Estimation of groundwater evaporation and salt flux from Owens Lake, California, USA

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Abstract

Groundwater evaporation and subsequent precipitation of soluble salts at Owens Lake in eastern California have created one of the single largest sources of airborne dust in the USA, yet the evaporation and salt flux have not been fully quantified. In this study, we compare eddy correlation, microlysimeters and solute profiling methods to determine their validity and sensitivity in playa environments. These techniques are often used to estimate evaporative losses, yet have not been critically compared at one field site to judge their relative effectiveness and accuracy. Results suggest that eddy correlation methods are the most widely applicable for the variety of conditions found on large playa lakes. Chloride profiling is shown to be highly sensitive to thermal and density-driven fluxes in the near surface and, as a result, appears to underestimate yearly groundwater evaporation. Yearly mean groundwater evaporation from the playa surface estimated from the three study areas was found to range from 88 to 104 mm year^{-1}, whereas mean evaporation from the brine-covered areas was 872 mm year^{-1}. Uncertainties on these mean rates were estimated to be ±25%, based on comparisons between eddy correlation and lysimeter estimates. On a yearly basis, evaporation accounts for approximately 47×10^6 m^3 of water loss from the playa surface and open-water areas of the lake. Over the playa area, as much as 7.5×10^8 kg (7.5×10^5 t) of salt are annually

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concentrated by evaporation at or near the playa surface, much of which appears to be lost during dust storms in the area. © 1997 Elsevier Science B.V.

1. Introduction

Owens Lake in eastern California is a source of major wind-blown dust pollution in the USA. It is estimated that 6% of the breathable dust in the continental USA is produced from Owens Dry Lake (Blum, 1993). This source of dust is a relatively recent phenomenon, caused by diversion of the Owens River and subsequent desiccation of the lake in the early part of this century. Much of the dust produced from the lake bed is salt derived from evaporation of the saline groundwater. Before the effort described in this work, the magnitude of evaporation and the yearly salt flux to the lake bed surface were not well quantified.

Efforts are currently underway to develop dust control strategies for Owens Lake. Many of these efforts involve the use of groundwater to suppress the dust production. To determine the impacts of groundwater pumping, a water budget for the basin must be developed. As the basin is hydrologically closed, it is crucial to estimate the volume of water lost to evaporation if the water budget is to be balanced. It is hoped that some portion of the water lost to evaporation can be diverted before it reaches the land surface and be used for dust control strategies.

The objectives of this effort were twofold: (1) to develop and test techniques capable of measuring the small anticipated evaporative fluxes under harsh environments; (2) to develop a lake-wide estimate of groundwater evaporation and salt flux. We begin with a brief description of the region and previous work on evaporation from Owens Lake and other playa environments. We then present detailed comparisons of methods for estimating evaporation (eddy correlation, chloride profiling and microlysimeters) at two sites representative of the major surface characteristics of the current lake environment. Seasonal estimates of groundwater evaporation from these two sites, along with evaporation measurements from the remnant brine pool, are then presented to develop a yearly evaporation budget from the entire lake.

