evaporation with precipitation during the years since to estimate evaporation in earlier years.

[h] Data below the lines in each column are estimated by starting from direct measurements of data of the indicated type. Earlier data are approximated by correlations with other types of data for which measurements began earlier or through the use of lake water balance computations and must be regarded as gross approximations. For the purpose of estimating lake level probabilities, however, the earlier approximations are useful in representing the wet conditions in the 1860s and 1870s and thus show high levels to be more likely than one would infer from the period of record below the lines alone. In reality, none of the data are fully measured. Stream and groundwater flow enter the lake from areas not captured by the three river gages. Precipitation and evaporation are measured at points nearby, rather than on, the lake. Evaporation varies with salinity at the lake surface, and temporal and spatial salinity patterns are poorly understood.

most representative estimate of areal precipitation (in terms of proximity and spatial distribution) found by James et al. (1979) was obtained from a set of five precipitation gages at Corinne, Kelton, Lakepoint, Farmington, and Midlake. However, the common period of record for these gages is only 10 years (1920-1929), and therefore it was necessary to correlate this series with a longer series to extend this estimate of average areal lake precipitation. The period, 1871-1983, was covered by using a three-station set of gages at Salt Lake Airport, Ogden Pioneer Powerhouse (Ogden P.H.) and Corinne. The period, 1851-1870, was covered by using a single gage (reconstructed Salt Lake Airport). Salt Lake City Airport records began in 1929, and therefore it was necessary to reconstruct a data series for this location for the period 1851-1928. This section is divided into three parts describing adjustment of precipitation records for consistency over time, estimation of average areal lake precipitation, and reconstruction of a Salt Lake Airport record.

Adjustment of precipitation records for consistency

Each precipitation record utilized was checked for consistency by preparing double-mass plots using a base network of other stations in the area. Based on breaks in the double-mass plots, several adjustments were made to the precipitation data to achieve a consistent record. All data series used in this project included these adjustments. All adjustments were made so as to be consistent with the most recent period of record. An outline of these double-mass comparisons, as well as a summary of the resulting adjustments, is presented in Table 2-2.

Table 2-2. Summary of double-mass comparisons and resulting adjustments made to precipitation records.

Precipitation Station	Precipitation Stations in Base Network	Period Plotted	Resulting Adjustments to Station
Salt Lake Airport	Alpine, Corinne, Logan, Ogden P.H., Salt Lake City Downtown, Tooele	1929-1981	Multiply 1929 through 1939 values by 1.14
Salt Lake City Downtown	Alpine, Corinne, Logan, Ogden P.H., Salt Lake Airport, Tooele	1929-1981	Multiply 1957 through 1966 values by 1.15
Corinne	Alpine, Farmington, Logan, Midvale, Ogden P.H., Salt Lake City Downtown, Tooele	1912-1964	Multiply 1912 through 1929 by 1.25
Corinne	Farmington, Kelton, Logan, Ogden P.H. Salt Lake City Downtown, Tooele	1900-1929	Continue previous correction by multiplying 1910 and 1911 by 1.25
Corinne	Salt Lake Airport (estimated record)	1875-1981	Multiply 1871 through 1899 values by 1.40
Ogden P.H.	Alpine, Corinne, Farmington, Logan, Midvale, Salt Lake City Downtown, Tooele	1912-1964	Multiply 1912 through 1921 values by 1.20
Ogden P.H.	Corinne, Farmington, Kelton, Logan, Salt Lake City Downtown, Tooele	1900-1929	Continue previous correction by multiplying 1900 through 1911 values by 1.20
Ogden P.H.	Salt Lake Airport (estimated record)	1875-1981	Multiply 1871 through 1886 values by 1.50 and continue previous correction by multiplying 1887 through 1899 values by 1.20
Midlake	Alpine, Corinne, Farmington, Kelton, Logan, Midvale, Salt Lake City Downtown, Tooele	1920-1929	Multiply 1920 through 1924 values by 1.90

Table 2-2. Continued.

Precipitation Station	Precipitation Stations in Base Network	Period Plotted	Resulting Adjustments to Station
Farmington	Alpine, Corinne, Logan, Midvale, Ogden P.H., Salt Lake City Downtown, Tooele	1912-1964	Multiply 1920 through 1924 value by 0.73
Lakepoint	Alpine, Corinne, Kelton, Logan, Midlake, Midvale, Ogden P.H., Salt Lake City Downtown, Tooele	1921-1928	None
Kelton	Alpine, Corinne, Farmington, Logan, Midvale, Ogden P.H., Salt Lake City Downtown, Tooele	1912-1929	None

Estimation of average areal lake precipitation

James et al. (1979) concluded that the set of precipitation gages that best estimates average areal lake precipitation contains Corinne, Kelton, Lakepoint, Farmington, and Midlake. The observed precipitation from these stations, when weighted according to the Theissen weighting method, is judged to approximate average precipitation over the lake. However, this set of stations has only a short record (1920 through 1929), and it was necessary to determine the relationship between the precipitation predicted by this set of stations and estimates based on a group of stations having a much longer record. As discussed by James et al. (1979), a group composed of precipitation gages from Salt Lake City, Ogden Pioneer Powerhouse (Ogden P.H.), and Corinne was selected because of the relatively high correlation of its estimate with the more accurate, five-station estimate, its relatively equal Thiessen weights for the three gages, and its relatively long period of record. In this study, the Salt Lake Airport precipitation record was used in place of the Salt Lake City record. Since it was considered that changing to the airport record would improve the estimate from this group of stations because of the better consistency (as determined by double-mass curve analysis) of the Salt Lake Airport gage and also because of its closer proximity to the Great Salt Lake.

A Thiessen weighting procedure was used for spatial integration of the point precipitation values at the Salt Lake Airport, Ogden P.H., and Corinne gages. 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 lake surface area changes more rapidly with elevation in some sections of the lake than in others. Therefore, Thiessen weights were calculated at three different elevations (see Tables 2-3 and 2-4). Weights for other lake stages were interpolated between the tabulated values.

The relationship between the Thiessen weighted precipitation for the most representative, five-station group and the three-station group having the much longer period of record was determined by regression of the corresponding lake precipitation estimates from the years of common record. The resulting regression equation for the 10 years of common record (1920 through 1929) for the two groups is:

$$\mathrm{LPREC} = -\,0.846 + 0.660\ \mathrm{R1} \qquad (2\text{-}1)$$

where R1 is the three-station estimated average precipitation (inches) on the lake in a given year and LPREC is the five-station estimate (inches) which is assumed to be equal to the average areal precipitation over the

Table 2-3. Thiessen weighting coefficients for the group of three precipitation stations with data for the period 1870-1983.

Precipitation Station	Lake Level High (4212 ft above MSL)	Mean (4200 ft above MSL)	Low (4193 ft above MSL)
Corinne	0.442	0.412	0.379
Ogden	0.243	0.282	0.326
Salt Lake Airport	0.316	0.307	0.295

Table 2-4. Thiessen weighting coefficients for the group of five precipitation stations with data for the period 1920-1929.

Precipitation Station	Lake Level High (4205 ft above MSL)	Mean (4203 ft above MSL)	Low (4201 ft above MSL)
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

lake. The coefficient of determination (r^2, corrected for the degrees of freedom) was 0.67, and the standard error of the regression was 1.63 inches. The regression relationship showed the Thiessen-weighted estimate based on the Salt Lake Airport, Ogden P.H., and Corinne gages to be considerably higher because these three stations are located in a relatively wetter area near the base of the Wasatch Mountains on the leeward side of the lake.

The time series of lake precipitation used for this study was computed by weighting the annual totals measured at each station in each year (1871 through 1983) according to the Thiessen factors for the lake stage during that year. Each R1 was then converted to LPREC by Equation 2-1 with the results shown as the lake precipitation in the third column of Table 2-1.

Reconstruction of Salt Lake Airport records

In using Equation 2-1, Salt Lake Airport precipitation values were needed. However, the first complete water-year record from this gage is 1929. Consequently, a relationship between annual precipitation at the Salt Lake City Downtown and the Salt Lake Airport gages was determined by regressing the corresponding values obtained from the 1929 through 1981 period of common record. The resulting equation is:

$$R2 = 1.91 + 0.825\ R3 \qquad (2\text{-}2)$$

where R2 is the annual precipitation (inches) estimated at the airport gage and R3 is the annual precipitation (inches) at the downtown gage. The coefficient of determination was 0.79 and the standard error of the regression was 1.38 inches. Equation 2-2 was utilized to provide estimates of Salt Lake Airport precipitation between 1875 and 1928.

For going back further than 1875, the values of annual precipitation at the Salt Lake Airport for water years 1875 through 1882 as estimated from Equation 2-2 were regressed against the Salt Lake City data recorded by M. E. Jones (Henshaw et al. 1914). The relationship between the two records is:

$$R2 = -1.04 + 1.01\ R4 \qquad (2\text{-}3)$$

where R4 is the annual precipitation reported by Jones, and R2 is the annual precipitation estimated for the Salt Lake Airport. The coefficient of determination was 0.73 and the standard error of the regression was 2.05 inches. This equation was used to estimate annual precipitation at the airport from 1863 through 1874.

Prior to 1867, estimates of the annual precipitation at the airport were determined from data reported by W. W. Phelps (Figgins 1981). The values of airport precipitation predicted by Equation 2-3 from the Jones data were 80 percent of the precipitation reported by Phelps for calendar-years 1863 through 1866. Data from W. W. Phelps could not be checked by double-mass analysis since no base network was available; however, when the 80 percent factor was used to estimate airport precipitation from 1851 through 1866 the adjusted record appeared to be biased towards low values based on the lake level response during the period. Consequently, the Phelps data were adjusted as follows. Annual precipitation at the Salt Lake Airport (estimated as described above) averaged 15.55 inches from 1864 through 1982. Estimates of annual airport precipitation based on the Phelps data (as described above) averaged only 10.93 inches during the 1851 through 1863 period. All Phelps data were therefore multiplied by the ratio of 15.55 to 10.93 or 1.42. A check of this adjustment was made by noting that lake levels during the 1920 through 1929 period fluctuated very similarly to those in the 1851 through 1860 period. During these two periods, average lake precipitation estimates using the adjustment described previously were almost identical (less than a one percent difference). Consequently, the adjustment to the Phelps data seemed reasonable.

From 1863 through 1866, precipitation measurements by both Jones and Phelps data were available. Estimates derived from the Phelps data appeared to better match lake level changes during the period and were consequently selected for use. It should be emphasized that in all of these procedures, the adjusted annual precipitation values based on the analyses described previously and summarized in Table 2-2 were utilized.

No precipitation records exist before 1870 at either Corinne or Ogden Pioneer Powerhouse. Thus, it was necessary to estimate average annual lake precipitation for this period based solely on the record from Salt Lake City (the estimated record at the Salt Lake Airport described above). In order to have a relationship for this purpose, annual lake precipitation estimated by the three-station group used in Equation 2-1 was compared to annual precipitation at the Salt Lake Airport for the 1929 through 1982 period. Based on regression analyses, the relationship between the two series is:

$$LPREC = 1.74 + 0.568\ R5 \qquad (2\text{-}4)$$

where LPREC is the average annual lake precipitation and R5 is the annual precipitation measured at the Salt Lake Airport (distinguished from R2 which is estimated airport precipitation). The coefficient of determination was 0.75 and the standard error of the regression was 1.11 inches. Equation 2-4 was utilized to estimate the annual precipitation over the lake from 1851 through 1870.

As explained in James et al. (1979), the results of Equation 2-4, based on only Salt Lake Airport data, were adjusted slightly in order to correct for differences in Thiessen weights as the lake rises. Precipitation simulated at stage 4191 was adjusted by multiplying the lake precipitation determined from Equation 2-4 by 1.014. Similarly, precipitation simulated at stages 4170, 4200, and greater than or equal to 4211 was multiplied by the factors 1.014, 0.999, and 0.989 respectively. Factors for intermediate stages were found by linear interpolation between pairs of these values.

