The "Water Chemistry" section addresses the overall salinity and ion concentrations of the water of GSL. Biological and other chemical water constituents are briefly discussed in the "Water Quality" and "Biology" sections.

The water chemistry and salinity differentials and trends are significant to the aquatic and avian biology of GSL and to the extraction of mineral salts from lake brines. The impacts of varying water chemistries and salinities to the wildlife and mineral industries of the lake are discussed in the "Biology" and "Minerals and Hydrocarbon" extraction sections, respectively. This section focuses on the physical and chemical aspects of GSL, factors influencing nutrient inputs and losses from the lake and the lake hydrologic processes.

The planning team has identified the following lake water salinity and chemistry conditions and trends as relevant to lake management:

- **The continuation of separate and distinct salinity areas in GSL is an issue.**
- **There is an apparent change in the exchange of salts between the north and south arms. This has resulted in the south arm being less saline than before the high water years for a given elevation.**
- **There is a lack of an accurate accounting for the quantities and locations of salts in the lake system.**
- **There is a lack of knowledge regarding nutrient chemistry and its influence on biological productivity in the lake**.

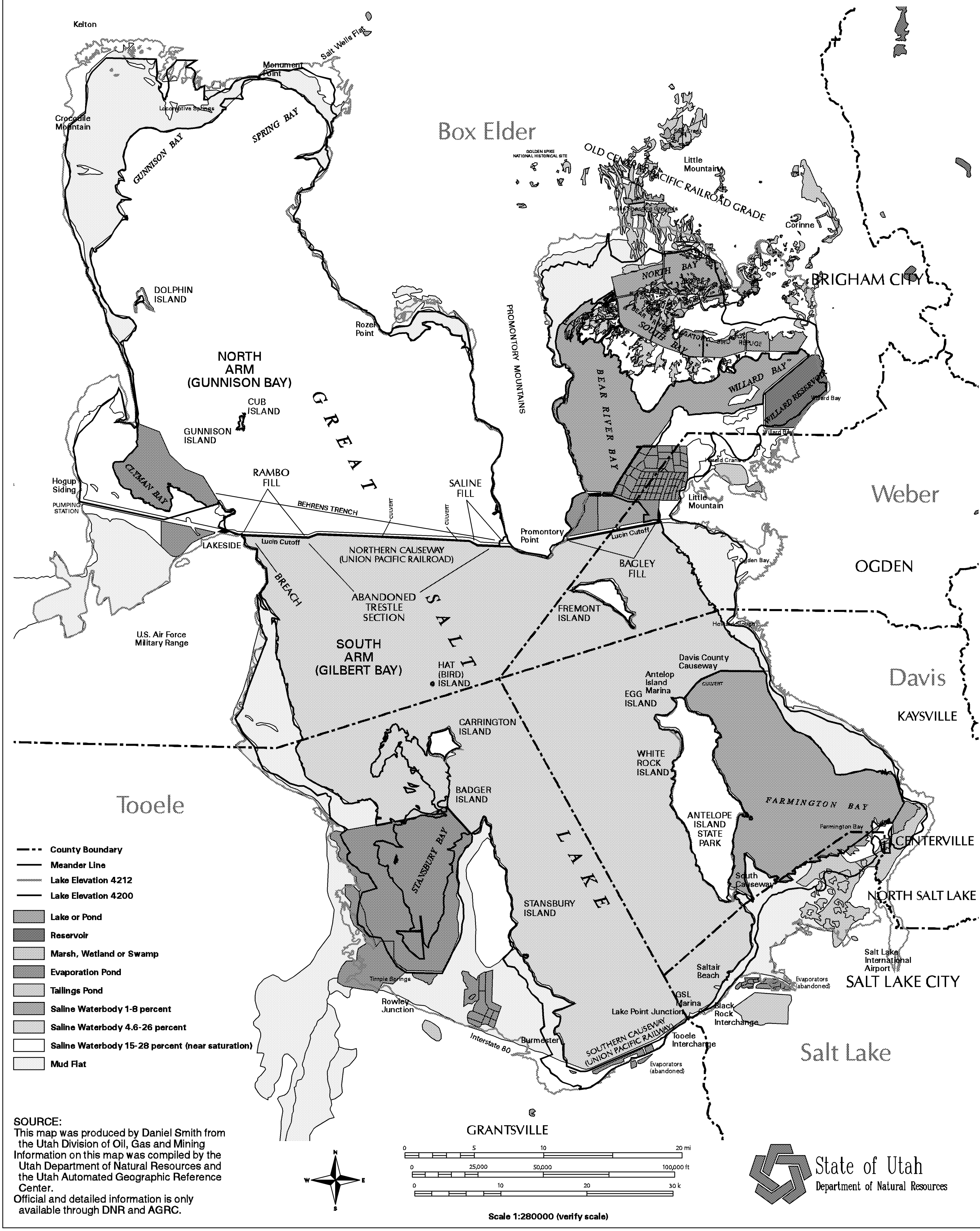
Separate Water Salinity Areas in the Great Salt Lake

