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Assessment of Control Alternatives for the Great Salt Lake

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INTRODUCTION

Over the last few years, the rising level of the Great Salt Lake has changed Utah. It has inundated vast waterfowl feeding areas, crippled the salt industry, required raising transcontinental freeways and railroads, threatened metropolitan waste treatment plants, caused a major electrical outage, and damaged many properties. If nothing is done, approximately $3.6 billion of damages in 1985 dollars can be expected by 2050 (James et al. 1985, p. 4). This threat led the State Legislature to set aside $100 million (an amount approximating the damages that had then occurred) in January 1985 to identify, select, and implement remedial measures. The rise has slowed. However, the lake entered February 1986 at its highest level since 1877, and a large storm of tropical origins brought a record one-month rise, tying the high of the previous spring at 4209.95, with heavy snowpacks in the mountains and at least three months of precipitation left before the normal date of the annual peak. Nevertheless, the legislature is diverting some of the funds to other purposes.

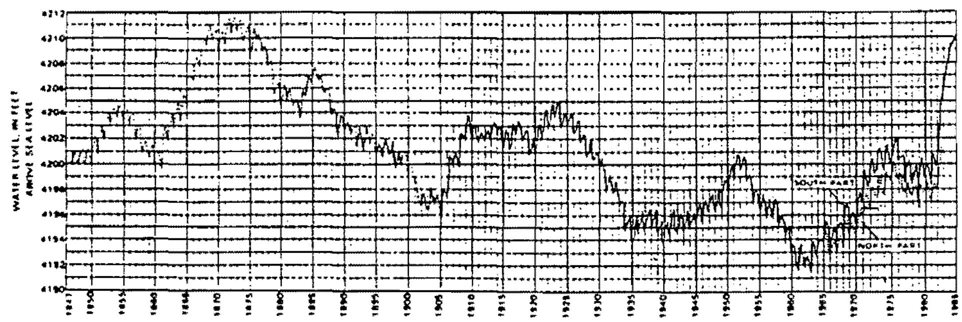

Figure 1. Plotted series of Great Salt Lake levels and salinities, 1851-1984: Adapted by Arnow (1984) from Currey (1980).

As shown in Figure 2, the rise has greatly enlarged the surface area of a shallow water body. Table 1 shows how the historic variation has increased the lake surface area from 587,000 to 1,556,000 acres, a range that varies normal annual evaporation from 1,470,000 to 4,800,000 acre feet. The lake will rise as long as inflows exceed actual evaporation. Total inflows were 5,300,000 acre feet in 1983, 6,200,000 acre feet in 1984, and 3,800,000 acre feet in 1985. The rise continued in 1985 because of abnormally low evaporation.

PROPOSED CONTROL MEASURES

Causeway Breaching: The lake was divided into north and south arms (Figure 3) by construction in 1959 of a railroad causeway. The rivers flow into the south arm while the north arm accounts