Lake Evaporation

Overview

Bear River Refuge pan evaporation data were used as a basis for estimating an annual series of lake evaporation. Published data for the warmer months (typically April through October) were available for the period 1938-1983. However, some summer values were missing, and no winter evaporation data were available. Consequently, the missing values had to be estimated before an annual equivalent pan evaporation amount could be determined. In addition, the annual equivalent pan evaporation series had to be extended through the 1851-1937 period before the pan was installed.

Estimating missing months

A modified form of the Blaney-Criddle consumptive use equation was selected because the extra effort required to compile and use daily data did not seem justified. It was then utilized to estimate data for months in which no pan evaporation data were available during the 1938-1983 period. The equation, as modified by Borrelli et al. (1981), is as follows:

$$BRPE_i = a_i + b_i(0.00328\ T_i + 0.65)\ T_iP_i/100 \tag{2-5}$$

where

$BRPE_i$ = pan evaporation for month i at the Bear River Refuge (in)

T_i = average temperature for month i (°F)

P_i = percent of the total annual daylight hours in month i

a_i, b_i = regression coefficients for month i

The a_i and b_i coefficients were determined by regression analyses for each month of the year for the period in which Bear River Refuge pan evaporation data were available. Since no such data were available from November through March, a different approach had to be used. Monthly average equivalent pan evaporation values for the Salt Lake Airport have been estimated by NOAA (1982). These Salt Lake Airport estimates were utilized along with mean monthly temperatures and the monthly percent daylight hours to estimate the coefficient b_i in Equation 2-5, assuming that the coefficient a_i is zero. These estimates of the b_i's were then assumed to be applicable at the Bear River Refuge. All missing monthly pan evaporation data in the 1938-1983 period were estimated using Equation 2-5 and the coefficients listed in Table 2-5. Annual equivalent pan evaporation estimates were determined by summing the monthly pan evaporation values over each water year.

Reconstruction of the Bear River Refuge pan evaporation record

Reconstruction of the Bear River Refuge pan evaporation record for the period 1851-1937 was divided into three subperiods in which different methods were used. Each method is described in this section.

1897-1937. For this period, Bear River Refuge pan evaporation estimates were based on estimates of the pan evaporation at Corinne made from Corinne temperature data using Equation 2-5 and the coefficients presented in Table 2-5. It was not possible to estimate equivalent pan evaporation at the Bear River Refuge prior to 1938 since temperature data were not available. Because of the close proximity of Bear River Refuge and Corinne, the use of the coefficients of Table 2-5 seemed justifiable. A regression performed on the 1938-1982 period resulted in the equation to relate Bear River Refuge and Corinne pan evaporation estimates:

Table 2-5. Coefficients for Equation 2-5.

i	Month	P_i	a_i	b_i	Coefficient of Determination (R^2)	Standard Error (inches)
1	Oct	7.681	-1.616	1.542	0.40	0.35
2	Nov	6.612	0*	0.994	-	-
3	Dec	6.410	0*	0.694	-	-
4	Jan	6.625	0*	0.828	-	-
5	Feb	6.619	0*	1.024	-	-
6	Mar	8.268	0*	1.386	-	-
7	Apr	8.974	-2.072	1.970	0.36	0.55
8	May	10.130	-6.392	2.749	0.50	0.88
9	Jun	10.233	-8.252	2.874	0.55	0.82
10	Jul	10.387	-5.799	2.369	0.15	0.87
11	Aug	9.655	-0.285	1.587	0.14	0.99
12	Sep	8.405	-0.732	1.544	0.20	0.73

*Assumed equal to zero in order to estimate b_i (see text for further explanation).

$$\text{BRPE} = 15.8 + 0.6487\ \text{CPE} + 76.04/\text{LPREC} \qquad (2\text{-}6)$$

where

BRPE = annual reconstructed pan evaporation at the Bear River Refuge (in)

CPE = annual pan evaporation at Corinne estimated from temperature data (in)

LPREC = annual estimated lake precipitation (in)

The coefficient of determination (R^2) and standard error of Equation 2-6 are 0.427 and 3.29 in, respectively. Equation 2-6 was used to obtain the first estimates of the 1897-1937 Bear River Refuge pan evaporation. The mean and standard deviation of these estimates were 61.9 and 3.32 in, respectively. The standard deviation of the more accurately measured 1938-1983 values was 4.34 in. The 1897-1937 values were adjusted so that they also had a standard deviation of 4.34 by using the equation:

$$ABRPE = (BRPE - \text{Average of } BRPE)\ (4.34/\text{Standard Deviation of } BRPE) \qquad (2\text{-}7)$$

where

ABRPE = adjusted estimate of annual Bear River Refuge pan evaporation (in)

BRPE = first estimate of annual Bear River Refuge pan evaporation (in)

Values obtained from Equation 2-7 were utilized for the 1897-1937 portion of the data series.

1875-1896. For this period, Bear River Refuge pan evaporation estimates were based on estimates of pan evaporation at Salt Lake City using Salt Lake City temperature data. Thus equivalent monthly pan evaporation values at Salt Lake City were estimated for 1875-1927 using Equation 2-5 coefficients a and b from Table 2-5, and mean monthly temperatures and percent daylight hours for Salt Lake City. Monthly estimates were summed to produce annual equivalent pan evaporation estimates at Salt Lake City. Regression of Bear River Refuge estimates determined from Equations 2-6 and 2-7 against the equivalent pan evaporation estimates at Salt Lake City and annual lake precipitaion resulted in the following equation:

$$BRPE = 39.5 + 0.545\ SLCPE - 1.16\ LPREC \qquad (2\text{-}8)$$

where

SLCPE = annual estimated Salt Lake City pan evaporation (in)

Equation 2-8 was used to obtain the first estimates of the annual equivalent pan evaporation at the Bear River Refuge for the 1875-1896 period. The mean and standard deviation of the 1875-1896 annual estimates were 61.1 and 3.55 in, respectively. The 1875-1896 annual estimates were modified by use of Equation 2-7 for the 1897-1937 period to maintain the mean of 61.1 in but increase the standard deviation to 4.34 in.

1851-1874. For this period, annual totals for the Bear River Refuge pan evaporation were estimated from a regression of estimated Bear River Refuge equivalent pan evaporation on estimated lake precipitation for the 1875-1982 period which resulted in the equation:

$$\mathrm{BRPE} = 103.6/(\mathrm{LPREC})^{0.22774} \qquad (2\text{-}9)$$

Equation 2-9 was used along with the 1851-1874 estimates of annual lake precipitation to provide the first estimates of the annual equivalent pan evaporation for the 1851-1874 period. The mean and standard deviation of these estimates were 60.5 in and 3.92 in respectively. These values were adjusted by the use of Equation 2-7 to increase the standard deviation to that of the 1938-1982 period of 4.34 in. The entire pan evaporation time series is presented in Table 2-1.

Lake Inflows

In order to calculate a statistically homogeneous series of lake levels, the levels of the lake through time were estimated using inflows adjusted to reflect present levels of consumptive use, or 1.5 million acre feet of consumptive use per year. Estimates of consumptive use through time were extracted from the "Great Salt Lake Elevations Adjusted for the Effects of Man-Caused Reduction of the Inflow to the Lake" (Division of Water Resources 1970).

Using the calibrated lake model, the inflow to the lake from 1851 to 1930 was calculated using evaporation and rainfall estimates provided by UWRL and lake stage data from the U.S. Geological Survey. After the model had calculated historical combined flow of the Bear, Weber and Jordan Rivers, those flows were then adjusted for present upstream conditions of consumptive use. The procedure for computing present modified flow is as follows:

$PR = C +$ Historical Inflows

if $PR > 3.0\text{x}10^6$: $PMF = PR - 1.5\text{x}10^6$

otherwise: $PMF = PR / 2$.

where

PR = pristine flows, i.e., without the effects of man

C = estimated consumptive use from the effects of man

PMF = present modified flows

CHAPTER 3

LAKE WATER BALANCE MODEL

Introduction

Lake inflow sequences are converted to lake stage sequences using a lake water balance model which was originally developed by the Utah Division of Water Resources (1974). In the previous study (James et al. 1979), this model was modified to provide the option to represent any of the conditions associated with each of the lake level management alternatives under consideration in 1977 (see also Allen et al. 1983). In this study, the model was further modified to improve estimates of the annual peak lake stages, ungaged surface and subsurface inflows, and the conversion of pan evaporation to lake evaporation; to refine the lake stage-surface area-volume relationship based on new survey information; to add the capability for simulating the performance of the proposed Puddle Valley Reservoir and West Desert pumping; and to recalibrate the model based on the historical period, 1944 through 1983. In addition, lake inflow from the Bear, Weber, and Jordan Rivers were treated as a lumped stream inflow rather than three separate series as they were by James et al. (1979).

This chapter is divided into two major parts: a presentation of the Lake Water Balance Algorithm and changes made to it during this study and a description of the representation of Management Alternatives in the model. As with other chapters in this report, this material complements the James et al. (1979) report and therefore the interested reader is referred to that report for further details on the Lake Water Balance Model.

Lake Water Balance Algorithm

Annual water balance

A lake water balance model developed by the Utah Division of Water Resources (1974) for application to the Great Salt Lake was adapted in the James et al. (1979) study. The basic relationship is the water balance equation:

$$V_t = V_{t-1} + Q_{s,t} + S_t + G_t + (p_t - e_t)AA_t \tag{3-1}$$

in which

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

$Q_{s,t}$ = total surface inflow from the Bear, Weber, and Jordan rivers and the outflow from Willard Bay to Great Salt Lake 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)

AA_t = average of lake surface areas at the beginning of the t^{th} year and at the peak stage of the t^{th} year (ac)

In applying Equation 3-1, the initial stage can be translated into corresponding values for the lake volume (V_{t-1}) using the lake stage-surface area-volume relationships given in Table 3-1. Annual totals for the flows represented by all the other terms on the right-hand side of

Table 3-1. Stage-area-volume-evaporation data for the Great Salt Lake.

Water Surface[b] Elevation (feet)	Surface Area[b] 1000 Acres	Storage Volume[b] 1000 Acre-feet	Estimated Evaporation 1000 AF/year[a]
4170	118	250	297
4180	407	2951	1023
4184	482	4733	1212
4186	509	5725	1280
4188	535	6769	1345
4189	550	7311	1383
4190	564	7868	1419
4191	580	8440	1458
4192	602	9031	1513
4193	633	9646	1591
4194	678	10301	1704
4195	720	11002	1810
4196	773	11750	1943
4197	840	12556	2111
4198	890	13422	2292
4199	970	14350	2557
4200	1079	15370	2908
4201	1140	16481	3133
4202	1175	17641	3288
4203	1201	18829	3413
4204	1223	20041	3524
4205	1251	21277	3648
4206	1330	22542	3923
4207	1375	23808	4100
4208	1410	25075	4240
4209	1450	26341	4397
4210	1490	27607	4550
4212	1572	30669	4862
4216	2227	38671	6900
4218	2519	43417	7900

[a] Based on mean evaporation rate and provides a rough indication of the level at which the lake would stabilize given an average inflow over a period of years.

[b] Personal communication, Utah Division of Water Resources, October 1984.

Equation 3-1 are then used to calculate the first estimate of V_t one year later. In this first estimate, AA_t is not yet known so AA_{t-1} is used.

Estimation of annual peak stage

The annual peak stage, which occurs between April and July on the Great Salt Lake, is the primary concern for a study of lake stage control measures. To account for the fact that the lake level peaks at the end of the spring runoff season, 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. These fractions are determined as follows:

$$C1 = 0.632 + 0.0094\ Q_{s,t}/A_{t-1} + 0.0240\ e_t^P \qquad (3\text{-}2)$$

$$C2 = 0.574 + 0.0309\ Q_{s,t}/A_{t-1} - 0.0836\ e_t^P + 0.182\ p_t \qquad (3\text{-}3)$$

$$C3 = 0.972 + 0.0923\ Q_{s,t}/A_{t-1} - 0.0643\ e_t^P - 0.110\ p_t,\ C3 \leq 0.970 \qquad (3\text{-}4)$$

where A_{t-1} is the end of the previous water year surface area of the lake; and C1, C2, and C3 are the fractions of annual gaged inflow lake, evaporation, and lake precipitation, respectively, which occur before the date of the recorded peak.