2. Study site location

Owens Dry Lake is in the Basin and Range physiographic province of the western USA and was the modern terminus for the Owens River draining a large portion of the eastern Sierra Nevada (Fig. 1). In recent geologic time, Owens Lake represented one of a chain of Pleistocene lakes beginning at Mono Lake (glacial Lake Russell) in the north and extending as glacial Lake Manly as far south as Death Valley, California (Smith, 1984). The historic shoreline of the lake (referred to in subsequent text as Owens Lake) encompasses an area of approximately 280 km^2 at an elevation of 1094 m above mean sea-level. The climate of the area is typical of high desert conditions. Annual precipitation
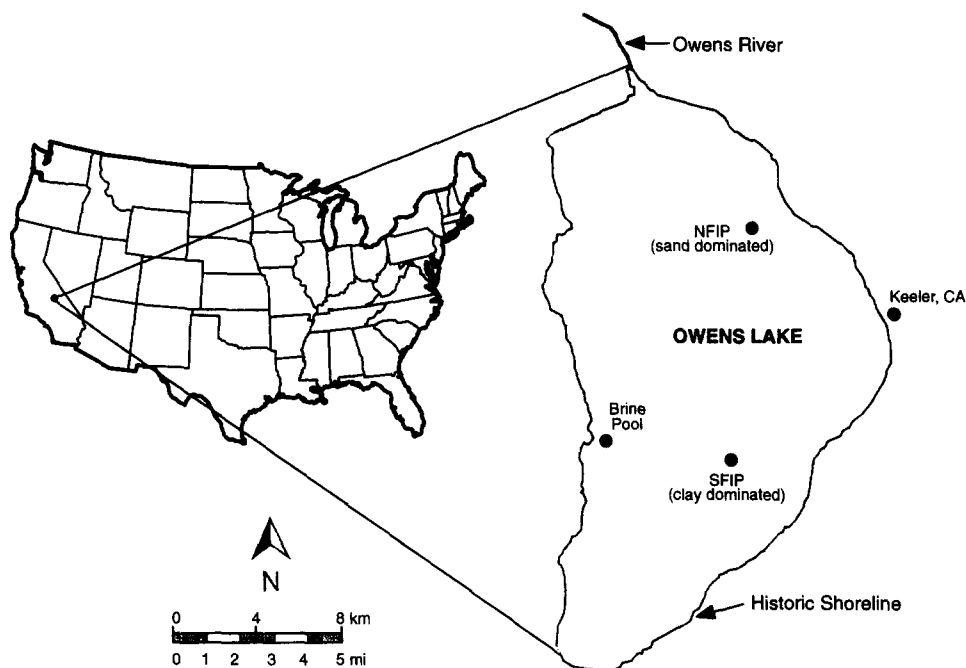
Fig. 1. Location of Owens Lake and sites described in this study.

on the lake bed has been estimated to range from 100 to 140 mm year^{-1} (Lopes, 1986). Summer temperatures often exceed 37°C, with an average summer temperature of 27°C (Hollet et al., 1991). Average winter temperature is 3°C, although temperatures as low as −18°C have been recorded (Hollet et al., 1991).

Agricultural development, beginning in the 1860s, and the completion of the Los Angeles Aqueduct in 1913 caused the lake to shrink in volume (and increase in salinity); by 1923, it had reached its present status. Much of the surface area encompassed by the historic shoreline is now dry and consists of efflorescent salt crust, eolian sand sheets or exposed lacustrine sediments. In the text, this area is termed Owens Lake playa. Springs along the western margin, as well as occasional local and regional flood events, maintain a small brine pool of varying size. The chemistry of the Owens Lake brine pool is dominated by sodium salts of carbonate, sulfate, and chloride (Friedman et al., 1976).

Owens Lake is subjected routinely to strong northerly and southerly winds associated with storm fronts and local convective systems. Salts precipitated on the playa from groundwater evaporation, along with the fine lacustrine sediments, are easily eroded and produce large dust storms which impair visibility and violate air quality standards for sub-10 μm particulates (PM-10). Whereas many playas produce little dust owing to the stability of their halite crusts, the predominant salts found at the surface of Owens Lake playa are salts of sodium carbonate and sodium sulfate, which form a friable crust that is easily eroded by wind or sand saltation. As a result, evaporation of the underlying groundwater leading to the subsequent precipitation of salts is an important process in the formation of dust from Owens Lake.

In many arid environments, playa evaporation represents the ultimate point of discharge in a basin's hydrologic cycle, yet quantifying the rate is difficult because of the harsh conditions found in these areas and the relatively low evaporative fluxes. As a result, few studies have been conducted to determine evaporation from Owens Lake or other playa environments. Early estimates (Lee, 1912) focused on open-water evaporation and reported rates of 1.5 m year^{-1} using evaporation pans. Evapotranspiration estimates from the surrounding vegetated areas suggested rates of 1.5–6.5 mm day^{-1} (Wilson et al., 1992). Lopes (1986) and Cochran et al. (1988) estimated playa evaporation rates of 0.03 mm day^{-1} (10 mm year^{-1}) from lysimeter measurements in the southeastern portion of Owens Lake. The reduction over open-water rates was attributed to the presence of a thick (800 mm), unsaturated salt crust overlying the saturated lacustrine sediments. Ullman (1985) reported long-term evaporation rates ranging from 9 to 28 mm year^{-1} from the salt-crusted surface of Lake Eyre in south–central Australia. The low rate of evaporation was attributed to the reduced albedo of the salt surface. Allison and Barnes (1985) reported groundwater evaporation rates of 90–230 mm year^{-1} from Lake Frome, also in south–central Australia, based on isotopic and chloride profiles in the sediments. Malek et al. (1990) reported groundwater evaporation of 229 mm year^{-1} from a playa surface in eastern Utah. In all of these previous studies, evaporation estimates were developed using only one approach (solute profiling, lysimeters, etc.), with no independent check on the validity of the estimate using other approaches. In this work, we provide several independent estimates of groundwater evaporation to compare various methods and to provide confidence in the estimates.

