Reports

Salt Migration to the Northwest Body of Great Salt Lake, Utah

Abstract. *Interchange of saline lake water between the northwest body of Great Salt Lake, Utah, comprising about one-third of the lake area, and the main body of the lake, has been severely restricted by the completion of a railroad embankment across the lake in 1959. The northwest body has a relatively small volume of inflow and a somewhat greater rate of evaporation than the main body. As a result, there has been a net flow of saline water northward and accompanying deposition of a thick layer of salt over the bottom and shore of the northwest body. A unique set of hydrologic and physical-chemical influences are in action, and further important effects on the entire lake are expected.*

The Great Salt Lake of Utah has been undergoing notable changes in the last few years. The northwest body of this lake, comprising about one-third the total area, was separated from the main body when a new embankment of the Southern Pacific Railroad Company's Lucin Cutoff route across the lake was completed in 1959. Between 1903 and 1959, railroad traffic was carried on a combination of embankment and wood trestle. The trestle was 19 kilometers long and allowed free interchange of water between the northwest body and the main body of the lake. Since replacement of the trestle by fill, flow between the two parts of the lake has been severely restricted.

This construction and natural conditions have caused large-scale salt migration to the northwest part of the lake, where solid deposits of salt have formed on the shores and bottom. A brief description of the natural conditions affecting the lake will aid in understanding the phenomenon.

Great Salt Lake is the principal remnant lake of the closed Bonneville basin in the eastern Great Basin province of western United States. The water area of the lake varies from less than 2500 (1963) to more than 5000 square kilometers (1870), and its greatest depth from less than 9 meters to nearly 15 meters. The slope of the bed and shores is commonly less than 2 or 3 meters per kilometer. Large areas have a slope of less than 20 centimeters per kilometer.

The lake is highly saline, frequently reaching salt saturation, which is about 27½ percent by weight. Percentage composition on a dry salt basis is: Cl, 54.60; Na, 32.70: SO_4, 7.28; Mg, 2.91; and K, 1.70. Minor constituents total less than 1.00 percent. When the lake reaches the concentration of salt saturation in warm weather, sodium chloride (halite) crystallizes. In the winter, sodium sulfate (mirabilite, $Na_2SO_4 \cdot 10\,H_2O$) crystallizes. During most years since 1930, solid deposits of these salts have exchanged position seasonally on the bottom of the lake.

Water is supplied to the lake mostly during the fall, winter, and spring from direct precipitation (rain and snow), ephemeral flow from surrounding low lands and nearby small drainage basins, surplus water from the three major river systems which drain to the lake (Bear, Weber, and Jordan), waste flow from irrigation and metropolitan areas, and some seepage. Because of low precipitation and the withholding of stream flow by water conservation projects, the lake has been at a relatively low level for the last three decades. Drought has prevailed for the last 4 years, and the lake is approaching a new low level, near 1.71 meters below zero on the gage maintained at Saltair on the southeast shore. An average level is +1.22 meters on this same gage, and the highest level recorded (approximate estimates extend back to about 1830) occurred in the early 1870's and was +4.44 meters.

The climate is semi-arid. Precipitation occurs mainly in the winter and spring months and probably ranges from 30 to less than 15 centimeters per year over the lake area, being least in the northwest part.

The total quantity of water contributed to the lake by precipitation and runoff from nearby lands is disproportionately greater for the main body of the lake, and this portion receives all the surplus water from the three major river systems and waste water.

Evaporation occurs mostly in the summer. It provides the only discharge from the lake. The annual rate of evaporation (measured in centimeters of depth lost to the atmosphere) varies with the salt concentration and also with climatic factors. In the climate of the lake, the annual rate of evaporation from a fresh-water surface is about 150 centimeters. The rate of evaporation from the lake at salt saturation is less than 100 centimeters, and the rate at lower salt concentrations is between these two rates. Hence the total volume of water that is evaporated from the lake depends on the salt concentration as well as on the area of the water surface and climatic factors.

An annual change of surface level of the lake of about 50 centimeters occurs because inflow and evaporation occur mostly at different times of the year. A large, irregular secular change (occupying several years) in the surface level also occurs because of irregular inflow from year to year. The high annual level usually occurs in May or June and the low level usually occurs in November.