Thus, the volume corresponding to the annual peak stage, $V_{p,t}$, is estimated as follows:

$$V_{p,t} = V_{t-1} + C_1(Q_{s,t} + S_t + G_t) + (C_3 p_t - C_2 e_t)AA_t \qquad (3\text{-}5)$$

Coefficients in Equations 3-2, 3-3 and 3-4 were estimated by regression analysis using data for the period 1944-1983, the lake water balance verification period.

Estimation of ungaged surface and subsurface inflows

Of the five flow variables on the right-hand side of Equation 1, historical data are available for three ($Q_{s,t}$, p_t, and e_t), and these are therefore generated using the multivariate model. It is necessary to estimate the other two flow variables, ungaged surface (S_t) and subsurface inflows (G_t) by establishing relationships with the three measured variables. These relationships were estimated as follows:

$$S_t = (0.296\ p_t - 0.0226\ e_t)\ AA_t \tag{3-6}$$

$$G_t = 0.0150\ Q_{s,t} + 0.0150\ Q_{s,t-1} + 0.0150\ Q_{s,t-2} \tag{3-7}$$

The coefficients in Equations 3-6 and 3-7 were obtained by a calibration procedure performed by the Utah Division of Water Resources using MINPACK-1, an optimization package developed by the Argonne National Laboratory (More et al. 1980). Specifically, a least squares method, the Levenberg-Marquardt algorithm, was used. Coefficients of calibration included a coefficient to convert pan evaporation to equivalent fresh lake water evaporation, a coefficient for lake precipitation and evaporation in order to estimate ungaged inflows, including the coefficient to convert pan evaporation to equivalent fresh water evaporation. Groundwater inflow coefficients were determined from estimates made by the United States Geological Survey in "Great Salt Lake Estimated Inflow and Evaporation 1931-1976" published as Cooperative Investigations Report No. 20 by the Utah Division of Water Resources.

Conversion of pan evaporation to lake evaporation

Evaporation is input to the model as fresh water annual equivalent pan evaporation. Pan evaporation is converted to equivalent freshwater lake evaporation by using a pan coefficient as follows:

$$e_t^T = 0.797\ (e_t^P) \tag{3-8}$$

in which

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

e_t^P = pan evaporation in the t^{th} water year (ft)

The reduction in evaporation caused by salinity is estimated as outlined by James et al. (1979) with the linear equation:

$$e_t = e_t^T(1-0.00833\ C_t) \tag{3-9}$$

in which

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 ($62.4 \times 43560\ V_t/2000$) based on the current year volume, V_t, multiplying by 100, and truncating the value of C_t at its estimated saturation value of 27.5 percent when lake levels are low.

The computer programming for the lake water balance model is documented in Appendix B with a program listing, input description, and sample input and output.

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 as those giving the best match of historical stages. In probability applications, one begins from flows generated stochastically and representing homogeneous watershed conditions. If future probabilities are desired, one either has to assume that present conditions will continue into the future or 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 for the model to select from among the various management options which are described in the following sections.

Management Alternatives

Upstream development

The water balance model permits the user to evaluate the effects on lake levels of upstream water development projects that increase consumptive use. At present, nearly 1.5×10^6 acre feet annually are consumptively used in the Great Salt Lake Basin in the average year. The model provides for an increase in basinwide consumptive use as would occur by putting new land under irrigation. The plan is modeled by specifying an increase in consumptive use which the program subtracts from the lake inflows. The increase in annual consumptive use which was studied in this project was 300,000 AF beginning in 1994.

One can use the damage simulation model described in Chapter 5 to determine the effect of a proposed increase in upstream consumptive use on damages caused by fluctuating lake stages so that these benefits can be used in economic feasibility studies. A more refined analysis simulating more realistic reservoir operating policies can be developed later if specific schemes prove promising and are more carefully defined.

West Desert pumping scheme

A capability for representing the operation of a plant pumping water from the Great Salt Lake to the West 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 rates specified by the user. These rates can be different each year. The pumping continues at these specified rates as long as the water surface is above the control elevation at the beginning of the water year. In determining the annual peak lake elevation, it is assumed that 75 percent of the pumping for the year occurs by the time of the peak.

In this study, the effect of pumping into the western desert was examined by using a proposed pumping system design (Eckhoff, Watson and Preator Engineering 1983) to specify the operation schedule for the system shown in Table 3-2. This schedule accounts for the water required to fill the ponds after pumping starts, the evaporation from the operating ponds in the western desert, drainage from the ponds after pumping ceases, and flow maintained through the ponds to preserve the salt balance and keep salt from being deposited in the desert. Pumping starts whenever a water year begins with a lake level over 4202 and continues until the lake falls below that level.

Puddle Valley pumped storage

Capability for simulating operation of the Puddle Valley pumped storage project was added to the water balance model in this study. Puddle Valley is located west of the south arm of Great Salt Lake. The valley bottom is at about 4307 ft above MSL or about 100 ft higher

Table 3-2. Water balance within West Desert ponds during pumping period.

Inflow	1.77 maf/yr (2450 cfs)
Capacity	1.33 maf
Evaporation	1.06 maf from 450,000 Ac

(Net of mean flow of 500 cfs through ponds in years with pumping to provide return of salt brine to the lake and thus prevent salt accumulation in the desert).

Annual Water Balance Amounts in million of acre feet (maf)

Year	Pumped	Evaporated	Δ Storage	End of Year Storage	Returned	Net Water* Removal
1	1.43	1.03	0.40	0.40	0.00	1.43
2	1.43	1.03	0.40	0.80	0.00	1.43
3	1.43	1.03	0.40	1.20	0.00	1.43
4	1.43	1.03	0.13	1.33	0.27	1.16
5 to n	1.43	1.03	0.00	1.33	0.40	1.03
n+1	0.00	0.93	-1.33	0.00	0.40	-0.40

n is the number of the last year of pumping
n+1 is the year in which the ponds drain back into the lake after pumping ceases

*The column on the right gives the net water removal from the lake in each year in which pumping continues from 1 through n.

than the present lake stage. During periods of rising lake levels, water can be pumped into a storage reservoir created in Puddle Valley. Water could later be released back to the lake for low lake level control or for generating hydropower. Operating rules included in the model were:

1) Four alternative maximum reservoir storage levels:

Maximum Level (ft above MSL)	Maximum Storage (million AF)
4440	3.0
4460	3.9
4500	4.7
4580	10.0

2) Pumping from lake at rate of 2500 cfs when lake level exceeds 4202 ft above MSL.

3) Releases from the reservoir to Great Salt Lake at 2500 cfs for hydropower generation.

4) Evaporation from Great Salt Lake at the rate of 41 inches per year.

Change of causeway opening size

The lake water balance model initially calculates a stage for the Great Salt Lake as if it were "one lake" without the difference in elevation which results from the Southern Pacific causeway. Separate stages (both peak and end of water year) for the south arm were then estimated using Equations 3-10 and 3-11 developed by UDWR (1977) based on a study by Waddell and Bolke (1973). These equations relate the difference in elevation between the south arm lake level and the average lake level (determined assuming the lake is a single body with no head difference in the north and south arms) with the annual combined flow from the Bear, Weber, and Jordan Rivers, the previous years elevation of the lake, and a coefficient based on the size of causeway opening. These equations are:

$$\mathrm{ELPS} = \mathrm{ELPA} + 0.375\ B_1\ C \tag{3-10}$$

and

$$\mathrm{ELVS} = \mathrm{ELVA} + 0.375\ B_2\ C \tag{3-11}$$

in which

ELPS = peak elevation of the south arm (ft)

ELPA = peak elevation of "one lake" (ft)

ELVS = end of water year elevation of the south arm (ft)

ELVA = end of water year elevation of "one lake" (ft)

C = coefficient that varies with size of causeway opening

The value of C can be changed to simulate various sizes of causeway openings. B_1 and B_2 are determined from the equations based on results given in Waddell and Bolke (1973):

$$B_1 = -574 + 0.137\ ELVA_{t-1} + (0.452 \times 10^{-6})Q_{s,t} \qquad (3\text{-}12)$$

$$B_2 = -320 + 0.764\ ELVA_{t-1} + (0.391 \times 10^{-6})Q_{s,t} \qquad (3\text{-}13)$$

in which

$ELVA_{t-1}$ = end of water year elevation of "one lake" for previous year (ft)

B_1 is constrained within the range 0.5 to 4.0. B_2 is constrained within the range 0.3 to 3.8. The effect of breaching the causeway with a 300 ft opening was examined in this study.

CHAPTER 4

STOCHASTIC INFLOW GENERATION MODEL

Background

One modeling approach to assessing the risk of rising levels in the Great Salt Lake would be to develop and apply a model for the direct stochastic generation of lake level sequences. However, there are problems with both the modeling and the application. The modeling taxes the capability of our present ability to calibrate representative stochastic model forms because of the large number of lags that must be preserved to represent the high degree of lake level persistence (James et al. 1979). The application problem is that direct representation of the lake levels provides no way to examine the effectiveness of measures for inflow and outflow management as control methods.

The fluctuations in the annual peak levels of the Great Salt Lake can be attributed to the variability in annual lake inflows (streamflow, precipitation on the lake, and subsurface flow in a probable order or decreasing effect) and, to a lesser extent, evaporation from the lake. For representing these fluctuations and how they could be modified through a lake level control program, a multivariate stochastic model was developed to generate sets of the measured inflow (streamflow and precipitation) and outflow (evaporation) sequences that when taken as a whole preserve the statistical characteristics of the annual lake level variability. The annual flow sets generated by the model are input to the lake water balance model in order to convert them to lake level sequences.

In the James et al. (1979) study, several types of stochastic models were tried. Numerical solution difficulties were experienced with some models and innovative methods were devised to overcome these problems. The outcome was that a multivariate AR(1) (equivalent to a multivariate ARMA (1,0)) model (Box and Jenkins 1970) was selected and fitted to the period, 1937-1977, for which measured inflow data were available. In a follow-up study, James et al. (1981) examined several other stochastic model forms, but again the AR(1) model was selected as providing the best preservation of historical statistics over the period, 1937-1977.

In both studies (James et al. 1979 and 1981), the selected models were fitted to the period of record, beginning in 1937, for which streamflow, lake precipitation, and lake evaporation were all based on measured data. By using only this period, the calibration avoided the inconsistencies in the cross-correlation properties of the reconstructed inflow series that resulted when part of the series was developed from independent measurements and the rest was estimated by cross correlation. However, by ignoring the period prior to 1937, the high inflows, which occurred in the late 1800s (approximately 1862-1873), were not taken into account. Therefore, the stochastic models in these previous studies did not generate inflow series that exhibited these historically high inflow levels. Consequently the probabilities of high lake levels were underestimated.

The present study, therefore, sought to include the effect of these higher flows and yet preserve the cross-correlation structure found when all three data series were measured by 1) analyzing the statistical characteristics of the 1862-1873 period relative to the remainder of the record; 2) seeking possible physical explanations for the high inflows during these years; and 3) devising an approach to model the inflow series which would adequately represent the high inflows experienced in the 1800s.

The following section summarizes the steps in a systematic approach to hydrologic time series modeling. The remainder of the chapter describes how these steps were applied to the modeling of Great Salt Lake inflows, including the analysis and modeling of the apparent nonhomogeneity of the 1800s.

A Systematic Approach to Hydrologic Time Series Modeling

Operational hydrology encompasses a variety of stochastic models for generating synthetic hydrologic time series. The modeling can be approached in a logical and systematic manner (Box and Jenkins 1970). Their iterative modeling approach, generalized to encompass a broader class of stochastic streamflow models by James et al. (1981), comprises the following five steps (see Figure 4-1). 1) identification of the water resources system and model composition (e.g., univariate or multivariate, annual or seasonal); 2) choice of model type--short term or long term persistence model (e.g., autoregressive or fractional Gaussian noise); 3) identification of model form (e.g., order of the autoregressive model); 4) parameter estimation; and 5) model performance evaluation.