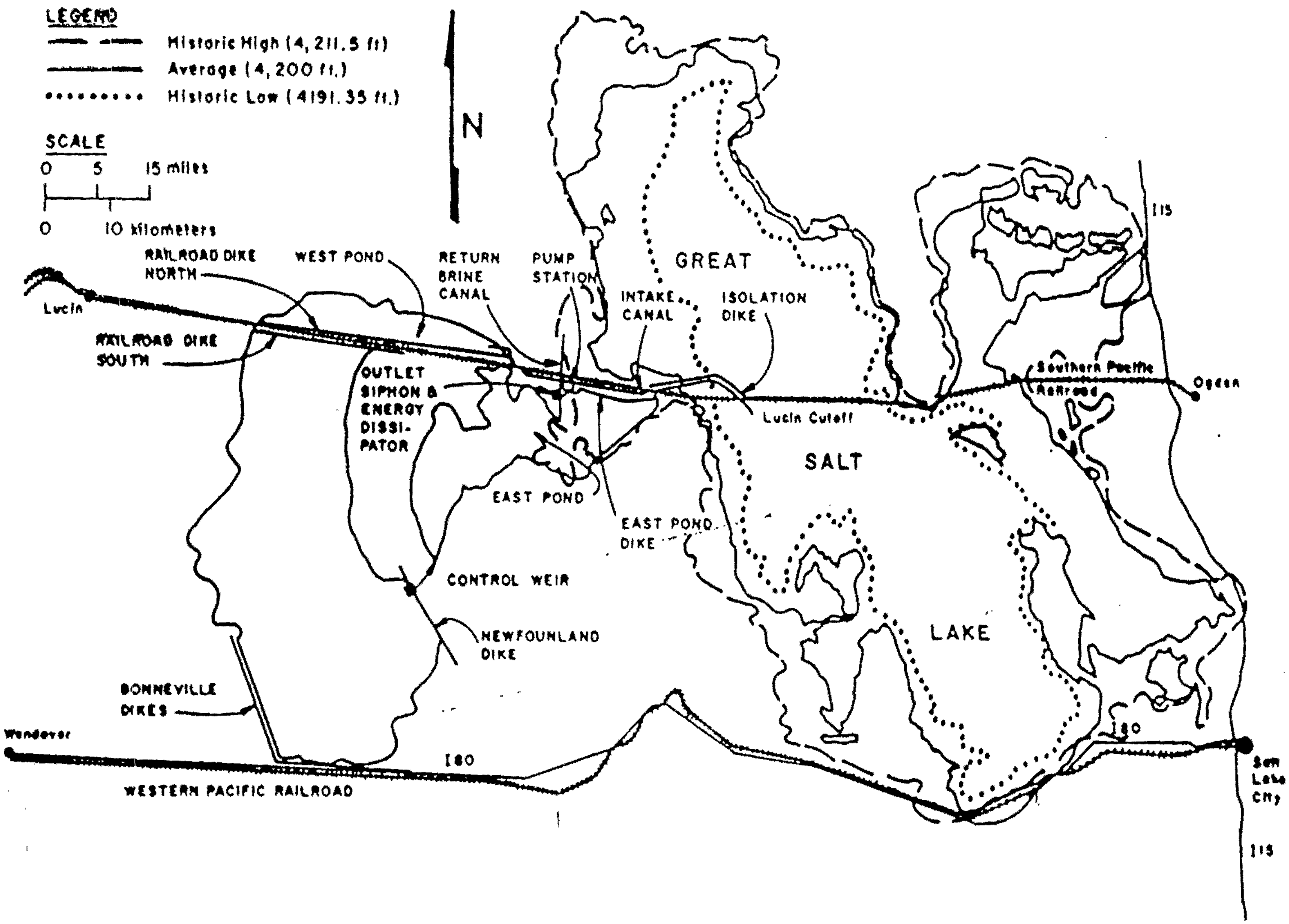

Figure 2. Map Outline of the West Desert Pumping Scheme. Source: Eckhoff, Watson, and Preator Engineering, 1983.

What can be done about a rising terminal lake? Serious proposals include shoreline levees to protect areas with high damage potential, island-connecting levees that partition the lake so that separated levels can be varied, upstream projects to increase the consumptive use of fresh water in the tributary basin, pumping excess water to the West Desert for controlled storage and added evaporative surface, and flow diversions to adjacent basins. This paper describes how one can estimate meaningful hydrologic probabilities, use them to assess the risk of economic loss, and assess the proposals. This background will then be used to discuss the principles of lake level control that can be used over the long run at the Great Salt Lake and elsewhere.

LAKE LEVEL HISTORY

As shown in Figure 1 the lake stood at about 4200 feet msl when Utah was settled in 1847. In 1862, it began a rapid rise to 4211.6 feet msl in 1873. This historic peak was followed by a downward trend to a low of 4191.35 feet msl in 1963. Many took the 90-year drop as a sign that increasing consumptive use in the tributary basin would cause the lake to go dry, and development that profited from the Lake drew closer to it. However, the level instead rose to about 4200 in 1982 and to almost 4210 in 1985.

Table 1. Physical Data for the Great Salt Lake.