It is believed that, prior to construction of dikes, causeways and mineral extraction facilities in GSL, lake brines were similar in composition and concentration throughout the lake (Appendix H). Since the early 1900s, dikes and causeways have been constructed in GSL for a variety of purposes. Several of these inhibited the unrestricted movement of lake brines among large areas of the lake. Coupled with the fact that most of the freshwater inflow to the lake occurs on the eastern shore, distinct salinity conditions have developed in four main areas of GSL. From freshest to most saline, they are; Bear River Bay, Farmington Bay, the main body of the lake (sometimes referred to as the "south arm" or Gilbert Bay) and Gunnison Bay, often referred to as the "north arm." Exhibit 8 shows the areas of salinity in GSL. Bear River Bay and Farmington Bay are both shown with salinities of 3-6 percent. Bear River Bay is generally fresher than Farmington Bay.

Bear River Bay is separated from the main body of the lake by IMC Kalium Ogden Corp.'s dike and the Bagley Fill which was constructed about 1900 and extends eastward from Promontory Point to Little Mountain. Construction on the northern railroad causeway began in

Exhibit 8 - Areas of Salinity

Plotted March 29, 2000



1956 and was completed in 1959. This rock-fill causeway separates the main body of the lake between Promontory Point to Lakeside and was known as the Southern Pacific Railroad Causeway. This causeway includes the Rambo and Saline Fills which were constructed about 1900. This created a separation between Bear River and Gunnison Bays from the main body of GSL.

With the completion of the causeway, the main body of GSL was now divided into two parts, the south and north arms. Even with the engineered permeability of the causeway and the incorporation of two 15-foot-wide by 20-foot-deep box culverts through the causeway, brine mixing was greatly diminished. Since 1960, the two main arms of the lake have developed different physical and chemical characteristics which vary as the lake level changes, and as changes are made to the structure.

Farmington Bay was part of the main body of the south arm of GSL until it was isolated by the construction of two earthen causeways. The first causeway (southern fill) was built from the south end of Antelope Island southeastward to the mainland between 1951-1952. This structure inhibited water exchange between the main body of the lake and the bay at the south end of the island, and channeled the full flow of the Jordan River into Farmington Bay. The second causeway (Davis County) extending from the north end of Antelope Island eastward to the mainland, was constructed in 1969. With the construction of this causeway, Farmington Bay was essentially isolated from the main south arm of the lake, with the exception of two bridged openings, and mixing between the two bodies of water was severely restricted (Gwynn, 1998a).

Farmington Bay

Farmington Bay is isolated from the main body of GSL when its level is below the top elevation of the Davis County Causeway and the Antelope Island southern causeway fill. Because of the inflow of freshwater from the Jordan River and groundwater inflows, the lake brines tend to be "flushed" from the bay through openings in the Davis County Causeway. Periodically, denser brines from the main body of the lake flow back into Farmington Bay underneath the lighter, fresher brines from the bay. This phenomenon is known as "bi-directional flow," and prevents the waters of Farmington Bay from becoming completely fresh. Bi-directional flow occurs through the Davis County Causeway's bridged openings, and through a narrow culvert to the east which was installed in 1992.
Bi-directional flow through these two openings is illustrated in Exhibit 9 and describes a similar dynamic occurring through the northern railroad causeway. When the lake's elevation is below 4208, the salinity of Farmington Bay is approximately half or less than that of the main body because of freshwater flows of the Jordan River into the bay. When the lake's elevation rises above 4208 and the causeway is over topped, the waters of Farmington Bay and the main body are free to mix (Gwynn, 1998a).