Model performance may be judged by certain criteria such as the preservation of historic statistics, or the independence of residuals calculated by applying the stochastic model to the historical record. During model building, inadequate performance detected at step 5 may result in changing the values assigned to model parameters or, if this does not work, the model form. If inadequate model performance still persists, it may be necessary to return to step 2 to select an alternative type of model, or to step 1 to simplify the model composition. The steps outlined in Figure 4-1 were followed in this study as described in the remaining sections of this chapter.

Model Composition

Water flows into the Great Salt Lake through three major tributaries, many smaller ungaged streams, subsurface groundwater movement, and precipitation on the lake surface. It leaves by evaporation. One would expect these four different types of inflow and one type of outflow to have distinct distributional characteristics. Evaporation would not vary much from year to year and not be highly serially correlated from one year to the next. Precipitation, in Utah's arid climate, would vary more, not be highly serially correlated, and tend to be inversely related to evaporation (prolonged rainy weather reduces evaporation). The inflow from the larger streams would be correlated with precipitation (however, heavy snows in the mountains producing large spring runoff may occur in different years than the large summer rainstorms on the lake surface) and display greater persistence from year to year because of the effect of carryover soil moisture. The inflow from the smaller streams would have still greater persistence in an arid climate that produces little if any runoff until years when the soil moisture has reached some threshold levels. Finally subsurface inflow takes months or years to get to the lake and would be expected to display the greatest persistence of all.

Data were only available for the first three of these series. The measured streamflows were combined into one variable because they do have the same general distributional and serial correlation characteristics and because the fewer variables in a parsimonious stochastic model make the generation more reliable. Therefore, the stochastic model generated series of streamflow, lake precipitation, and lake evaporation. The three series were simultaneously generated with a multivariate model (see Figure 1-2) since significant cross-correlations were estimated (see Table 4-2b).

Analysis of Historical Time Series

Outline

Before model building can begin, the available records must be analyzed in order to develop an understanding of the statistical structure which the stochastic model must preserve. For modeling Great Salt Lake inflows, three types of statistical information were needed:

1) Distributional properties of each inflow series (i.e., mean, variance, skew, and probability distribution)
2) Serial correlation structure of each inflow series (i.e., autocorrelogram)
3) Cross-correlation structure among the inflow series (i.e., cross-correlation matrices at say, lags 0, 1, and 2)

Inflow series are presented in Chapter 2 for combined streamflow, lake precipitation, and lake evaporation for the period 1851 through 1984.

Nonhomogeneities

Before estimating any of the above statistics, each series was checked for homogeneity or stationarity to identify times, if any, when its statistical properties changed significantly within the period of record. The double-mass analyses and data adjustments performed to identify and correct for nonhomogeneities in the precipitation records used to estimate lake precipitation are described in Chapter 2. Due to the lack of other nearby evaporation stations, it was not possible to perform double-mass analyses of the evaporation record. However, the evaporation time series was plotted, found to be linear, and judged to be homogeneous for the period of historical record, on the basis of visual inspection.

Inspection of the combined streamflows revealed the period of high inflows in the 1800s referenced in the introduction to this chapter. The statistical significance of this apparent nonhomogeneity was examined by testing the difference between the means and standard deviations of the combined streamflows for the high flow period (1862-1872) and two longer periods (1873-1983 and 1938-1983) (see Table 4-1). In both comparisons the mean flows for 1862 to 1872 were shown to be significantly higher at the 5 percent level. The standard deviations were not significantly different at the 5 percent level. Thus the nonhomogeneity affects the mean but not the variance. No significant increase in precipitation levels during this period was detected, but this may have been due to the poor quality of these early precipitation records.

The timings of the occurrence of the high inflow period and of other less dramatic fluctuations in inflows found in the reconstructed and historical record were compared with the occurrences of exogenous events such as volcanic eruptions or sunspot cycles. This was done in an effort to seek a possible physical explanation for the period of higher inflows. If such a relationship had been found the next step would have been to study the possibility of relating the exogenous events to the occurrence

Table 4-1a. Statistical tests of mean of high flow period (1862-1872) against mean for two longer periods.[1]

Period									$w_1 =$	$w_2 =$			$w_1t_1 +$	$\frac{w_1t_1 + w_2t_2}{w_1 + w_2}$	T_{crit}	
1	2	$\bar{X}_1$	$\bar{X}_2$	S_1	S_2	n_1	n_2	$(\bar{X}_1-\bar{X}_2)$	S_1^2/n_1	S_2^2/n_2	$t_{1,.05}$	$t_{2,.05}$	w_2t_2			Inference
1862 to 1872	1873 to 1983	3,137,000	1,898,968	794,742	798,679	11	111	1,238,032	5.742×10^{10}	5.747×10^{9}	2.20	1.98	1.377×10^{11}	2.180	4.93	Significantly different means
1862 to 1872	1938 to 1983	3,137,000	1,803,807	794,742	954,596	11	46	1,333,193	5.742×10^{10}	1.981×10^{10}	2.20	2.01	1.661×10^{11}	2.151	4.80	Significantly different means

[1] Values of the means and standard deviations given in this table may differ slightly from values presented in other parts of this chapter. This is because they were estimated at different times during the data preparation process and does not affect the conclusions drawn from the values presented.

Table 4-1b. Statistical tests of standard deviation of high flow period (1862-1872) against standard deviation for two longer periods.[1]

Period 1	Period 2	S_1	S_2	n_1	n_2	N	$\sum_{i=1}^{2} (n_i-1)\ln S_i^2$	$\sum_{i=1}^{2} (n_i-1)S_i^2/N-2$	Q	$\sum_{i=1}^{2} (1/n_i-1)$	h	$\chi^2 = Q/h$	$\chi^2_{.975,1}$ $\chi^2_{.025,1}$	Inference
1862 to 1872	1873 to 1983	794,742	798,679	11	111	122	3261.67	6.374×10^{11}	0.004	0.109	1.034	0.004	0.001 5.020	Not significantly different standard deviations
1862 to 1872	1938 to 1983	794,742	954,596	11	46	57	1510.93	8.604×10^{11}	0.506	0.032	1.005	0.500	0.001 5.020	Not significantly different standard deviations

[1] Values of the means and standard deviations given in this table may differ slightly from values presented in other parts of this chapter. This is because they were estimated at different times during the data preparation process and does not affect the conclusions drawn from the values presented.

of high inflow periods and then to superimpose these effects on the stochastic model of lake inflows. However, no statistically significant relationships could be found.

Time series statistics

Streamflow, precipitation, and evaporation statistics were calculated for six time periods. These periods were selected to match shifts in the method of data measurement or estimation and are as follows:

1) 1938-1983: Essentially all inflow data are measured (the only exception being Jordan River between 1938 and 1943, but this represents less than 10 percent of the total surface inflows, including precipitation).
2) 1890-1983: Major inflows measured, includes some reconstructed records for Weber (1890-1907) and Jordan (1890-1943) Rivers and evaporation (1890-1937), all of which can be expected to be reasonably reliable.
3) 1851-1983: Entire period of measured and reconstructed record.
4) 1890-1937: Period of reasonably reliable reconstructed record.
5) 1851-1937: Entire period of reconstructed record with some measured inflows.
6) 1851-1889: Essentially all inflow data are reconstructed for this period.

The 1862-1872 period of high flows was not listed since it is relatively short and therefore statistics calculated from it would be unreliable. Also, it was omitted because the main purpose underlying the selection of these periods was the evaluation of the effects of record reconstruction. In general, one would expect the relative effects of record reconstruction on the reliability of the statistical information to increase from period 1 to period 6.

Table 4-2 presents the statistics of the three lake inflow series for all six periods defined above. The table is divided into two parts: 1) univariate statistics and 2) cross-correlation matrices which include autocorrelation coefficients for lags 1 and 2. A comparison of the univariate statistics for the different time periods shows little difference between the means or standard deviations for lake evaporation or lake precipitation. However, for combined streamflow the effects of the high inflow period (1862-1872) is apparent in the larger values of the mean and standard deviation for periods which include fewer years outside of the high inflow period. Values of the Hurst coefficient do not show an unusual amount of variation between time periods. Hurst coefficient values for streamflow exceed those for the climatological variables. A similar result was found for this geographical region by James et al. (1979) and is to be expected considering the effects of basin soil and groundwater storage on increasing the persistence in streamflows relative to the climatologic variables.

Inspection of log-normal probability plots of the lake evaporation, lake precipitation, and combined inflows showed that the distribution of each variable was approximately log-normal. Thus each series can be transformed to be approximately distributed standard normal by using the following transformation:

$$Z_i(t) = \frac{Y_i(t) - \hat{\mu}_{iy}}{\hat{\sigma}_{iy}} \qquad (4\text{-}1)$$

$$Y_i(t) = \ln(X_i(t) - \beta_{ix}) \qquad (4\text{-}2)$$

Table 4-2. Statistics for lake inflow sequences.[1]

a) Univariate statistics

	Lake Evaporation (E) (ins)			Lake Precipitation (P) (ins)			Combined Streamflows (Q) (ac-ft)		
Period	Mean	Standard Deviation[2]	Hurst Coefficient	Mean	Standard Deviation[2]	Hurst Coefficient	Mean	Standard Deviation[2]	Hurst Coefficient
1 1938-1983	60.91	4.49	.66	10.76	2.37	.64	1,774,458	819,192	.63
2 1890-1983	61.24	4.34	.44	10.44	2.28	.48	1,883,760	826,542	.78
3 1851-1983	61.13	4.31	.50	10.54	2.51	.49	1,966,921	877,976	.73
4 1890-1937	61.55	4.22	.59	10.13	2.15	.51	1,988,506	837,218	.72
5 1851-1937	61.25	4.23	.50	10.43	2.58	.58	2,068,682	900,664	.68
6 1851-1889	60.86	4.24	.69	10.80	3.00	.72	2,167,359	980,961	.76

[1] Values of statistics given in this table may differ slightly from values presented in other parts of this chapter. This is because they were estimated at different times during the data preparation process and does not affect the conclusions drawn from the values presented.

[2] Fiering corrected standard deviation (Fiering 1963).

Table 4-2. Statistics for lake inflow sequences.[1] (Continued)

b) Cross-correlation matrices[2] (underlined terms are significantly different from zero at the 5 percent level)

	Lag-zero (M_0)			Lag-one (M_1)									Lag-two (M_2)									Critical Value at Significance Level of 5%
Period	EP	EQ	PQ	EE	EP	EQ	PE	PP	PQ	QE	QP	QQ	EE	EP	EQ	PE	PP	PQ	QE	QP	QQ	
	-.642	-.471	.684	.409	-.121	-.228	-.103	.245	$\underline{.356}$	-.545	.720	.769	.284	-.085	-.059	-.188	$\underline{.317}$	.225	$\underline{-.319}$	$\underline{.441}$	$\underline{.397}$	
1 1938-1983	$\underline{-.630}$	$\underline{-.466}$	$\underline{.624}$	$\underline{.385}$	-.057	-.154	-.005	.108	.172	$\underline{-.452}$	$\underline{.607}$	$\underline{.581}$	.261	-.012	-.036	-.125	.188	.176	-.228	.177	$\underline{.355}$	.29
2 1890-1983	$\underline{-.735}$	$\underline{-.354}$	$\underline{.496}$	$\underline{.206}$	-.065	-.005	.014	.101	.034	$\underline{-.419}$	$\underline{.478}$	$\underline{.448}$	.150	-.047	-.113	-.117	.146	.123	-.084	.084	$\underline{.314}$	.20
3 1851-1983	$\underline{-.829}$	$\underline{-.318}$	$\underline{.398}$	$\underline{.186}$	-.094	-.076	-.061	.144	.128	$\underline{-.361}$	$\underline{.387}$	$\underline{.475}$	.108	-.039	-.102	-.085	.110	.133	-.113	.114	$\underline{.302}$	.17
4 1890-1937	$\underline{-.847}$	$\underline{-.278}$	$\underline{.424}$	.033	-.062	.086	.057	.058	-.010	$\underline{-.418}$	$\underline{.406}$	$\underline{.332}$	-.048	-.071	-.207	-.103	.084	.173	.028	.039	.247	.28
5 1851-1937	$\underline{-.933}$	$\underline{-.263}$	$\underline{.322}$	.085	-.114	-.055	-.088	.157	.138	$\underline{-.333}$	$\underline{.319}$	$\underline{.415}$	.033	-.056	-.131	-.067	.083	.141	-.063	.099	$\underline{.246}$	.21
6 1851-1889	$\underline{-1.000}$[3]	-.234	.229	.183	-.173	-.237	-.249	.224	.280	-.228	.234	$\underline{.483}$	.079	-.071	-.089	-.087	.098	.139	-.121	.108	.210	.31

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[1] Values of statistics given in this table may differ slightly from values presented in other parts of this chapter. This is because they were estimated at different times during the data preparation process and does not affect the conclusions drawn from the values presented.