Surface Elevation (feet)a	Surface Area (1000 acres)	Storage Volume (1000AF)	Lake Evaporation (1000AF/year)b	Mean Salt Concentration (percent)
4191.35-L	587	8,570	1470	27.5
4200	1079	15,370	2908	22.5
4205	1251	21,277	3648	16.3
4211.60-H	1556	30,057	4800	11.4
4216	2227	38,671	6900	8.9

aL = historic low - 1963; H = historic high - 1873.
bEvaporation that would occur during an average evaporation year and an index of the inflow required to maintain the given water surface elevation.

Table 1. Physical Data for the Great Salt Lake.

for about a third of the evaporation. The head required for flow into the north arm through small culverts and by seepage causes a level difference that reached almost 4 feet during the rapid rise of 1984. The first action to slow the rise was to breach the causeway with a 300-foot opening in August 1984. The head difference required for the enlarged opening is about 0.8 foot, and the south arm has been lowered by about 1.5 feet.

Shoreline Levees: Levees are a viable method for protecting areas with high damage potential. The property types shown on Table 2 parameter values by are protected by levees as shown on Table 3. About half of the damages would be prevented by the 19 shoreline levees shown on Figure 3. Of these, 12 were classified as high priority based on a criterion of protecting the public

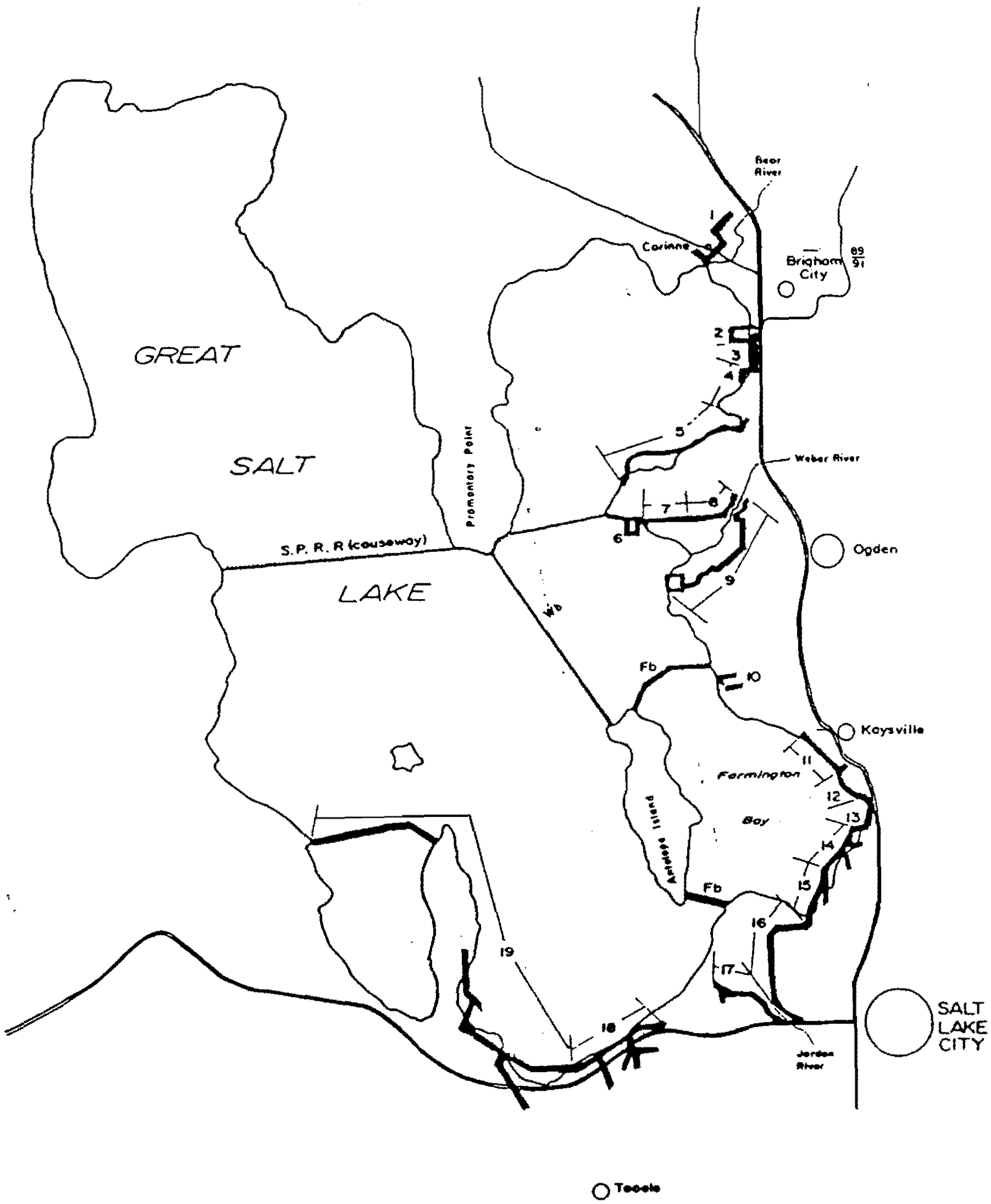

Figure 3. Site map with levee locations.

health and safety specified by Governor Matheson, and 8 are shown to be potentially economically feasible on Table 3.

In-Lake Levees: Two in-lake levee configurations have been proposed and gained some political popularity. The Farmington Bay enclosure would connect Antelope Island to the mainland with levees at its north and south ends (Fb on Figure 3). The West Bay

Table 2. Property Types Near the Lake.

	Property Type
A	Mineral Extraction Companies
B	Main-route Railroads
C	Spur Railroads
D	Interstate Highways
E	Other Roads
F	Waterfowl Refuges
G	Recreation Areas
H	Agricultural Lands
I	Residential Buildings
J	Industry
K	Wastewater Treatment Lagoons
L	Wastewater Treatment Plants
M	Utilities
N	Airports