In the present work, we compare and discuss results from eddy correlation, micro-lysimeters and solute (chloride) profiles from two sites on the Owens Lake playa. The sites were chosen to represent the dominant soil surface conditions found in the dust-producing areas to estimate yearly evaporation and salt flux. Based on the success of these various methods, a seasonal monitoring program was implemented to measure the seasonal variation of evaporation from the playa, as well as evaporation from the brine pool.

3. Study site overview

The large area of Owens Lake required that study-site locations be chosen to represent the typical surface and subsurface conditions. On the surface, three types of conditions are typically found: coarse eolian sand cemented to various degrees by salts, a salt crust overlying lacustrine sediments ranging in thickness from 0 to 3 m or areas of open water and brine. The salt crust on the Owens Lake playa is often friable, generally porous, and easily disturbed. It is the friable nature of the crust resulting from the dominance of sodium carbonate and sodium sulfate salts that is responsible for much of the dust pollution from the lake (Saint-Amand et al., 1986). In the western and central portions of Owens Lake, which represent the deepest portions of the pre-diversion lake, evaporite sequences of trona, mirabolite and halite are present at the surface and can be as much as 3 m in thickness (Friedman et al., 1976; Saint-Amand et al., 1986).

Depth to groundwater varies over the lake bed but is generally near the land surface. Depth to groundwater may have some effect on evaporation in those areas dominated by thick sand sheets; however, the lacustrine sediments remain nearly saturated well above the water table owing to capillary rise.

Three principal study areas were chosen for this research to be representative of the major surface and subsurface features of Owens Lake and are shown in Fig. 1. The first study area, denoted NFIP (North Flood Irrigation Project), is located in the northeastern portion of the playa and was chosen to represent evaporation from areas of eolian and deltaic sands overlying lacustrine sediments. Sand sheets and dune fields represent a large proportion of the playa area. The depth to groundwater in this area was approximately 0.9 m. The surface conditions at the NFIP area are dominated by a salt-cemented, sandy crust with small (less than 20 mm) depressions filled with windblown sand. The subsurface consists of 1–2 m of sand with varying amounts of lacustrine sediments. Below this sand mantle, the sediments are lacustrine in nature.

The second study area, denoted SFIP (South Flood Irrigation Project), was chosen to represent those areas of the playa in which the lacustrine sediments are present very close to the surface and is located in the southeastern portion of the lake bed. The area is covered by a thin (30–80 mm) veneer of friable salt crust which contains some eolian sands. Particle-size analysis from the material beneath the crust in the upper 100 mm of the profile ranges from clay to clay loam. Depth to groundwater in this area during summer 1993 ranged from 2.35 to 2.5 m below ground surface; however, the soils appeared nearly saturated up to the contact with the salt crust. The final study area, the brine pool site, is located on a promontory of the west–central lakeshore and was surrounded on three sides by open brine and water-saturated evaporite deposits. This site was chosen to estimate the evaporative flux from open water and saturated salt crust.

No study areas were placed in the central portions of the lake bed, owing to inaccessibility. Evaporite sequences thicken from east to west, with depth to groundwater slowly approaching the surface to the west. The surface salt crust in the central portion of the lake bed appears similar to that found at the SFIP site to the southeast and evaporation estimates were extrapolated from the SFIP site.

Measurements of evaporation at Owens Lake reflect the sum of both groundwater evaporation and evaporation of precipitation. Measurements were made in 1993 and 1994 during a 7 year period of below normal precipitation. Precipitation had not directly preceded any measurement periods. Observations of the playa surface following precipitation, however, indicate that evaporation quickly dries the surface. Irrigation experiments, conducted in 1991 and 1992 to reduce dust emissions, indicated that up to 10 mm of irrigation water was evaporated within a 30–60 min period of high winds following irrigation. Intermittent and convective storms are generally followed by periods of high potential evaporation resulting in rapid loss of precipitation water from the surface. Malek et al. (1990) also reported that precipitation from such intermittent storms was evaporated from the surface in 2–14 days. The long, dry periods before the field measurements and high potential evaporation during the study periods imply that the evaporation measured was primarily groundwater evaporation, with no or little effect of antecedent moisture.