Brine returning to the bay from bi-directional flow tends to resist mixing with the fresher water, and remains in a fairly coherent "tongue" which extends some distance to the south underneath the lighter Jordan River/brine mixture. This forms a stratified brine condition

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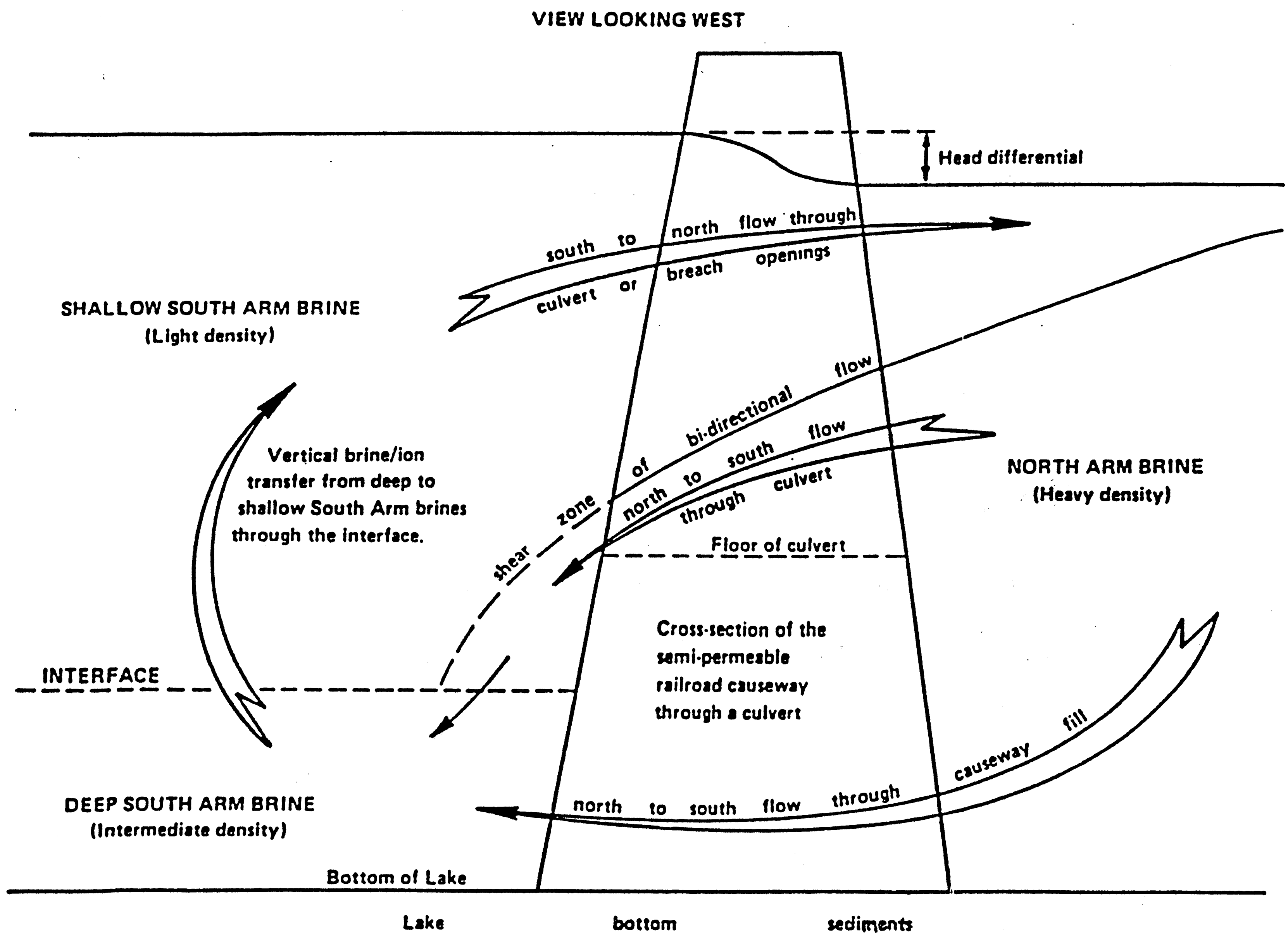
Exhibit 9