enclosure (Wb) would connect the north end of Antelope Island Promontory Point. The Farmington Bay scheme costs about $80 million (design elevation of 4212) compared with $28 million for shore line levees of the same height. The present worth of the benefits to the additional recreation and waterfowl facilities that would be protected is only about $1.2 million (James et al. 1985).

Table 3. Summary Data on Control Measures.

		Property Types														Levees at 4217
Measure	Pr	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Value	B/C[b]
L1-Corinne	H					X			X	X		X				1734	0.39
L2-Perry Lg	H											X				4217	0.32
L3-Perry	L				X				X	X						6580	0.96
L4-Willard Lg	L											X				300	0.53
L5-UPRR-Weber	H			X		X			X	X	X	X				65222	0.72
L6-LMtn Lg	H											X				300	0.23
L7-LMountain	L										X				X	40000	1.30
L8-WWarren	L					X			X	X						7993	1.65
L9-Taylr-Hpr	L					X			X	X						4802	0.29
L10-NDavis	H												X			38000	8.35
L11-WKaysvl	H								X				X	X		13925	0.30
L12-WhlrFarm	L								X					X		5138	0.60
L13-Cntrvl	H			X	X	X			X	X				X		21916	2.35
L14-SDvsGrp	H					X			X	X	X		X	X		25159	0.34
L15-JordanR	H					X			X	X	X		X	X		589000	20.21
L16-Airport	H														X	25159	1.33
L17-IndPark	L										X					11700	0.13
L18-SShore	H	X	X		X	X					X					98600	2.05
L19-TooeleCo	H	X	X	X	X	X			X		X			X		542000	5.51
Unprotected		X	X			X	X	X	X	X						36350	
FarmngtnBay																720[c]	1.28
WestDesPump																1865[c]	14.31

[a]Estimated value of property protected in $1000.
[b]Benefit-cost ratio for the one-percent simulated sequence sorted damage wise.
[c]Rounded in $ million.

Additional benefits would accrue from a shorter levee highway route from Ogden to Tooele and from greater recreation opportunities on Antelope Island; but these are far too small to make up the difference. In addition, inflows are insufficient to maintain fresh water in Farmington Bay, and past municipal waste deposits may cause a significant odor or health hazard (Israelsen et al. 1985). These problems would be less with the West Bay enclosure because of the larger inflows from the Bear River, but the cost of the scheme would also be much greater.