4. Evaporation measurement techniques

Several approaches for estimating evaporation from the Earth's surface are available. Evaporation (or latent heat flux) can be directly measured at the land surface, measured as

latent heat flux in the atmosphere or inferred from the direction and magnitude of vertical water flux in the subsurface. Many approaches have been developed for agronomic purposes, where ambient conditions are not extreme and evaporative fluxes are large. The harsh climatic conditions and low anticipated evaporative flux from the Owens Lake playa eliminated several methods from this study as being either impractical or insensitive. The remaining methods were tested in the first phase of this study to determine their feasibility and reliability.

Measurement of evaporation from playa surfaces has generally focused on two major areas: direct measurement of evaporative discharge, and inferential estimates based on solute profiles in the subsurface. Direct measurements can be made from lysimeters (Boast and Robinson, 1982) or from measurement of latent heat fluxes in the atmosphere via Bowen ratio (see, e.g. Malek et al., 1990) or eddy correlation (Parlange et al., 1995). In each of these approaches, the time scale of measurement is short, ranging from days to months, and the spatial resolution ranges from less than 1 m^2 (lysimeters) to 10^4 m^2 (micrometeorological methods).

Allison and Barnes (1985) presented a simple model for evaporative enrichment of solutes within the soil profile as a technique to estimate the long-term evaporation rate from playas. In their model, the upward advective flux of solutes driven by evaporation is balanced (at steady state) by the downward diffusion of solutes in the soil. These opposing fluxes lead to an exponential profile of solute concentration, controlled by the evaporative flux and the effective diffusion coefficient in the soil. This approach provides a long-term average rate, but is limited to point measurements in the soil profile.

In this research, two direct measurements (Class A pan and microlysimeters), two micrometeorological methods (Bowen ratio and eddy correlation) and one subsurface technique (chloride profiling) were tested and compared. Given below are brief summaries of the techniques and instruments used.

4.1. Class A evaporation pan

Standard Class A evaporation pans measuring 1.21 m in diameter and 0.255 m in depth were installed following Shaw (1988). Water used in the pans was from local drinking water sources and was of low total dissolved solids. Daily level measurements were taken to estimate the evaporation rate.

4.2. Microlysimeters

Microlysimeter design was modified from Boast and Robinson (1982) and consisted of 100 mm i.d. PVC pipe 305 mm in length nested inside 127 mm i.d. PVC pipe (Kranz, 1994). This outer casing serves as a silo for the inner casing, which is filled with soil. The microlysimeters were installed by first driving the outer casing into the soil and removing by hand the soil contained within. During installation and measurement, elevated wooden planks were used to reduce soil surface disturbance.

The inner casing was first driven into the soil at some distance (less than 20 m) from the final installation site to eliminate surface disturbance and excavated and capped on the bottom to produce an intact core of native soil. The core barrel was carefully cleaned of all

clinging soil, weighed in the field and placed in the previously excavated silo. Each core was wrapped with a piece of thin foam insulation to prevent thermal convection in the annular space.

Subsequently, daily weight measurements were taken by carefully extracting the core and weighing on a precision load cell balance (± 0.1 g, Denver Instruments 8KD, Denver, CO). Evaporation was calculated from the daily weight loss divided by the density of water and cross-sectional area of the microlysimeter. Daily measurements were made for up to 1 week, after which time numerical simulations indicated that the evaporation may have become influenced by the sealed bottom boundary.