The total volume of water removed from the northwest body of the lake by evaporation is larger than the annual water supply of this body (estimated to be three times larger), so that there is a net northward flow of salt water from the main body of the lake, and salt migration is a direct consequence.

Currents, wind tides (seiches), and profound stirring of the water of the lake by storms at frequent intervals contribute to the phenomenon of salt migration. Storms restore uniformity of salt concentration and temperature, both in depth and in the area covered. Wind tides may raise the water on the lee shore more than a meter, with consequent overflow of large areas of the adjacent, flat, dry lake bed. An oscillation with a cyclic period of several hours and considerable decrement extending through several cycles into calm periods follows a high wind.

The railroad fill which has caused the salt migration is about 32 kilometers long. It is composed in part of quarry-run rock. The fill is therefore permeable, and a considerable amount of water probably flows through it. The fill is interrupted by two culverts of rectangular cross section, each with inside width of 4.3 meters and inside height of 6.1 meters. Water was 2.2 meters deep in the culverts in October 1963. The net northward flow of lake water through these culverts and through the fill carries salt into the north body of the lake.

About 30 or more centimeters of solid salt now covers the bed of the northwest water body and the band of adjacent dry lake bed. This quantity of salt is about 10^9 metric tons. Coincidentally, the main body of the lake, which before 1959 became saturated in the summer when the surface elevation reached −30 centimeters on the gage at Saltair, now (in 1963) does not become saturated until the surface elevation reaches about −140 centimeters (*1*). These observations of change in surface elevation at which salt saturation occurs may be used in conjunction with the known salt concentration at saturation and the change in the water volume with surface elevation to calculate that about 10^9 metric tons of salt have been removed from solution in the main body of the lake. This is one-quarter of the salt formerly in solution in this body. Five summer seasons, 1959 to 1963 inclusive, have passed since the railroad embankment was completed.

The part of the salt layer above the present water level is an important part of the total solid salt. It results from stranding of salt by annual lowering of lake level as well as from progressive net lowering for several years, and from stranding of salt which has crystallized from the water brought to the otherwise dry area by wind tides.

The solid salt layer in the northwest body is mainly sodium chloride. But small quantities of other salts containing potassium, magnesium, and sulfate ions may even now be present because of (i) evaporation of water stranded on the exposed flat salt layer after summer wind tides (which would result in crystallization of all salts contained in the stranded bittern), (ii) crystallization of mirabilite during winter, and failure of all of this salt to redissolve during the warm part of the year, and (iii) summer deposition of small quantities of salts containing potassium, magnesium, and sulfate ions along with sodium chloride (*2*). Bittern of the northwest body has undergone concentration and modification of composition by enrichment in these three ions (*3*).

Reasonable deductions can be made with regard to the progress and effects of salt migration caused by the railroad fill.

1) A flow of salt water from the main body of the lake to the northwest body will continue and the salt layer in the northwest body will thicken. An effort has been made to estimate the rate of salt migration in terms of freshening of the main body of the lake. The result is that this body will reach one-half of the saturation concentration in about 15 years.

2) The bittern of the northwest body is likely to be further enriched in potassium, magnesium, and sulfate ions (which would increase the tendency for salts of these constituents to crystallize and create a heterogeneous solid salt layer). However, the bittern is not expected to reach the high content of these ions derived by an assumed exclusive northward flow of lake water. Some southward flow of bittern and interchange with lake water occurs, thereby reducing accumulation of the saline constituents in the bittern. Southward flow follows under several conditions: (i) When the lake is calm, density currents occur in culverts and probably through the fill—higher density bittern flows southward beneath the northward flowing lake water (*4*). (ii) Seiches (wind tides) of differing periods and amplitudes occur in the two bodies and generally are out of phase along the fill. Thus an irregularly varying difference of elevation is created at the ends of culverts and along the sides of the rock fill, which in turn causes flow first one way and later in the reverse direction. (iii) High winds blow spray across the fill. (iv) Cumulative variation of lake level over a period of more than 1 year will at times cause bittern to be drawn from the northwest body. (v) A time occurs during the year when southward flow of bittern will result from a variation of the relative water supply and the rate of evaporation between the main and northwest bodies.

3) If heterogeneous salt crystallization in the northwest body occurs, cost of recovery of salts will be increased. The crystalline layer must be mined and redissolved. This will be an added burden compared with direct use of lake brine, and the recovery of salts may become economically impossible for a competitive market.