Water Development: Reservoirs constructed and operated to supply water for consumptive use would reduce inflows to the lake. Reasonable projects could reduce flows into the lake by 300,000 acre-feet annually. A possible storage variation would be to manage groundwater in the tributary basin so as to draw levels down by pumping for beneficial use during dry periods for recharge during wet periods (Jenab et al. 1985). Difficulties with the water development approach are:

1. The large amount of storage required to lower so large a lake gives low benefits per unit of water consumed (about $1.30 per acre foot (James et al. 1984)).

2. The reservoirs could not be completed until after 1995 whereas the benefits are much larger now when the lake is high.

3. Individuals dependent on the water supply lack flexibility to reduce their use during dry periods, and this would accentuate the problems caused by falling lake levels during dry cycles.

West Desert Pumping: Excess water within the lake can be pumped (average lift of 10 to 20 feet) into proposed Western Desert evaporation ponds configured as shown in Figure 2 (Eckhoff, Watson, and Preator Engineering 1983). The ponds would cover about 450,000 acres to a design depth of a little over 3 feet and would provide an estimated 1,100,000 acre feet of annual evaporative outflow capacity. Costs are about $40 million for constructing and $4.2 million annually for maintenance and energy. Issues to be resolved before implementing this scheme include:

1. The military uses the West Desert as a bombing range, and a substantial share of the cost of the scheme is for internal diking to keep water out of their area. Even with such dikes, the military is concerned that fog caused by the added water surface will interfer with their operations.

2. The West Desert evaporation will add humidity to the air passing over the lake and may substantially reduce evaporation. The effect of storage in the West Desert alone can achieve about 3 inches of level reduction whereas the full evaporation could increase the amount to about 4 feet for future rises. Negative evaporative feedback would reduce this larger amount.

3. The entire operation would be drowned out at very high lake levels. Operations for the 4220 range should be carefully examined.

4. The west desert already serves as an evaporative sump for a drainage area about the size of the basin tributary to the Great Salt Lake. The volumes of water involved and the effects of mixing the ponds with the natural processes during the extremely wet years of particular concern are unknown.

5. The benefits from the scheme could be increased by joint use for salt management in mineral extraction or by energy generation in salt-gradient solar ponds.

Diversions: Proposals have been made to convey excess water from the Bear River in a canal for discharge down the Portneuf River and hence down the Snake and Columbia Rivers, to pump excess water from Utah Lake for use in desert basins to its south and west, or to build a canal along the north slope of the Uintah Mountains for discharge to the Colorado River. All three alternatives are costly, and the additional flow in the Portneuf River may cause flooding and erosion problems.

Storages: Several sites exist immediately to the south and west of the Great Salt Lake where water could be pumped, temporarily stored for lake level control, and used to generate electricity within a pumped storage operation to partially pay for the cost. Utah Water Research Laboratory (1984) performed a reconnaissance of the Puddle Valley site, the most promising one, and found that the scheme would not be cost effective.

SIMULATION MODELS

Planning lake level control requires 1) statistical representation of the correlation and year-to-year relationships found in lake inflow and outflow, 2) stochastic generation of a large number of sequences of lake level fluctuation, and 3) estimators of damages wrought by rises and falls and the benefits from control measures. The interactions among climatic, topographic, and economic factors create a complicated joint probability situation that is best analyzed by simulation.

The large storage volume to inflow ratio of the Great Salt Lake makes the risk of inundation highly dependent on the current level. The point is illustrated with Figure 4. The top portion shows flood frequency curves for riverine stages to remain uniform. The lower portion shows how, given an initial stage, the frequency distribution for lake levels starts with a relatively narrow band for the following year, expands over time, and requires many years (presently about 35 for the Great Salt Lake) to stablilize. Furthermore, these lake distributions cannot be directly used to estimate damages as can the single riverine distribution. The initial distribution indicates what one can expect during the coming year, and the range shows extremes that might be reached during a rise or fall. However, the lake distribution do not show the year-to-year sequence of level changes necessary for estimating damages in a situation where a lake rise measured in years gives the threatened parties damage-reduction opportunities that are not available in riverine situations. The damage is highly dependent on the rate of rise