4.3. Bowen ratio energy budget

The Bowen ratio method relies on the assumption that latent and sensible heat flux transport mechanisms are identical. Simultaneous measurement of thermal and vapor density gradients near the surface, along with net radiation and soil heat flux, is needed to calculate the ratio and latent heat flux (evaporation). The Bowen ratio instrumentation was similar to that described by Malek and Bingham (1993). The vertical temperature gradient, averaged over 20 min periods, was collected from 36-gauge chromel–constantan thermocouples located at 1.3 and 2.8 m above the ground surface. Vapor densities were continuously measured in a flowthrough chamber using a relative humidity–temperature sensor (HMP35C, Campbell Scientific, Logan, UT). Vapor samples were continuously drawn at a rate of 0.5 l min^{-1} from the tower locations and were alternately passed across the single humidity sensor every 2 min. Relative humidities were converted to vapor density using the temperature of the sensor, with a resulting accuracy in the vapor density measurement of $\pm 5 \times 10^{-4}$ kg m^{-3}. Net radiation was measured using a net radiometer (Q-6, Campbell Scientific), and two soil heat flux plates (HFT 3, Radiation Energy Balance Systems, Seattle, WA), placed just below the soil surface, were used to calculate 20 min averages of latent heat flux.

4.4. Eddy correlation method

Eddy correlation methods require measurement of the covariance of vertical wind speed and vapor density to calculate latent heat flux (Parlange et al., 1995). For this study, a one-dimensional sonic anemometer (CA27, Campbell Scientific) and open-path hygrometer (KH20, Campbell Scientific) were employed operating at 10 Hz, both located 2 m above the soil surface. Surface topography at all sites was generally less than 50 mm and upwind fetch exceeded 0.5 km at all study locations. The 20 min averages and covariances were measured and stored on a datalogger (21X, Campbell Scientific). Owing to the low vapor densities in the field, oxygen correction was necessary and was accomplished during data processing (Tanner et al., 1993). The ratio of latent to sensible heat flux was small, and corrections suggested by Webb et al. (1980) were also made before final estimates of the latent heat flux.

To close the energy budget, sensible heat, net radiation and soil heat flux were also measured. A fine-wire thermocouple, located at the midpoint of the anemometer path, was used to measure air temperature fluctuations and the covariance was calculated using

vertical wind-speed fluctuations. Net radiation and soil heat flux devices were similar to those employed on the Bowen ratio station.

4.5. Soil chloride profiling

Accumulation of soluble salts near the land surface is a consequence of bare soil evaporation. Under conditions of a steady upward flux driven by evaporation, the concentration in soil water of chloride (or any other conservative ion) has been shown (Allison and Barnes, 1985) to be related to the solute diffusion coefficient in the soil, D^*, and the evaporation rate, ϵ, as

$$\frac{C(z) - C_x}{C_0 - C_x} = \exp\left(z \frac{\epsilon}{nD^*}\right) \tag{1}$$

where C_0 and C_x are the time invariant concentrations of chloride at the land surface and underlying groundwater reservoir, respectively; n is the soil porosity, and z is vertical coordinate taken positively upward and measured from the soil surface. Additionally, D^* represents the product of the free-water diffusion coefficient, D_0, and the tortuosity, τ. Under steady-state conditions, the concentration of chloride at the land surface can be assumed to be at its solubility limit.

Soil chloride concentrations were analyzed on cores collected by hand auger or percussion coring. Chloride analyses by colorometric titration were completed on either 1:1 dilution extracts (corrected back to soil water concentrations from volumetric water contents), or on pore water squeezed in a modified Manheim press (Manheim, 1970). Below the water table, pore waters were collected from percussion-installed piezometers completed over short (less than 20 mm) intervals.

Effective diffusion coefficients were measured on intact subsamples of fine-grained sediments using a modification of the Stoessell and Hanor (1975) method (Kranz, 1994). One end of the sample (16 mm diameter by 30 mm length) was exposed to a well-mixed reservoir from which small (10 ml) samples could be periodically withdrawn. The increase in concentration in the reservoir was controlled by the diffusive transfer of solute from the core and could be predicted from

$$\frac{C_{res}(t)}{C_i} = \frac{2A}{V}\left(\frac{n^2 D^*}{\pi}\right)^{1/2} t^{1/2} \tag{2}$$

where $C_{res}(t)$ is the concentration of solute in the reservoir, C_i is the concentration of solute initially present in the core, A and V are the cross-sectional area of the core and reservoir volume, respectively, and n is the core porosity. Eq. (2) requires that the sediment samples be initially fully water saturated to ensure that all solute transport is by diffusion only. Subsamples were chosen to represent only fine-grained sediments, which were at or very close to fully water saturated.

Owing to the high ionic strength of the pore waters and the predominance of sodium clays, it was necessary to adjust the ionic strength of the reservoir solution to match that of pore waters. Pore-water activity was measured on squeezed pore waters using a chilled mirror hygrometer (Decagon Instruments, Pullman, WA). The ionic strength of the reservoir solution was adjusted using reagent-grade sodium chloride.