Schematic of bi-directional brine movement through the causeway within the Great Salt Lake, Utah (from Gwynn and Sturm, 1987).

within the central, deeper portions of Farmington Bay. The salt content of the upper Farmington Bay waters is maintained through vertical mixing of the tongue of denser, main body brine with the fresher water above it (Gwynn, 1998a).

Bear River Bay

Bear River Bay is similar to Farmington Bay as a brine system. It is separated from the main body of the lake by the rock-fill causeway which contains a mid-point, bridged opening through which bi-directional flow takes place. The brine is stratified within the deeper portions of Bear River Bay. The upper layer of water contains 1-2 percent salt. Below the upper layer of water lies a tongue of salty water which periodically moves into the bay by the bi-directional flow through the opening in the railroad causeway.

The salinity of the lower brine tongue is similar to that of the adjacent main body of the lake. The thickness of the tongue of denser brine and that of the overlying less-saline water depends upon the rate of inflow into the bay and on prevailing wind conditions. South winds raise the level of the lake at the causeway, forcing the tongue of main body brine farther into the bay, making it thicker. North winds lower the level of the south arm at the causeway, causing the brine to extend a shorter distance into the bay, and it becomes thinner. When the tongue of main body brine thickens and extends farther into the bay, the overlying fresher brine layer thins (Butts, 1998).

Gilbert Bay

The salinity (total-dissolved-solids) of Gilbert Bay varies inversely with lake elevation, and since 1966 has fluctuated from a high of 250 grams/liter in 1966 (approximately 21 percent salinity) to a low of about 50 grams/liter in 1986 (approximately 5 percent total salinity). The south arm of the lake receives nearly all of the freshwater inflow to the lake, including flows from the Jordan, Weber and Bear Rivers, and numerous, minor, east- and south-shore streams (Exhibit 3).

From 1966 until about mid-1991, the south arm of the lake was density-stratified into two brine layers. A dense, turbid, hydrogen sulfide-laden brine extended from an elevation of about 4180 to the bottom of the lake. A less dense, clearer, odor-free brine extended upwards from about 4180 to the surface. The two brines were separated by a relatively sharp transition zone. The deeper, denser brine layer disappeared in mid-1991, after the high-water years (1983-87). During the 1980s, the surface elevation of the lake rose from about 4200 to nearly 4212 by 1986-87. The disappearance of south-arm stratification is probably due to diminished north-to-south return flow through the causeway brought about by the apparent changes in the hydraulic conductivity (permeability) in the northern railroad causeway (Appendix H). Since mid-1991, brines of the south arm have been thoroughly mixed from top to bottom. This may have been caused by the addition of fill material used to increase the height of the causeway from 1983 through 1987 and subsequent compaction of the causeway. It may also have been influenced by the effect of the large head differential that existed between the two arms of the lake which minimized the potential for return-flow to the south arm.

The differences in salinity from east to west can be documented at the present time from the work being done by USGS in conjunction with DWR wherein samples are taken from a number of sites throughout the south arm within a day or so of each other. These differences are very minor (perhaps within a percent or two) compared to the dramatic differences that currently exist between the north and south arms of the lake (15+ percent).

Gunnison Bay

The salinity of the north arm does not exhibit as direct an inverse relationship with lake elevation as does the south arm. This is because the north arm receives small quantities of fresh surface water inflow and large quantities of salty water inflow from the south arm (Exhibit 3). Evaporation from the surface of the north arm is sufficient to maintain the north-arm salinity at a high concentration. From 1966 until about 1982, the salinity of the north arm remained within the 310-350 grams/liter range (25.7-28.4 percent). Due to this high salinity, a layer of sodium chloride precipitated on the lake's bottom during this time. North-arm salinity dropped to only 160-170 grams/liter in 1987 (14.5-15.3 percent), as evaporation was unable to keep up with increased, dilute inflows from the south arm. Since the high-water years, the north-arm salinity has climbed back into the 290-310 grams/liter range 24.3-25.7 percent or greater (Exhibit 10).