4) Freshening of the main body of the lake will increase the rate of evaporation. This in turn will cause a reduction of area and a lower surface level and result in a large expanse of dry lake bed which will become a place of origin for dust storms, which will be detrimental to metropolitan areas east of the lake (Salt Lake City, Ogden, and other municipalities). The economic usefulness of the lake as a tourist attraction will be impaired.

It is obvious that the balance of naturally operating complex hydrologic, meteorological, geographic, and physical-chemical factors of the lake has been disturbed by construction of the railroad fill. Accurate observations of salt migration occurring in Great Salt Lake and a reasonably full explanation of the attending phenomena will require a major research study.

Inasmuch as the effects of salt migration are generally unfavorable, remedial action should be contemplated. Diverting fresh water inflow into the northwest body, bringing about freer interchange of water between the two bodies, stopping the northward flow entirely, and pumping bittern back into the main body of the lake have been suggested.

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References and Notes

1. When Great Salt Lake becomes saturated in the summer, a layer of solid sodium chloride forms on the bottom and on the dry lake bed adjacent to the water line, salt being supplied by the rapidly evaporating lake water. The observations are mine and cannot now be duplicated.
2. As an aid to judging the extent to which K, Mg, and SO_4 ions may have deposited, or perhaps will deposit, in the solid salt layer, the result of a laboratory experiment (No. VI) was selected from a paper by J. M. Glassett and S. J. Anderson, ["Recovery of salts from the waters of the Great Salt Lake," *Univ. Utah Engrg. Expt. Sta. Progress Rept.* (1961)]. A large sample of lake water was evaporated at room temperature to dryness in successive stages. The crystal "crop" of each stage was collected, drained, weighed, and analyzed. Also the volume of bittern remaining after each stage was measured and its weight was obtained. I extended the computations of this experiment and constructed graphs. Data show steady increase of bittern density from 1.211 to 1.320 as evaporation proceeds from lake water at the point of saturation to bittern with 12 percent of the volume at saturation (PVS). At density of 1.232 (equivalent to an observed

density of the lake bittern in October 1963) the experimental PVS is 48, and 2.5 percent Mg, 2.8 percent K, and 8.8 percent SO_4 are contained in the deposited salt crystal. Except for the smal' quantities of these constituents, the crystal is sodium chloride. Further evaporation results in an increasing rate of deposition of Mg, K, and SO_4 ions, but crystallization mainly of NaCl, until a density of 1.320 is reached at PVS 12. There much of the sodium chloride has crystallized and a rapid crystallization of salts of Na, K, and SO_4 begins. Density stays constant for a considerable following range. It is supposed this experiment illustrates approximately what occurs during the summer in the northwest body of the lake. It is not known whether, in the earlier stage, Mg, K, and SO_4 are deposited with the NaCl crystals in the form of adhering water, as inclusions in NaCl crystals, or as individual crystals. Industries engaged in commercial recovery of sodium chloride from the lake have found it necessary to limit evaporation in salt recovery ponds to PVS 60 in order to avoid too great a concentration of $MgSO_4$ in the harvest.

3. Use was made of analyses reported by D. C. Hahl and C. B. Mitchell ["Chemcial analyses of water draining into Great Salt Lake, Utah, and of the lake brine," in open-file report of the Quality of Water Branch, Water Resources Division, U.S. Geological Survey, (1963), p. 34] and an additional analysis made in January 1963. On a graph with time as absissa, lake level, total dissolved solids, and proportion of Mg, K, and SO_4 were plotted. The graph shows that the concentration of total salts in the main body of the lake and the proportions of Mg, K, and SO_4 ions have remained essentially constant from 1959 to the present. (This is explained, in the presence of migration of a large quantity of salt from this body, by the coincidental lowering of the lake surface which fortuitously has kept the main body of the lake near saturation during the 5-year period.) Further, it appears from the graph that the proportion of K in the bittern of the northwest body has increased until at the end of the past summer (1963) this proportion was about 60 percent higher than it was in the spring of 1959 when the bittern began as normal lake water. A similar result appears for Mg and SO_4 ions. Among the considerable number of valuable analyses of lake water there are many inconsistencies and much scattering of data. Hence statements made in this report are based as far as possible upon direct observations of the lake and well-established information regarding it. Substantial difficulties interfere with adequate, representative sampling of lake water and the deposited salt layers.
4. Density currents occur when two bodies of water (or other liquid) of different density and usually having a free surface are made to face one another without a separating diaphragm. Density may vary because of temperature, salinity, silt content, and so on. The more dense liquid flows under and toward the less dense, which in turn flows above and counter. Such currents are reported to have been observed in the railroad culverts.