[2] "EP" (typical) signifies cross-correlation between E (annual lake evaporation) and P (annual lake precipitation). Q = annual gaged inflow to lake.

[3] This cross-correlation is equal to -1.000 because lake evaporation was estimated from lake precipitation using Equation 2-9.

where

i = index for lake inflow variables:

= 1; lake evaporation

= 2; lake precipitation

= 3; combined streamflow of Bear, Weber and Jordan Rivers

$Z_i(t)$ = transformed value of i^{th} lake inflow in t^{th} year, distributed standard normal, N(0,1)

$Y_i(t)$ = transformed value of i^{th} lake inflow in t^{th} year, distributed normally, $N(\hat{\sigma}_{iy}, \hat{\mu}_{iy})$

$X_i(t)$ = historical value of i_{th} lake inflow in t^{th} year, distributed approximately log normal $(\hat{\mu}_{ix}, \hat{\sigma}_{ix})$

$\hat{\mu}_{ij}$ = sample mean of i^{th} lake inflow series in j^{th} form

$\hat{\sigma}_{ij}$ = sample standard deviation of i^{th} lake inflow series in j^{th} form

j = form of lake inflow series, i.e. X, Y or Z

$\hat{\beta}_{ix}$ = lower bound parameter for log normal distribution

Table 4-2b contains the lag 0, 1, and 2 cross-correlation matrices for the six time periods. Data pairs used to estimate cross-correlation coefficients were plotted in order to identify outliers which might distort estimates. These outliers were then excluded for making the final estimates presented in Table 4-2b. Based on the length of record used to estimate the cross-correlation coefficients, those coefficients which are statistically different from zero at the 5 percent level of significance are underlined. Comparison of correlation coefficients shows a general consistency between values estimated from different time periods, that is, considering the magnitude of a coefficient required to show a significant difference from zero (see last column of Table 4-2b).

Some anamolies can be identified, however, and these can be attributed to the methods used for data reconstruction as follows:

1) Since lake evaporation for the period 1851-1938 is estimated from a regression relationship on estimated lake precipitation the lag-zero cross-correlation EP, between lake evaporation (E) and lake precipitation (P), increases for time periods in which the reconstructed period is a greater fraction of the period length (i.e., increases going from period 1 to 6).
2) The lag-zero cross-correlation PQ, between lake precipitation (P) and combined streamflow (Q), decreases as the effects of reconstruction in the streamflow time series becomes more dominant. This illustrates that the reconstructed streamflow series do not preserve the lag-zero cross-correlation, PQ. A similar trend is evident in the lag-one cross-correlation QP.
3) The effects of poor preservation of the autocorrelation structure in the reconstructed streamflow series can be seen by observing the decrease in the lag-one and lag-two autocorrelation, QQ, going from periods 1 to 6, as the fraction of reconstructed streamflow data increases.

Because of these relationships, use of the reconstructed data for estimating serial or cross-correlation properties gives poor results. Therefore, only the period 1938-1983, for which essentially all series were measured and no cross-correlations between series were used, should be used to estimate the serial and cross-correlation properties for the stochastic model. However, if this period is also used to estimate the mean and variance of the three series then the resulting model would not represent the high flow characteristics of the late

1800s. Therefore, it was decided to experiment with a stochastic model based on estimating the mean and variance from the entire reconstructed record of 1851 through 1983. An evaluation of the adequacy of this model for representing the full range of historical flows is presented in a following section, "Model Performance Testing."

Table 4-2b shows that for the 1938-1983 period all lag-zero cross-correlations are significantly different from zero at the 5 percent level. For the same period, the M_1 cross-correlation matrix contains significant terms at the 5 percent level for lag-one autocorrelations of evaporation and streamflow and for lag-one cross-correlations of streamflow with evaporation and streamflow with precipitation. At lag-two, only the autocorrelation term for streamflow is significant at the 5 percent level. The implications of these observations for model selection will be discussed in the following section.

Model Form Selection

The commonly used forms of a multivariate stochastic model are the multivariate Markov model (Haan 1977), the multivariate first-order autoregressive model (AR(1)) (Matalas 1967), and the multivariate autoregressive moving-average (ARMA) models (Salas et al. 1980). The first two types are actually special cases of the ARMA models. The multivariate Markov model preserves the complete M_0 matrix but only the diagonal of the M_1 matrix. It was eliminated because of the significant lag-one cross-correlations in the data (see Table 4-2b). Examination of the autocorrelation structures of the three inflow series showed a first-order autoregressive structure for evaporation and streamflow and an independent structure (equivalent to zero-order autoregressive) for precipitation. On this basis together with the experience gained in the previous studies (James et al. 1979 and 1981) a multivariate AR(1) model form was tentatively selected for representing Great Salt Lake inflows in this study. The final selection of this model was based on the results of model performance testing (see Figure 4-1). Mathematically the multivariate AR(1) model applied to lake inflows is represented as follows:

$$\underline{Z}(t) = A\underline{Z}(t-1) + B\,\underline{\varepsilon}(t) \qquad (4\text{-}3)$$

where

$\underline{Z}(t)$ = vector of three transformed lake inflow variables in t^{th} year transformed and standardized to be normally distributed with zero mean and unit standard deviation

$$= \begin{bmatrix} Z_1(t) \\ Z_2(t) \\ Z_3(t) \end{bmatrix} = \begin{bmatrix} \text{Lake evaporation in } t^{th} \text{ year} \\ \text{Lake precipitation in } t^{th} \text{ year} \\ \text{Combined streamflow in } t^{th} \text{ year} \end{bmatrix}$$

$\underline{\varepsilon}(t)$ = vector of three normally and independently distributed random variables in t^{th} year with zero mean and unit standard deviation. Elements of $\underline{\varepsilon}(t)$ are independent of elements of $\underline{Z}(t-1)$

A,B = 3 x 3 parameter matrices for multivariate AR(1) model

Parameter Estimation

In order to apply the selected AR(1) model given by Equation 4-3 for generating the three required data series, it is first necessary to estimate the stochastic model parameters. These parameters are of two types: 1) parameters for transforming the historical series, X_i, to the standard normal form, Z_i (see Equations 4-1 and 4-2) and 2) the parameter matrices, A and B.

The transformation parameters, $\hat{\mu}_{iy}$ and $\hat{\sigma}_{iy}$, are estimated as follows:

$$\hat{\mu}_{iy} = \frac{1}{2} \ln \left[\frac{(\hat{\mu}_{ix}{}^2 - \hat{\beta}_{ix})/S}{C_{vix}^2 + 1} \right] \tag{4-4}$$

$$\hat{\sigma}_{iy} = [\ln (C_{vix}^2 + 1)]^{1/2} \tag{4-5}$$

$$\hat{\beta}_{iy} = \ln (\hat{\beta}_{ix}) \tag{4-6}$$

where

C_{vix} = sample coefficient of variation of X_i series

$$= \frac{(\hat{\mu}_{ix} - \hat{\beta}_{ix})}{\hat{\sigma}_{ix}}$$

$\hat{\beta}_{ix}$ = sample estimate of lower bound parameter

The third transformation parameter, $\hat{\beta}_i$, can be estimated by modifying Equations 4-4 and 4-5 and adding a third equation such that parameter estimates are based on the first, second and third central moments of X_i (i.e., $\hat{\mu}_{ix}$, $\hat{\sigma}_{ix}$, and the skewness coefficient, $\hat{\gamma}_{ix}$) (Haan 1977). However, for the length of series available in this study, this procedure would not be expected to provide reliable estimates of the transformation parameters. Therefore, $\hat{\beta}_{ix}$ was estimated subjectively based on the smallest historical value of the series, X_i. Table 4-3 presents the estimated values of these transformation parameters based on the entire reconstructed record, 1851-1983.

Parameter matrices A and B were estimated using the following equations based on the cross-correlation matrices M_0 and M_1:

$$A = M_1 M_0{}^{-1} \tag{4-7}$$

$$BB^T = M_0 - M_1 M_0{}^{-1} M_1{}^T \tag{4-8}$$

Table 4-3. Parameters for the transformation of historical data (1851-1983).

i	Inflow variables	$\hat{\mu}_{iy}$	$\hat{\sigma}_{iy}$	Lower bound $\hat{\beta}_{iy}$
1	Lake Evaporation (E)	0.323	0.248	1.299
2	Lake Precipitation (P)	-0.155	0.234	0
3	Combined Streamflow (Q)	0.515	0.416	0

where

T = symbol for transpose of matrix

-1 = symbol for inverse of matrix

Table 4-4 presents the estimated values of A and B based on the sample cross-correlation matrices which are given in Table 4-2b.

Model Performance Testing

Adequacy of the selected model was evaluated on the basis of 1) the preservation of statistics of the historical time series including the generation of periods of high inflows similar to those in the late 1800s, and 2) residuals testing.

Preservation of historical statistics

For purposes of comparing the generated and historical statistics, 100 sets of the three inflow series were generated. Each series was 46 years in length, corresponding to the length of the 1938-1983 historical period with which comparisons were made. Also, to put these comparisons on an equal basis the initial conditions for the generated series were set equal to the 1938 observed values for each inflow variable; and means

Table 4-4. Parameter matrices for the multivariate AR(1) model.

		Lake Evaporation (E)	Lake Precipitation (P)	Combined Streamflow (Q)
A Matrix				
	E	0.563	0.377	-0.128
	P	0.127	0.072	0.184
	Q	-0.071	0.373	0.309
B Matrix				
	E	0.886	0	0
	P	-0.730	0.655	0
	Q	-0.419	0.347	0.515

and standard deviations were also based on the 1938-1983 period. Table 4-5 contains a comparison of the historical and generated statistics. Statistics which are included in this table are the mean, standard deviation, Hurst coefficient, and lag-zero, one, and two cross-correlation matrices. In all cases the historical values of statistics are included within one standard deviation of the mean of the generated values, thus indicating a good preservation of the historical values.

Another test of the adequacy of the preservation of the characteristics of the historical statistics was to plot generated traces of lake inflows and visually observe the occurrence of high inflow periods of equal or greater severity than that experienced in the late 1800s. This comparison was made for only the combined streamflows since the reconstructed historical estimates of the other two series, lake evaporation and lake precipitation, did not exhibit similar extreme sequences. Fifty series were generated, 25 years in length, using 1983 initial

Table 4-5. Means and standard deviations of 100 generated traces.

Historical statistics based on the period 1938-1983 (length 46 years)
Average of 100 generated series of length 46 years and with 1938 initial conditions
Standard deviation of 100 generated series

		Lake Evaporation (E)	Lake Precipitation (P)	Combined Streamflow (Q)
a) Mean				
Hist. Stats		60.94	10.74	1774458
Aver. of Gen. Means		61.18	10.79	1775080
St. Dev. of Gen. Means		1.11	0.44	204931
b) Standard Deviation				
Hist. Stats		4.44	2.32	819193
Aver. of Ge. St. Dev.		4.39	2.26	757244
St. Dev. of Gen. St. Dev.		0.56	0.32	190209
c) Hurst coefficient				
Hist. Corr.		0.66	0.64	0.63
Aver. of Gen. Hurst coef.		0.68	0.49	0.65
St. Dev. of Gen. Hurst coeff.		0.09	0.15	0.13
d) Lag-zero cross-correlation matrix				
Hist. Corr.	E	1.000	-0.622	-0.449
Aver. of Gen. lag-zero cr. corr.		1.000	-0.605	-0.433
St. Dev. of Gen. lag-zero cr. corr.		0.000	0.137	0.172
Hist. Corr.	P		1.000	0.614
Aver. of Gen. lag-zero cr. corr.			1.000	0.593
St. Dev. of Gen. lag-zero cr. corr.			0.000	0.104
Hist. Corr.	Q			1.000
Aver. of Gen. lag-zero cr. corr.				1.000
St. Dev. of Gen. lag-zero cr. corr.				0.000

Table 4-5. Continued.