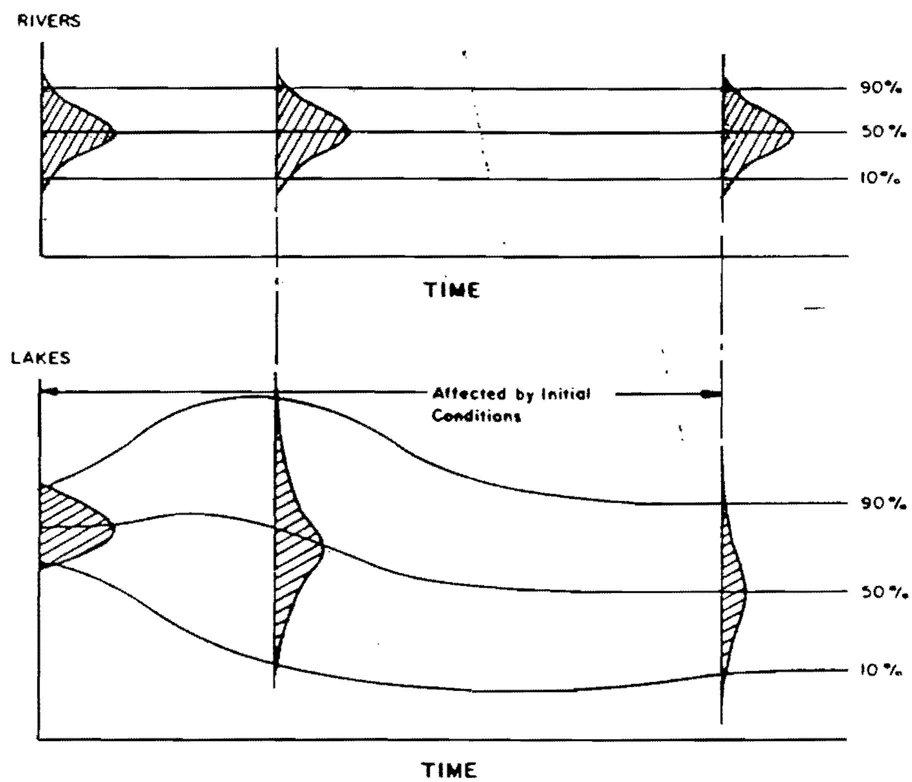

Figure 4. Time changes in flood frequency relationships, river v. lakes.

and exhibits a large hysteresis between rising and falling periods. These interactive hydrologic and economic factors were jointly assessed through a series of four simulation models: hydrologic, lake level, damages, and benefits.

<u>Hydrologic Sequences:</u> A trivariate first order autoregressive model was used to generate 1000/50-year sequences of annual gaged surface inflows, precipitations, and evaporations (Bowles et al. 1985). The model was calibrated, with good results, to match:

a. Mean, variance, skew, and probability distributions for all three data series as reconstructed for the total historical period beginning in 1851 and modified to represent present since 1961 land use in the tributary basin.

b. Serial correlations in each of these three series.

c. Cross correlations among the three series, both for the current year and for one-year lags.

<u>Lake Level Sequences</u>: The 1000 sequences were input to a lake water balance model beginning at the level of the current year and incorporating information on:

a. The surface area, storage volume, and salt content of the lake by water surface elevation,

b. The variation of lake evaporation with salt content,

c. The variation of precipitation on the lake as rising levels inundate areas with different average precipitation.

d. Estimates of ungaged stream and ground water inflows made by calibration to improve the match of simulated with historical lake levels.

Damage Sequences: A property owner can respond to rising lake levels by doing nothing and being inundated, evacuating, or investing in protective measures. Three response phases can be identified:

Self-Protection. As the lake rises, higher groundwater and storm waves cause increasing damage. When feasible, a manager will pump to hold down the water table and build levees as protection against rising water. The costs are losses that increase with lake level. At some level, the expense forces the owner to abandon the site. This wipeout is simulated when the lake either reaches a specified elevation or remains above a lower specified elevation for a specified duration. Managers are assumed to be willing to spend more for self-protection for a year than over extended periods.