Brine stratification was not present in the north arm of the lake from 1966 until about 1983. When the lake began its rapid rise from about 4200 in 1983 to its historic high of 4211.85 in 1986-87, however, a layer of less-dense brine formed on top of the very-dense north arm brine. This was due to increased precipitation, and the enormous inflow of less-saline, south-arm water as the railroad causeway was breached in August 1984 (see later discussion), and the large, bi-directional exchange of brines between the north and south arms through the breach opening which followed (Exhibit 4). By mid-1991, the level of the lake had dropped below the 4199.5-foot bottom elevation of the breach opening. Because of this, the constant flow of south-arm brine into the upper light-brine layer in the north arm nearly ceased, and the stratified-brine condition in the north arm soon disappeared due to evaporation and vertical mixing.

Net Northward Movement of Dissolved Salts from the South Arm to the North Arm

To help alleviate the flooding of the 1980s, the state implemented two flood-control measures which affected the dissolved-salt distribution and the total salt load within the lake.

Northern Railroad Causeway

In August 1984, the state created a breach in the northern railroad causeway consisting of a 300-foot-long opening near Lakeside (Exhibit 4). At the time the breach was opened, the water elevation of the south arm of the lake was about 3.5 feet higher than the north arm. After the breach was opened, great quantities of less-concentrated south-arm brine flowed northward into the north arm. Within about two months large quantities or dense, north-arm brine began flowing southward into the depths of the south arm as bi-directional flow. As a result of this bi-directional interchange of brine,

Exhibit 10

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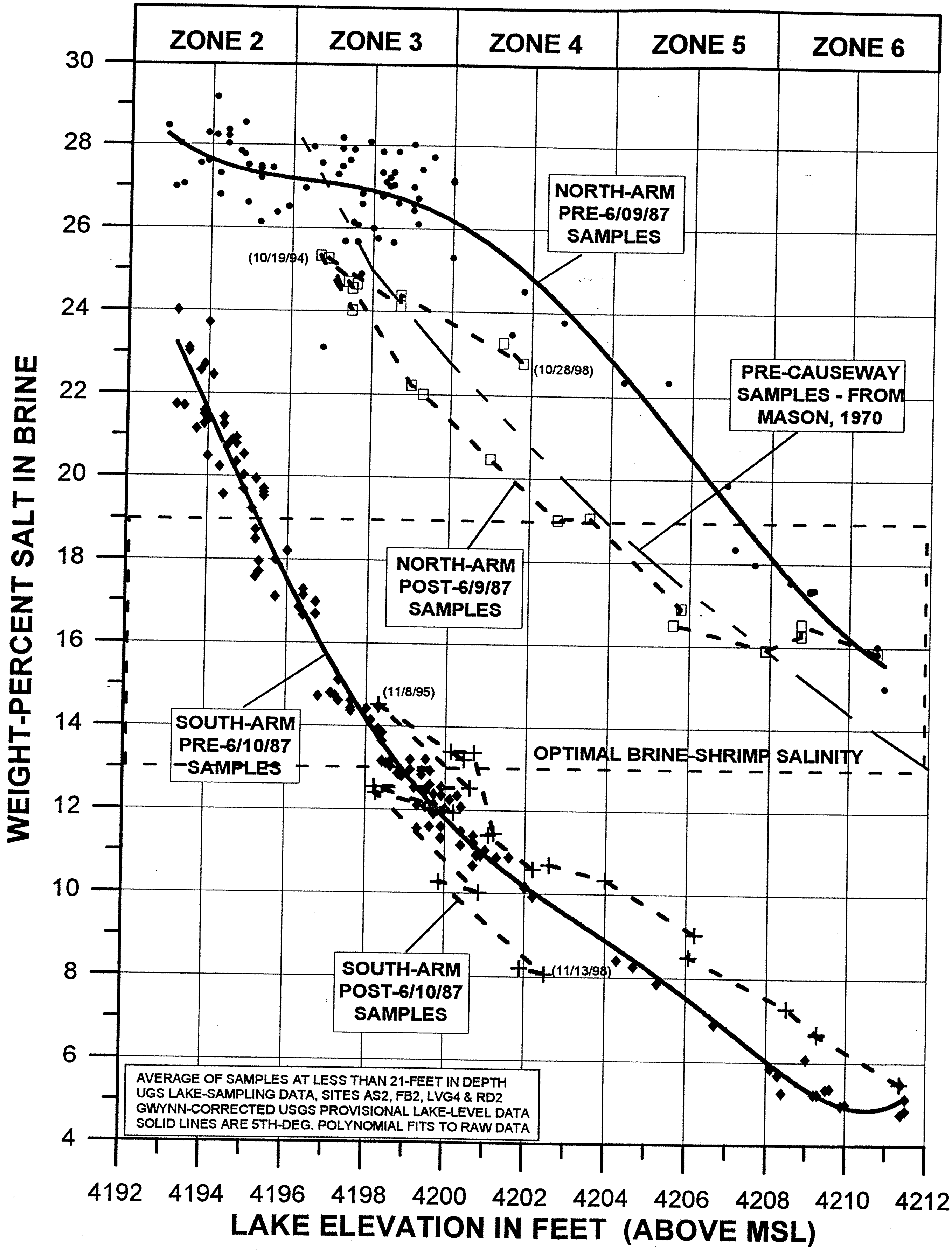