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Light Adaptation Kinetics: The Influence of Spatial Factors

Abstract. *Reducing the target diameter of an adapting (conditioning) flash of light results in a progressive rise in the conventional light adaptation curve, as measured with a small superimposed test flash presented at the end of adapting flashes of variable duration. When both targets are the same size, an abrupt and marked rise in threshold is obtained, resulting from a unique effect that occurs near the termination of the adapting flash. This effect can be demonstrated by means of a variable delay procedure, and it indicates that neural as well as photochemical processes limit the time course of light adaptation.*

It is traditionally assumed that the sensitivity of the visual system invariably decreases (threshold rises) during progressive exposure of the eye to light (*1*). Early psychophysical studies of light adaptation tended to support this viewpoint, since rising functions of negative acceleration were always obtained when threshold luminance was plotted against duration of antecedent light exposure (*2*). In these older experiments, the time course of light adaptation was estimated by measuring threshold with a brief "test" flash of light presented near the end of an adapting (or "conditioning") flash whose duration was systematically increased as the independent variable. More recent psychophysical studies, however, have shown that a different light adaptation function is obtained if threshold for the test flash is measured at various delays (time intervals) from the onset of a concentrically placed and larger conditioning flash of fixed duration and luminance (*3*). Under these conditions, the threshold rises when the test flash precedes the conditioning flash in time, reaches a maximum value near the point of the onset of synchrony (0 delay), and then falls with positive acceleration during the duration of the conditioning flash.

In a previous study in which we used the variable delay procedure just described, we showed that the magnitude of threshold changes over a period of time depended, in part, upon the spatial configuration between the test and conditioning targets (*4*). Specifically, a greater and more lasting change in the monocular threshold was obtained when the diameter of the conditioning target was made smaller and approached that of the brief superimposed test flash. This finding implies that interaction at target border is a critical pararmeter in determining the visual threshold, and supports the argument for a neural rather than a photochemical limiting mechanism (*5*). Before such a sweeping generalization is made, however, it would appear important to determine the role of these same spatial parameters when the time course of light adaptation is estimated in the more conventional fashion, that is, as a function of prior light exposure. This was the object of our study.

By means of a Maxwellian view system (*6*), monocular thresholds were measured in two trained observers (subjects I.H.W. and W.S.B.) by manipulating the luminance of a 5-msec test flash of light (F_t), the onset of which always occurred at the end of a concentrically placed conditioning flash (F_c) of fixed luminance (3.0 log mlam) but of variable duration (from 5 to 1500 msec). Thresholds were similarly measured for the test flash alone (resting threshold, or RT) and for the steady-state condition, in which the conditioning light was continually exposed ("infinite" duration). In all threshold determinations, numerous "blanks" (no test flash) were included to insure reliability and to provide a frame of reference for the observer. The target stimuli were presented upon a constant adapting background of 1 mlam and were centered at 7° of parafoveal displacement along the horizontal meridian in the temporal field of the right eye. The test target always subtended 40′ of visual angle, but the angular subtense of the conditioning target was varied as a parameter from 40′ to 4°40′ in four steps.

The results obtained with both observers are presented in Fig. 1, in terms of test-flash luminance at threshold on the ordinate (in long mlam) and duration of conditioning-flash exposure along the abscissa (in seconds). Four curves are shown for each observer, one for each conditioning-target diameter, as indicated. In confirmation of the earlier reports, these plots show that sensitivity decreased (luminance required at threshold rises) as the duration of prior light exposure was increased. In addition, the data show that the rate of this change in threshold, as well as the asymptotic level finally achieved, became greater with conditioning targets of smaller diameter. This inverse relationship between magnitude of threshold change and size of conditioning target was still apparent when the light emanating from the conditioning target was continuously exposed (∞ duration). It should be noted, however, that under