Historical statistics based on the period 1938-1983 (length 46 years)
Average of 100 generated series of length 46 years and with 1938 initial conditions
Standard deviation of 100 generated series

		Lake Evaporation (E)	Lake Precipitation (P)	Combined Streamflow (Q)
e) Lag-one cross-correlation matrix				
Hist. Corr.	E	0.378	-0.037	-0.149
Aver. of Gen. lag-one cr. corr.		0.326	0.008	-0.101
St. Dev. of Gen. lag-one cr. corr.		0.166	0.185	0.208
Hist. Corr.	P	0.005	0.090	0.167
Aver. of Gen. lag-one cr. corr.		0.035	0.048	0.110
St. Dev. of Gen. lag-one cr. corr.		0.158	0.182	0.176
Hist. Corr.	Q	-0.459	0.614	0.589
Aver. of Gen. lag-one cr. corr.		-0.446	0.589	0.519
St. Dev. of Gen. lag-one cr. corr.		0.169	0.118	0.138
f) Lag-two cross-correlation matrix				
Hist. Corr.	E	0.258	-0.017	-0.040
Aver. of Gen. lag-two cr. corr.		0.211	-0.040	-0.073
St. Dev. of Gen. lag-two cr. corr.		0.160	0.176	0.208
Hist. Corr.	P	-0.124	0.198	0.186
Aver. of Gen. lag-two cr. corr.		-0.013	0.075	0.071
St. Dev. of Gen. lag-two cr. corr.		0.182	0.162	0.166
Hist. Corr.	Q	-0.232	0.181	0.362
Aver. of Gen. lag-two cr. corr.		-0.144	0.177	0.188
St. Dev. of Gen. lag-two cr. corr.		0.195	0.184	0.203

conditions, with means and variances estimated from the 1938-1983 period. Six out of 50 series contained generated values for 1984 which exceeded the high 1983 inflow level of 5.1 million acre-feet which was higher than the highest combined streamflow in the late 1800s (4.5 million acre-feet in 1872, see Table 2-1). Inspection of generated combined streamflow series after the first few years of generation showed 11 generated series which exceeded the 1872 high combined streamflow level. Other comparisons involving sequences of high inflow years also compared favorably with the late 1800s period. On the basis of this type of model performance it was concluded that the model was capable of generating high inflow sequences equal to or more severe than those of the late 1800s.

Residuals testing

Residuals for a stochastic model are estimated by repeatedly using historical values for the variables to generate values of the variables for the next year. The residuals are the differences between the historical and generated values in the next year. This process is continued in a recursive manner throughout the historical period of record. In this study residuals series were estimated for the four periods 1938-1983, 1890-1983, 1852-1983, and 1852-1889. The residuals series are estimates of the series of terms $\underline{\varepsilon}(t)$ in Equation 4-3 for the historical period. If the selected stochastic model fits the historical record well, then each estimated series of residuals will be an independent series which is distributed normally with zero mean and unit standard deviation. Also there should be no significant cross-correlations between the three residual series corresponding to the three inflow variables.

Residuals series were calculated using the mean and standard deviation estimated from the 1851-1983 and 1938-1983 periods with the cross-correlation matrices estimated from the 1938-1983 period. Table 4-6 presents results of Porte Manteau lack of fit tests used to test for the presence or absence of significant autocorrelation structure in the residuals series for the four periods. No significant autocorrelation structure was inferred at the 5 percent level for lake evaporation or lake precipitation based on residuals estimated for the four periods and means and standard deviations estimated from either the 1851-1983 or 1938-1983 periods (see Table 4-6a and b, respectively). However, in the case of combined streamflows, the residuals showed significant autocorrelation at the 5 percent level during periods which included the high inflow period of the late 1800s. This suggests that the generated streamflows were showing less autocorrelation during the late 1800s than was observed. When tested at the 1 percent level the autocorrelation was inferred to be nonsignificant provided the mean and standard deviation from the entire period of record, 1851-1983, were used (see Table 4-6a). These observations would support the use of the 1851-1983 period for estimating the means and standard deviations.

Estimates of the means and standard deviations for the residuals series for the period 1851-1983 are presented in Table 4-7 based on means and variances estimated from the periods 1851-1983 and 1938-1983. Again the residuals for lake evaporation and lake precipitation indicate a satisfactory model because their means and standard deviations do not significantly differ from the theoretical values of zero and unity, respectively. However, some statistically significant differences do exist for the mean and standard deviation of the combined streamflow

Table 4-6. Porte Manteau lack of fit test results for residuals of multivariate AR(1) model.[1,2]

Period Number[3]	Period Used for Calculating Autocorrelogram of Residuals	Lake Evaporation	Lake Precipitation	Combined Streamflow
a) Means and standard deviations for AR(1) model estimated from 1851-1983 period[4]				
1	1938-1983	N-S	N-S	N-S
2	1890-1983	N-S	N-S	N-S
3	1851-1983[5]	N-S	N-S	S, N-S (1%)
6	1851-1889[5]	N-S	N-S	S, N-S (1%)
b) Means and standard deviations for AR(1) model estimated from 1938-1983 period[4]				
1	1938-1983	N-S	N-S	N-S
2	1890-1983	N-S	N-S	S, S (1%)
3	1851-1983[5]	N-S	N-S	S, S (1%)
6	1851-1889[5]	N-S	N-S	N-S

[1] N-S = autocorrelogram does not show significant autocorrelation structure.[2]
S = autocorrelogram does not show significant autocorrelation structure.[2]

[2] All test results are for 5 percent level of significance unless otherwise indicated by (1%) in which case test results are for 1 percent level of significance.

[3] Period numbers refer to periods described in subsection entitled, "Time series statistics" of this chapter.

[4] A and B parameter matrices estimated from 1938-1983 period.

[5] 1856 was excluded because it was judged to be an outlier. All pairs of data utilizing 1856 were dropped in the estimation of the autocorrelation coefficient.

Table 4-7. Means and standard deviations of residuals of multivariate AR(1) model[1] for 1851-1983 period. (Underlined values are statistically different from the theoretical values[2] at the 5 percent level of significance.)

	Lake Evaporation	Lake Precipitation	Combined Streamflow
a) Means and variances estimated from 1851-1983 period[2]			
Mean	-0.014	-0.002	0.022
Standard Deviation	1.12	0.87	1.64
b) Mean and variance estimated from 1938-1983 period[2]			
Mean	0.094	-0.117	0.57
Standard Deviation	1.11	0.96	1.79

[1] Theoretical values of mean and standard deviation are zero and unity, respectively.

[2] A and B parameter matrices estimated from 1938-1983 period.

series. For the case in which the mean and standard deviation were estimated from the same period as the residuals were estimated (i.e. 1851-1983), the mean of the estimated residuals is not significantly different from the theoretical value of zero (see Table 4-7a). However, for this same case, the standard deviation is significantly different from its theoretical value of unity. In depth inspection of the series for the source of this difference shows that it can be attributed to the larger values of the residuals estimated in the late 1800s and it is not a problem throughout the period.

For the second case in which the mean and standard deviation were estimated from the 1938-1983 period and the residuals were estimated from the 1851-1983 period the mean of the estimated residuals is statistically different from the theoretical value of zero. This difference may be attributed to the use of the lower mean from the 1938-1983 period through the earlier high flow period. This biasing effect, which increases the mean of the estimated residuals, also causes a slight increase in their standard deviation, which is also therefore statistically significant.

On the basis of these comparisons the mean and standard deviation were estimated from the 1851-1983 period. For these parameters the mean of the estimated residuals is not statistically different from zero and the standard deviation is acceptably close to unity except for the period from 1862 to 1872. However, visual inspection of generated series indicated that the model is capable of generating extreme sequences of the type observed in the late 1800s. A possible explanation for the significant difference in standard deviations is that the high inflows are such a rare occurrence that a Type I error (Haan 1977) occurs when applying the statistical test.

In summary, the use of the multivariate AR(1) model with mean and standard deviation estimated from the period, 1851-1983, and the multivariate parameters estimated from the period, 1938-1983, was judged to be acceptable for this study. The decision to accept this model was based on the preservation of the historical statistics and the evaluation of residuals.

CHAPTER 5

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 cost of control measures. 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 type 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 lake 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 materially 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 damage sequence could be estimated, and the amount the present worth of the damages is reduced by lake level control would be the net benefits to compare with the present worth of the control measure costs which include construction costs and OM&R. 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 activities are directly or indirectly affected by fluctuations in the levels of terminal lakes. Falling lake levels make lake access more difficult at beach areas, 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 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 terminated or suspended, 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.

Damage Simulation Model

The damages from the time sequences of annual stages were 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 for use in the 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 at the time 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 5-1 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. The process used to simulate the damage in a given year is outlined on another flow diagram on Figure 5-2.

The damage model needs to have north arm lake elevations for determining damages to entities located on the north arm. These elevations are calculated by the damage model using the peak south arm and the peak of the average, "one-lake" elevation which were determined by the water balance model with the relationship:

$$ELPN = ELPS - 2.632\ (ELPS - ELPA) \tag{5-1}$$

where

ELPN = peak elevation of the north arm

ELPS = peak elevation of the south arm

ELPA = peak elevation of the "one lake" lake elevation

This equation is based on the fairly realistic approximation that the surface area of the south arm is 1.632 times as large as the surface area of the north arm. Consequently, for every foot that the south arm is above the average elevation, the north arm would be below the average