Trends in salinity versus lake elevation for the north and south arms of Great Salt Lake before and after the lake's 1986-1987 high (modified from Gwynn, 1998a).

the south arm density and salt load increased, while those of the north arm decreased. Bi-directional flow continued until the end of 1988 when the lake dropped to the point that return flow through the breach opening ceased. From that time until 1999, flow through the breach opening was mainly south-to-north which has resulted in a decrease in south-arm salt load and an increase in the north arm load. During some summer months, salt has precipitated on the floor of the north arm where it will remain until conditions change and the north-arm salinity decreases.

Early in 1999 there was very little bi-directional flow observed moving through the breach. Later in the year, however, as the level of the lake rose and the head differential across the causeway decreased, deep north-to-south, return flow was observed within the breach opening.

Two box culverts, each approximately 15 feet wide by 20 feet high, were installed when the causeway was built. These openings in the causeway contributed to water circulation and allowed for passage of small boats through the causeway. The culverts have settled as the causeway has settled. With the lake level substantially higher than when the causeway was built and with the settling, the culverts are now completely submerged. Under this circumstance, the culverts are useless for navigation but still contribute to water circulation. The importance of the culverts in the exchange of brine between the north and south arms is well known. At present lake levels, the culverts are at sufficient depth to allow dense north arm brine to flow into the south arm. Maintenance of the culvert openings is difficult because of their depth under water and the fact that they are frequently plugged by .5 to 2-inch gravel transported by storms.

In a recent engineering evaluation by PSOMAS, studies were reviewed that determined the effect of deepening the existing breach opening to 4193 or 4190. The evaluation included open and closed culvert scenarios. PSOMAS also proposed five alternatives as potentially workable solutions to the lack of bi-directional flow in GSL. The USGS water-salt balance model is a very important tool in this endeavor.

West Desert Pumping

The second emergency flood-control measure was implemented after the lake continued to rise, following the opening of the breach in the northern railroad causeway. This measure involved pumping water from the north arm of the lake out into the West Desert to increase the total evaporative surface area and to physically remove water from the lake. To accomplish this, three giant pumps (1,000 cfs each) were installed near Hogup Ridge (about 12 miles west of Lakeside). The water was pumped from Hogup Ridge by way of a 4.1-mile canal to the west desert where it was impounded in a 320,000-acre pond, contained by dikes (Exhibit 6). WDPP was successful in helping to lower the level of the lake from 1987 to 1989, but in the process 600 million tons of crystalline salt, representing 10-14 percent of the total salt-load of the lake, were precipitated and/or deposited on the pond floor when the project was suspended in 1989 (See discussion on "Operating Consequences and Constraints," page 26).