Abandonment. After wipeout, the loss is the reduction in income to the property owner. If restoration is prevented (e.g., zoning prevents residential owners from returning), a cutoff date was employed to prevent continuing losses from justifying delayed alternatives.

Restoration. As the lake falls, the manager has increasing incentive to return. He is unlikely to return as soon as the lake drops below the abandonment level because a reversal could cause another wipeout. Consequently, restoration is specified at a lake level lower than wipeout and requires that the lake remain that low for a specified period of years. Reinstatement cost is considered a loss. During a subsequent rise the owner would return to the self-protection made.

Benefit Sequences: The benefit analysis introduced algorithms depicting how control measures would alter the level sequences and repeated the damage simulation for the four most promising measures. Specifically,

Shoreline Levees. The simulation neglected the slight levee effect on the stage-area curve and assumed that the levees prevented all the damages up to their design level and no damages after overtopping. Costs were estimated for wave damage during storm periods.

In-Lake Levees. When the lake was divided into two parts, the levels was kept lower in the part near the major damage centers. The maximum head difference across the levee was limited to five feet to avoid foundation failure.

Water Development. The lake inflows were decreased by the projected consumptive use.

West Desert Pumping. Rules were devised for turning the pumps on and off. The pumped water was routed through storage in the West Desert, either to flow back to the lake or to evaporate. After the pumps are turned off, the desert storage drains back into the lake within the water year.

HYDROLOGIC RESULTS

The simulated level probabilities given the initial conditions for the current water year are in Table 4. The precipitation to March exceeded the 25 level and indicates a 1986 peak higher than last year, as has already occurred.

ECONOMIC RESULTS

The economic assessment of the control alternatives (Table 3) shows some of the levees highly beneficial. The West Desert pumping scheme is the only other measure close to justification. Since about 80 percent of its benefits are to the private sector and most of these are to be a few large industries, charging the beneficiaries is recommended. Payment of 25 cents per dollar of damage prevented would cover the cost.

Table 4. Probability distributions of annual high levels of the Great Salt Lake given 1851-1984 data, adjusted to reflect 1965 land use, assuming no predictable cyclic weather patterns, and using a water balance analysis. October 1985 Initial Conditions

	Probabilities of Exceeding			Mean	Probabilities of Dropping Below		
Year	0.01	0.10	0.25		0.25	0.10	0.01
1985	4209.9	4209.9	4209.9	4209.9	4209.9	4209.9	4209.9
1986	4211.2	4210.4	4210.0	4209.6	4209.2	4209.0	4208.6
1987	4213.0	4211.2	4210.1	4209.1	4208.1	4207.3	4206.4
1988	4214.1	4211.6	4210.0	4208.3	4206.9	4205.8	4204.2
1989	4214.7	4211.6	4209.7	4207.4	4205.7	4204.4	4202.1
1990	4215.3	4211.4	4209.0	4206.5	4204.6	4202.9	4200.5
1995	4214.9	4210.0	4206.2	4203.2	4200.3	4197.9	4194.0
2000	4214.6	4207.8	4204.1	4200.9	4197.9	4195.4	4191.1
2010	4214.5	4206.6	4202.7	4199.5	4196.5	4194.0	4187.6
2020	4213.7	4206.1	4202.5	4199.4	4196.1	4193.3	4186.3
2030	4212.5	4206.2	4202.3	4199.2	4196.3	4193.0	4185.3
2040	4213.0	4206.5	4202.4	4199.3	4196.2	4193.3	4184.4
2050	4213.3	4206.0	4202.5	4199.4	4196.6	4193.8	4186.8

ISSUES

A number of issues deserve further study. Research should be continued to provide answers and save costs as control options are selected and implemented.

Hydrologic Issues

1. Conceptual adequacy of flow generation as an approach to estimating lake level probabilities. Do statistics computed from an historical record provide a reasonable basis for estimating the magnitude of rare events? Arid climates have a particular problem in that many hydrologic processes occur rarely, and significant events introduce nonstationarity into recorded data sequences.