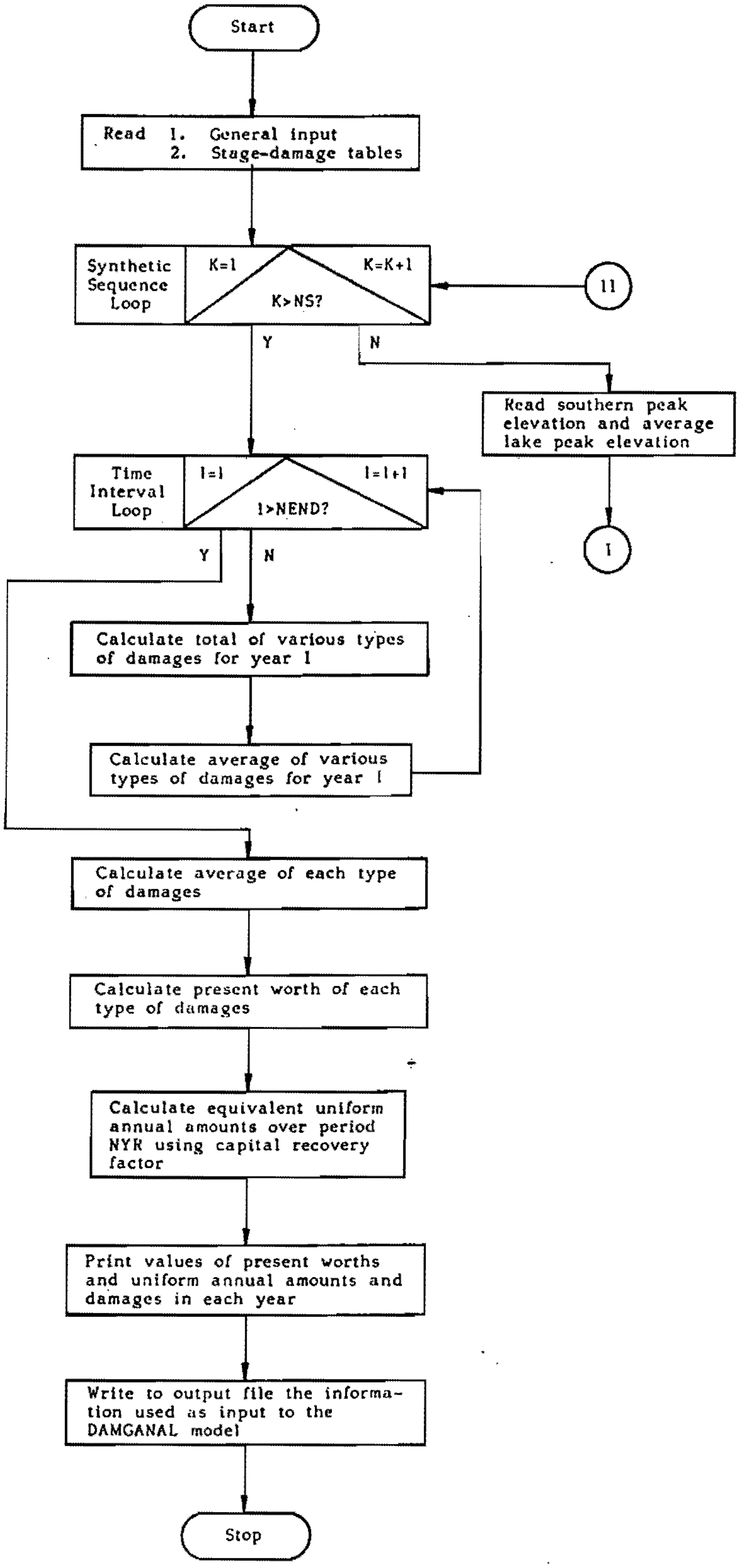

Figure 5-1. Overall flow diagram for the damage simulation model (see also Figure 5-2).

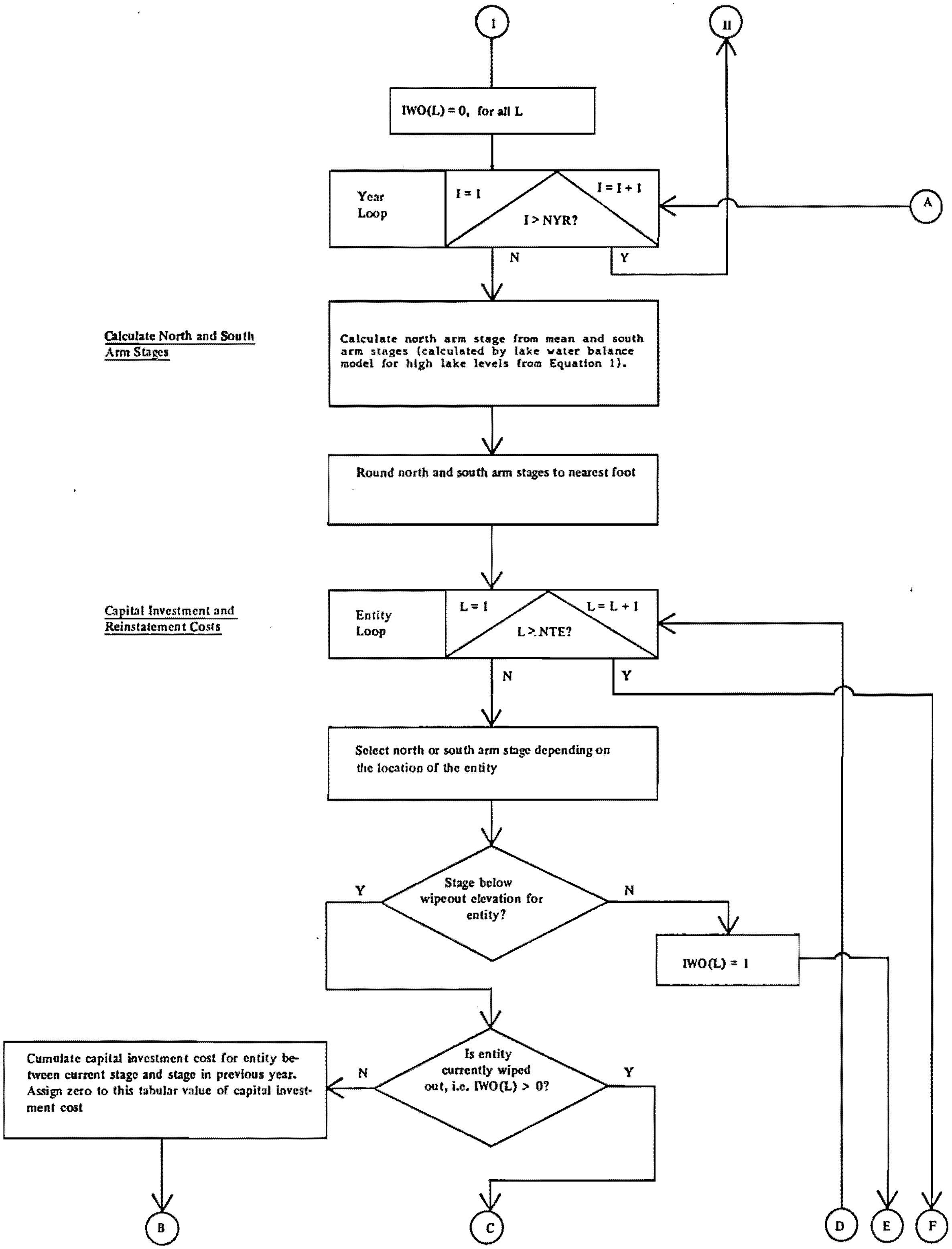

Figure 5-2. Flow diagram for the damage simulation algorithm.

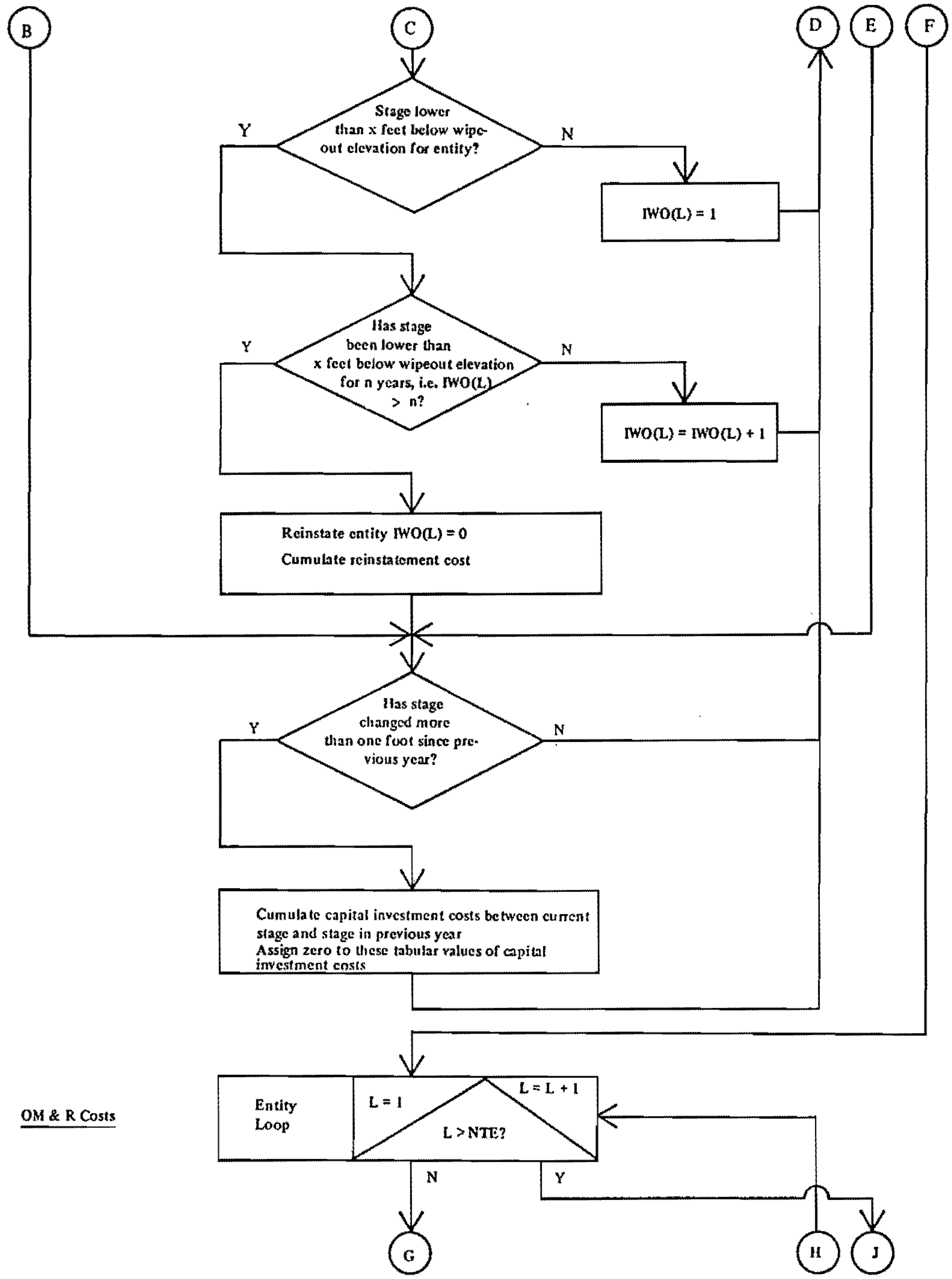

Figure 5-2. Continued.

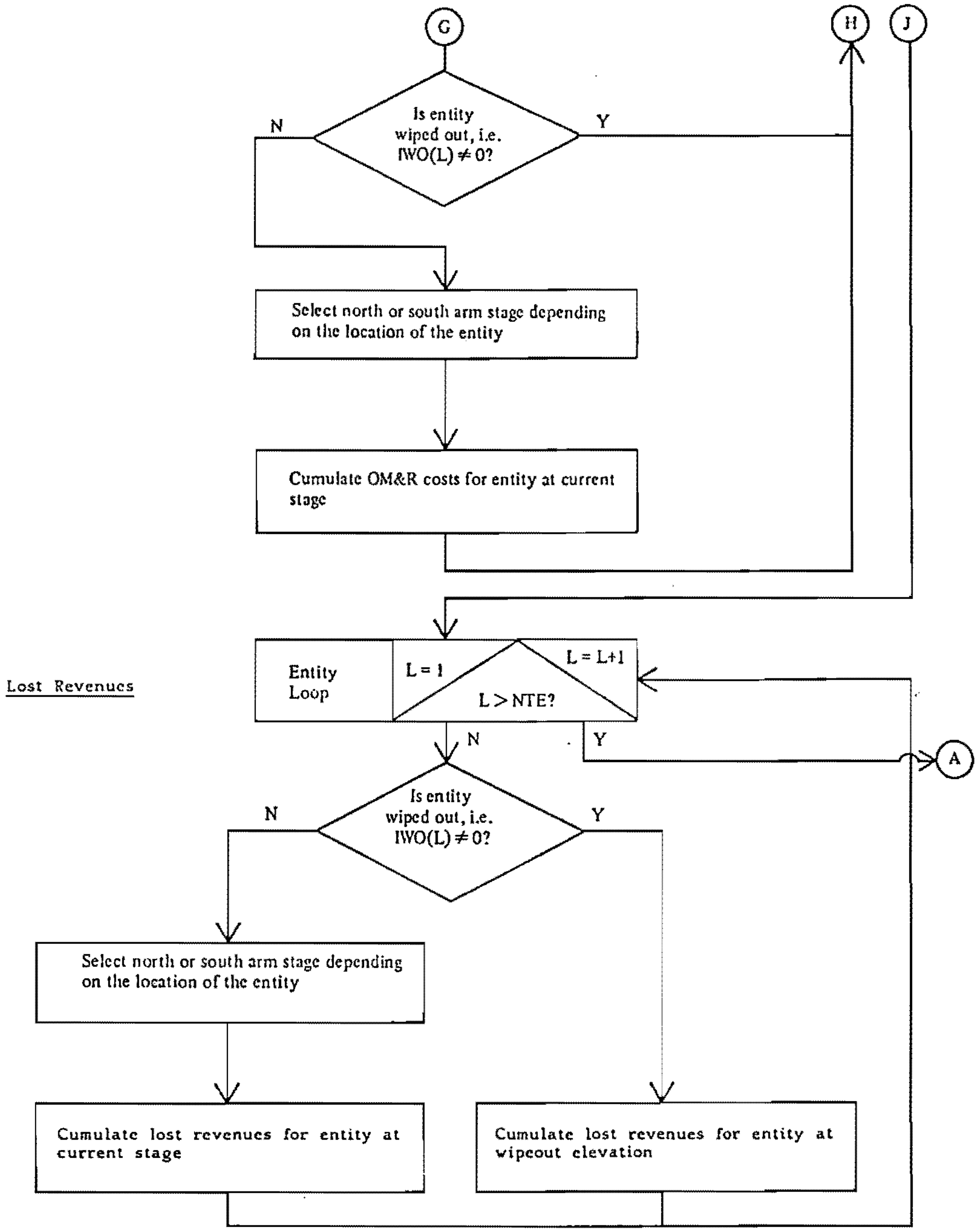

Figure 5-2. Continued.