Ion Concentrations in Lake Brines

Unlike the lake's variable salinity (total grams of dissolved salt per liter of solution), its chemical composition (ratio of various dissolved ions to one another) is relatively constant throughout the north and south arms of the lake, and within Bear River and Farmington Bays. This chemical consistency exists because: (1) chemical homogeneity existed throughout the lake prior to the construction of the railroad and other causeways and (2) continual brine mixing, however limited, occurs among all portions of the lake. Slight, long-term changes in ion-ratios have been observed throughout the lake as a whole. Table 3 gives an average chemical composition of the dissolved salts in GSL waters on a dry-weight-percent basis, as contained in the UGS-GSL database. The compositions of typical ocean and Dead Sea waters are given for comparisons.

Table 3. Average chemical composition of the dissolved salts in the waters of GSL, Utah, typical ocean water, and Dead Sea water (dry-weight-percent basis).

Ion	GSL (%)	Ocean (%)	Dead Sea (%)
Sodium	32.1	30.8	12.3
Potassium	2.3	1.1	2.3
Magnesium	3.7	3.7	12.8
Calcium	0.3	1.2	5.2
Chloride	54.0	55.5	67.1
Sulfate	7.6	7.7	0.1
Bicarbonate*	0.62		

* Value from DWQ June 9, 1994 Lab Analysis Report for GSL Brine from UGS Sampling site AS

Table 4. In addition to the main ions listed above, the UGS database includes the three most abundant trace elements: lithium, bromine and boron. The average levels of these elements in the south and north brines are reported as follows in units of (mg/L).

Element	South Arm	North Arm
Lithium	24	45
Bromine	66	121
Boron	21	24

Table 5. The minor trace metals in GSL brines which are included in the DWQ's (June 9 and 22, 1994) Lab Analysis Reports.

Metal	Site AS2 (south arm) g/L	Site LVG4 (north arm) g/L
Arsenic	130	218
Cadmium	<3.0	<11
Chromium	<5	<5
Iron	<220	<220
Silver	<2	<2
Zinc	<330	360
Mercury	<.2	<.2
Barium	180	170
Copper	<220	<220
Lead	<30	<12
Manganese	<55	<55
Selenium	<12	31

(< = less than)

It has been postulated that the absolute quantities of the ions of magnesium, potassium, calcium and sulfates in lake brines is decreasing relative to sodium and chloride. Data collected by UGS since 1966 show a slight decline in the yearly average, south-arm dry weight percentages of magnesium, potassium, calcium and sulfates over time, while sodium and chloride show a slight increase (Gwynn, Work in Progress). During the low surface-elevation stages of the lake, from 1935 to 1945 and from 1959 to the mid-1960s, sodium chloride precipitated in Gilbert and in Gunnison Bays (the south and north arms respectively). Madison (1970) states that salt precipitated at lake elevations below 4195 and Whelan (1973) reports that some 1.21 billion metric tons of sodium chloride precipitated throughout the lake at those low elevations.

While the precipitated salt in the south arm had redissolved by mid-1972, it took until about 1986 before all the salt in the north arm had been redissolved (Wold et al., 1996). In 1992, salt again began to precipitate on the floor of the north arm during the summer months, and it is believed that precipitation continued through 1997. Dry-weight percentages of magnesium, potassium and calcium were increased during historic low lake levels because sodium chloride is the first salt to precipitate as the concentration of lake brine increases. Conversely, the concentrations of magnesium, potassium and calcium are believed to be recently decreasing relative to sodium because of the redissolution of sodium chloride from the lake bed, particularly in the south arm. Notwithstanding slight fluctuations in relative ion ratios in lake water with changes in lake elevation, it is not believed that the overall chemistry of lake brines has changed greatly. It is believed that the lake model currently being verified and calibrated by USGS will provide answers related to the salt-load balance between the two main arms of the lake and change in salinity and chemistry (Appendix G and H).