Given this problem, what statistics should be preserved, and what approach should be used in their preservation? For example, is it better 1)to generate a multivariate series that preserves only one year's lag or 2)to generate a single variate series that preserves two years of lag and then use correlation to generate the other variables? This was done in a study for the Southern Pacific Railroad (Adams et al. 1985)? The first option was chosen here because it does a better job of preserving cross correlations in the secondary variates, and cross correlations are particularly important to linkage with a water balance model. ARMA models are available to preserve 2-year lags with cross correlations among three variables, but the greater number of parameters makes calibration less reliable.

2. Reliability of the reconstructed data. The data series for streamflow, precipitation, and evaporation were reconstructed back to 1851 from fragmentary records in order to cover the wet years from 1862 through 1872. The principal reliability issues are:

a. Increasingly greater approximation as one goes back past 1938 when Jordan River gaging began, 1890 when Bear River gaging began, and 1875 when systematic precipitation measurement began.

b. Uncertainty in estimating lake evaporation because of poor information on the effects of humidity from upwind evaporation and on the spacial variability of salinity and temperature mixing.

c. Possibility of major surface and groundwater flows entering the lake from the West Desert during prolonged wet periods.

One alternate to using a reconstructed historic series would be to infer probabilities from geologic deposits. For the Great Salt Lake, the two methods give similar results.

3. Physical causes of climatic anomalies. Climatic disruptions might be caused by atmospheric darkening from volcanic emissions, anthropogenic pollutants, solar weather, and planetary tides. Warnings occur in upwind temperature, wind, and ocean current patterns (the anamolies of "El Nino") or movements of the jet stream.

4. Evaporation-Streamflow Feedback. Evaporation from the Great Salt Lake may increase downwind snowfall enough to add significant persistance to flows into the lake.

Water Balance Issues

1. Amounts of ungaged surface and subsurface flows into the lake.

2. Lake precipitation and evaporation are averaged over the lake surface when in fact they vary in ways that could affect the water balance calculations.

3. Significant water transpires from vegetation around the shores of the lake.

Damage Issues

1. The short and long term impacts of drowning the waterfowl areas may have important environmental implications.

2. A number of the damage estimates were based on the least alternative cost concept. Engineering designs should be made of pumping, relocation, or flood proofing costs for such major affected properties as the airport, highways, railroads, waste treatment plants, power lines to refine the present gross approximations.

3. High lake levels cause upstream backwater in both surface stream and groundwater gradients that can increase damages.

Benefit Issues

1. Development of operational procedures for joint lake management for level control and developing salt as a resource of value.

2. Negotiating equitable arrangements for cost sharing in lake level control between the public and private sectors?

SHORT-TERM ASSESSMENT

1. Major damages have already occurred. The quickest and most cost effective way to prevent additional damages is by the selective use of shoreline levees to protect valuable properties. Levee designs should provide wave protection and local pumping for surface and subsurface drainage.

2. The quickest and most cost effective way to achieve positive lake level control is by pumping into the West Desert. However, the achievable degree of control depends on the effects of upwind ponding on downwind lake evaporation and on the constraints imposed by the military on the lake level at which pumping can begin.

3. Financial planning is an important component. The lake will rise substantially sometime, and it could be soon. The slow institutional response to the 1983-4 rise demonstrates interacting state and federal agencies have difficulty in acting in the lake rise time frame. Investment in disaster mitigation should not be considered as money wasted should a major event not occur immediately.

4. The worst possible disaster would be to construct levees and experience failure. When levees are raised rising lake levels, foundation failures from excessive weight likely. The levees are in an earthquake zone, and the foundation materials are

subject to liquefaction. Levees should not be built on foundations that cannot support raising to at least a crest elevation having one chance in 100 of occurring, 4221 (4218 with the control provided by the West Desert pumping scheme).

LONG-TERM ASSESSMENT

Planning for the long term should develop the Great Salt Lake as a resource of great environmental, wildlife, recreational, mineral, and energy values. Facility designs and operating rules should maximize total values totaled over all uses. Water storage and use within the tributary basin and land use in areas subject to lake flooding should be managed in coordination with lake level control. The levees that are being built along the southeastern shores should be made both functional and aesthetic as they create a stable shoreline between the lake and the urban areas. Downwind fog is already having a major impact on local winter weather and should be given special attention in the operation of lake level control facilities.

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