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 elevation by 1.632 feet, and the difference between the two arms would be 2.632 feet.

Estimation of damages from a lake stage sequence

Figure 5-2 is a flow diagram for the damage simulation algorithm. The algorithm sums economic losses associated with rising or falling lake levels as classified into four groups:

1. Capital investment in damage mitigation measures.
2. Annual operation, maintenance, and repair costs (OM&R) 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.

For each year of the simulation, given the stage simulated by the water balance model, these four costs are estimated from relationships with the lake stages constructed by the Bureau of Economic and Business Research (1983) through a series of interviews with the managers of most of the relevant properties. A separate table was compiled for each entity (i.e. railroads, roads, bird refuges, beaches, marinas, industrial plants).

Damages are simulated for NTE (30 are used in the current data) damage centers over the NYR years in the synthetic sequences of rising and falling lake stages generated 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 wipeout elevation after a damage center L has been wiped out. Stages for the north or south arms are used as specified for each entity in the input data. The remaining computations 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 building or raising levees. As such an entity experiences lake stages that are higher than it has faced previously, it may raise its levees. If the lake subsequently falls and rises again, it will not be necessary to raise the levees (except as required because of settlement into the foundation muds) until stages higher than those previously experienced occur.

The damages estimated by property managers and owners for the Bureau of Economic and Business Research were summarized in tables of capital investment and annual maintenance costs associated with the lake rising or falling various distances from its present stage. Since the cost data were obtained by 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 5-1 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 4205 feet above mean sea level in 1983, the hypothetical company raised its levees to provide protection up to approximately 4206 feet. If, as was estimated at that

Table 5-1. Costs of damage mitigation measures in $1000's vs. stage for a hypothetical mineral extraction company on the Great Salt Lake.

Lake Stage Feet, msl	Capital Investment	Annual OM&R	Reinstatement[b] Cost	Lost Benefits
4185	0	0	0	0
4190	0	0	0	0
4193	0	0	0	0
4195	0	0	0	0
4199	0	0	0	0
4200	0	0	0	0
4201	0	0	0	0
4202	0	0	0	0
4203	0	50	0	0
4204	0	50	0	0
4205	0	100	0	0
4206	0	100	0	0
4207	1800	200	0	0
4208	0	200	4000	0
4209	2400	260	0	0
4210	0	260	0	0
4211	3600	400	0	0
4212	0	400	0	0
4213	0[a]	0[a]	0	1500
.	.	.	.	.
.	.	.	.	.
4220	0	0	0	1500

[a] Facility wiped out at 4213.

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

time, the lake rises to 4207 feet, the company estimated a cost of $1.8 million (1983 dollars) to raise its levee to provide an additional two feet of protection. For a rise to 4209 feet, an additional investment of $2.4 million was estimated as required. A rise to 4211 feet would require still an additional $3.6 million to provide flood protection to approximately 4212 feet. At an elevation of 4213 feet, the company could no longer afford further flood protection, perhaps because they could no longer raise their levees because of foundation problems. Thus, 4213 feet has been designated the "wipeout elevation."

Even though the company had already invested hundreds of thousands of dollars before the interview in raising their levees to provide protection to 4206 feet, these costs are not shown on Table 5-1. 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 after the lake recedes to where it is no longer needed for years. In each year of the damage simulation, OM&R costs are taken from Table 5-1 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 4207 feet are included in Table 5-1 between 4203 feet and 4206 feet.

In estimating damages, 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. has been "wiped out") and restored when facilities are reinstated. Reinstatement may occur more than once after wipeouts during a 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 wipeout. 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.

Reinstatement

After a wipeout occurs, the lake level will later fall to where a previous land occupancy could be restored. However, the reinstatement will probably not occur immediately. 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 wipeout elevation before they will restore property that they previously abandoned. The timing of reinstatement selected by the damage simulation model is determined by summing the number of years the lake has been continuously x feet below the wipeout elevation. When the number of years exceeds n, reinstatement is assumed at cost C. For the Great Salt Lake damage simulation, x, n, and C were varied by entity.

Computer programming

The damage simulation algorithm programmed following the flow diagram in Figure 5-1 and nested in a simulation model is documented in Appendix D. 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, 1983, by using any specified interest rate. In addition, an equivalent uniform annual series is calculated for each present worth by:

$$R_m = P_m \text{ (R/P, m years, i\%)} \qquad (5\text{-}2)$$

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, i%) = capital recovery factor for m years at i percent discount rate

Damage and Benefit Analyses

An additional program is used to determine the frequency distribution of damages or benefits. A large number of lake level traces can be generated. This model then sorts the damages estimated for selected years or over selected periods for any given lake level control option. For example, if 1000 synthetic damage traces had been generated by the damage simulation model, these traces would be read and sorted by the damage analysis program. The result is an array of 1000 damages which are ranked in order of decreasing damages. Selected damages in this list will then be printed as specified by the user. For example, if the 250th, 500th, and 750th damages in this list were printed, they would correspond to the 25th, 50th, and 75th precentile of total damages in the given year. Such an option can show how the damages are distributed. The sorting and printing can be performed for specified individual years, for specified types of damages (for example, revenue losses, state and local losses or total losses), and for specified percentiles of damages. The result is a very useful table that greatly aids a planner to determine the likelihood of various economic effects of lake level control options.

The analysis program also has the capability of comparing the damages of each trace developed from any specified option with the damages of each trace developed from other specified options. The difference between these traces yields a trace of marginal benefits from supplementing one option with another. These benefits can then be sorted to determine the frequency distribution of the benefits of any option compared to any other option. Appendix D contains a listing of the computer program and examples and descriptions of the input and output for the model.

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APPENDIX E

Approximate Method for Monthly Updating of Estimated Lake Highs

When estimating the probable lake high for the following summer at the beginning of a water year, one knows the beginning lake level, the antecedent moisture conditions in the basin, and the precipitation and evaporation totals for the previous year. Events during the year itself (streamflow, precipitation, and evaporation) are partially serially correlated with events during the previous year, but they are also partially random in that they cannot be predicted on the basis of what occurred before. Possibly some of this randomness could be reduced from information and relationships based on events external to normal weather patterns (such as volcanic eruptions, solar weather, planetary movements, etc.), but quantitative relationships based on these factors are yet to be developed. For the present, it is assumed that these external factors are to be neglected and that one can only predict event totals from one year to the next to the extent that an event series is serially correlated as determined from the analysis of historical data series.

The Great Salt Lake precipitation data show a relatively low level of correlation on an annual basis ($R = 0.104$). Month-to-month correlations are also very low. Thus one begins a year with a great deal of uncertainty as to what the lake levels will be at the end. However, as the year progresses, one can improve the estimate on the basis of updated information on moisture conditions. Precipitation measurements provide an excellent and easily obtained index that can be used for updating the coming lake level high.

For example, at the beginning of water year 1984, the annual model for estimating lake level probabilities gave the distribution shown in Table E-1. If 1984 were an average water year, one would expect, according to that table, an annual high of 4206.9. However, as the year unfolded, precipitation that occurred by December 31 showed the year to be much wetter than average.

In order to assign a frequency to these conditions, one has to adopt some index of wetness. The ideal information would be monthly flows into the lake and evaporations from the lake. However, such information is not readily available, and simplicity suggests precipitation as a single readily available index. Using precipitation measurements at the Salt Lake Airport and assuming that the rise in lake level is primarily affected by October through June precipitation, the historical frequency distribution of annual precipitation at the Salt Lake Airport (1940-1983) was plotted as shown in Figure E-1. By assuming no correlation from month to month in the precipitation data, one can apply Figure E-1 as outlined in Table E-2. In Table E-2, the above indexing, assumptions, and data apply precipitation data available through December 31 to estimate water year 1984 to be about a 10 percent water year. Table E-1 gives the best estimate of the 1984 lake level high for this event frequency to be 4208.4. The table can be easily updated and the results applied as the months go by. The final estimate of peak lake level made based on June data was 4209.0 which compares very favorably with the actual 1984 peak of 4209.25 recorded on July 1.

If one were able to make quantitative estimates of the effects of external happenings on precipitation, those estimates could be incorporated into Table E-2. However, that was not done here.

Table E-1. Probability of annual peak elevation of the Great Salt Lake exceeding various stages at least once by a given year given the information available on October 1, 1984.

Year	4207	4208	4209	4210	4212	4215	4218
1984	0.4700	0.1930	0.0460	0.0100	0.0020	0.0000	0.0000
1985	0.5540	0.3140	0.1820	0.0830	0.0220	0.0010	0.0000
1986	0.5850	0.3690	0.2300	0.1340	0.0430	0.0040	0.0000
1987	0.6000	0.3820	0.2470	0.1490	0.0600	0.0060	0.0000
1988	0.6160	0.3950	0.2600	0.1630	0.0650	0.0070	0.0000
1989	0.6240	0.4050	0.2770	0.1750	0.0710	0.0070	0.0000
1990	0.6300	0.4120	0.2880	0.1800	0.0740	0.0080	0.0000
1995	0.6500	0.4390	0.3110	0.2040	0.0860	0.0100	0.0000
2000	0.6680	0.4560	0.3240	0.2160	0.0920	0.0120	0.0000
2010	0.6890	0.4830	0.3530	0.2380	0.1000	0.0140	0.0000
2020	0.7210	0.5130	0.3720	0.2500	0.1040	0.0150	0.0000
2030	0.7450	0.5430	0.3920	0.2650	0.1120	0.0150	0.0000
2040	0.7590	0.5610	0.4030	0.2750	0.1210	0.0150	0.0000
2050	0.7720	0.5770	0.4190	0.2900	0.1330	0.0190	0.0000

Table E-2. Approximate method for monthly updating of lake level estimates.

Month	Mean Airport Precipitation	1983-84 Airport Precipitation	1983-84 Departure	Cumulative Departure	Precipitation Frequency	Most Probable 1984 High
						4206.9
October	1.33	1.62	+0.29			
				+0.29	45%	4207.1
November	1.27	2.23	+0.96			
				+1.25	33%	4207.5
December	1.36	4.37	+3.01			
				+4.26	10%	4208.4
January	1.32	0.50	-0.82			
				+3.44	15%	4208.2
February	1.23	0.95	-0.28			
				+3.16	18%	4208.1
March	1.81	0.95	-0.86			
				+2.30	23%	4207.9
April	2.08	4.43	+2.35			
				+4.65	9%	4208.5
May	1.59	1.98	+0.39			
				+5.04	8%	4208.6
June	1.06	1.86	+0.80			
				+5.74	5%	4209.0
Sum	13.05	18.89				

Note: Probability distribution is based on Salt Lake Airport precipitation records (1940-83). The method neglects any serial correlation in monthly precipitation amounts as these were found to be small from analysis of the historical data.