Accounting for Quantities and Locations of Salts

The location and amount of salts in the open lake are determined through water sampling and modeling (Appendix G). Data on locations and amounts of salts elsewhere are less available. Given recent attention to the salt balance in the lake and emerging disputes over mineral ownership, DFFSL would like to know more about locations and quantities of salts in the system. This information will be useful when considering potential recovery of the economic value of stockpiled and waste salt, and when planning for eventual reclamation.

Nutrient Chemistry

The biological productivity of the GSL is largely determined by the concentrations of plant nutrients in the water. Most often, nitrogen, phosphorous or combinations of these two nutrients control plant growth in freshwater lakes. Bioassay analyses of south-arm water of the lake have indicated that nitrogen concentrations most frequently control phytoplankton growth in the lake (Stephens and Gillespie, 1976). Unlike the conservative major ions discussed previously, the concentrations of nutrients in the lake are more dynamic and controlled both by nutrient loading from tributaries and the atmosphere, as well as hydrological and biotic processes in the lake. Upon entering the lake, dissolved forms of nutrients that limit plant growth will readily be taken up by the phytoplankton passed through the food web and repeatedly recycled until organic matter sedimentation buries it in the lake bottom. Nutrients entering in particulate form may settle out directly and not enter the lake's food web.

Relatively little information is available about the flux of nutrients into the lake and the concentrations present in the water. Studies conducted by Sturm (1980) and Wurtsbaugh (1995) reported high total phosphorus. Sturm (1980) also reported exceedingly high nitrate concentrations while a Wurtsbaugh (1988) study indicated algal nitrogen limitation. This discrepancy may be due to problems with measuring nutrient concentrations in the GSL's brines and/or different years when the measurements were made.

Anthropogenic factors undoubtedly have a large influence on the concentrations and distribution of nutrients in GSL. When tributary waters pass through wetlands prior to entering the lake, substantial portions of the nutrients may be removed (Horne and Goldman, 1994). Because most of the GSL's wetlands have been created or enhanced by diking, this likely results in a substantial loss of nutrients to the lake. Conversely, domestic sewage effluents and agricultural wastes from the watershed are possibly increasing the nutrient loading to the lake. In-lake diking greatly influences the distribution of nutrients.

The Davis County Causeway restricts water exchanges between Farmington Bay and the south arm. Because natural and anthropogenic loading into Farmington Bay is high, it is extremely productive and would be classed as eutrophic (Wurtsbaugh, 1995). Similarly, Bear River Bay receives a large portion of inflowing nutrients from the Bear and Ogden Rivers, but measurements of nutrients and biological productivity have not been made.

The northern railroad causeway influences nutrient distribution in the lake in two ways. As with the conservative major ions, nutrients are transported to the north arm, depleting the more productive south arm. Although limited measurements of nutrients have been made in the north arm, the limited available data (Sturm, 1980) found that nutrients there were often double the concentration of those in the south. However, limited bi-directional flow may also create a trap for nutrients in the south arm.

When dense underflow of highly saline water occurs, this layer does not mix readily with the overlying layer as prior to 1991. Sedimentation of phytoplankton and zooplankton carries nutrients into the deep-brine layer, thus removing them for months to years from the biological cycle. Phosphate, ammonia and total nitrogen and phosphorus concentrations in the deep brine layer were 10-100 times higher than the overlying, less-saline water (Wurtsbaugh and Berry, 1990), but it is not clear to what extent this difference was due to sedimentation of nutrients from the overlying water, and how much was due to the bi-directional flow transporting nutrients back from the north arm.

The amount of nutrient loading for the lake has not been determined. Excessive removal of nutrients would result in decreased brine shrimp and brine fly production and thus impact the bird community reliant on these food resources. Conversely, excessive nutrient loading from sewage and agricultural wastes entering the lake could produce intense and noxious blooms of algae that could be detrimental. The concentration of nutrients in Farmington Bay and the resulting biological production have produced eutrophic conditions that contribute to the odor problems in this area. Other salinity, chemistry and hydrology issues raised by the Scientific Review Committee (SRC) are addressed in Appendix H.