Although effective chloride diffusion coefficients are required in Eq. (1), the high chloride concentrations required for ionic strength adjustment in the reservoir solutions precluded its use as a solute in the laboratory analysis of diffusion coefficient. Fortunately, the soil waters found at Owens Lake contain elevated concentrations of boron owing to evaporative enrichment, and therefore boron was used as a surrogate for chloride. At the high pHs found in the pore waters, boron is most favorably found as either $B(OH)_{3aq}$ or $B(OH)_4^-$ (Hem, 1985) and therefore should behave as a fairly conservative species in solution. Boron concentrations in both the reservoir and from squeezed pore waters were analyzed by ion-coupled plasma spectroscopy with an estimated analytical uncertainty of ± 0.05 mg l^{-1}.

Using the free-water diffusion coefficient at laboratory conditions for boric acid (0.98×10^{-9} m^2 s^{-1}; Washburn, 1929), an estimate of the soil tortuosity can be obtained from the diffusion experiments. The calculated tortuosity can be subsequently used to estimate the effective diffusion coefficient for the chloride ion under field temperatures.

5. Estimates of evaporation from the NFIP area (sand dominated)

Measurement of evaporative flux from the NFIP site was initially conducted in the summer 1993. This initial phase of the study program was designed to evaluate the effectiveness of micrometeorological methods (Bowen ratio and eddy correlation), pan evaporation, microlysimeters and subsurface chloride profiling under the harsh conditions and low fluxes anticipated.

Measurements of groundwater evaporation were conducted between 21 June and 3 July 1993, at locations within the study site. Similar surface and subsurface conditions were found at all locations and hot, windy conditions, which are typical of summer conditions, existed throughout the observation period. No long-term precipitation records are available directly adjacent to the study site; however, records are available from a monitoring station 2 km to the north and at the town of Keeler, 8 km to the southeast. As expected in this arid region, precipitation records often differed at these two stations, although major precipitation events (greater than 10 mm day^{-1}) were generally recorded at both stations. Precipitation (3.8 mm) was recorded 15 days before 21 June at the northern station, with only a trace recorded at Keeler. Precipitation was also recorded on 22 June 1993, at the northern station; however, this recording appears in error, as no rain was physically observed during this period. No precipitation before this period had occurred for at least 30 days. Malek et al. (1990) observed that such light rain was evaporated from Pilot Valley Playa in western Utah within several days and that subsequent evaporation was supported strictly by groundwater. Potential evaporation during the summer months at Owens Lake was similar to that observed by Malek et al. (1990). Therefore, evaporative fluxes measured in June 1993 are believed to be dominated by groundwater discharge rather than transient precipitation evaporation.

As anticipated, pan evaporation estimates were very large (17–27 mm day^{-1}) and were correlated with daily average wind speed. These high rates, however, are not consistent with previous water budget estimates of evaporation and reflect the radical difference in surface conditions between the open-water surface of the pan and the dry soil surface.

Eight microlysimeter replicates were installed at locations within the study area. Microlysimeters were weighed daily and evaporation rate was calculated from weight loss. Sand transport, both on and off the microlysimeters, was a significant problem for three of the microlysimeter replicates, as the accumulation or loss of soil could not be separated from losses owing to evaporation. Daily observations confirmed that significant sand transport had occurred across these microlysimeters. Fig. 2 shows the calculated cumulative evaporative loss from the remaining five microlysimeters, which did not show significant losses or gains owing to surface erosion or deposition. Most of the lysimeters recorded the highest evaporation rates immediately after installation, which may reflect disturbance of the soil and enhanced drying near the surface. Ignoring this early-time behavior, the cumulative evaporation from each of the lysimeters is very similar. The mean slope from the five lysimeters is 0.52 mm day^{-1} with a standard deviation of 0.05 mm day^{-1}. The analytical uncertainties associated with field weight of the microlysimeters are small (approximately 0.01 mm day^{-1}) in comparison with the average daily evaporation rate.

Bowen ratio measurements of evaporation were conducted from 20 to 24 June 1993. Negative Bowen ratios were routinely calculated during both daytime and evening periods when gradients in vapor density were observed to be negative. These results, however, are not consistent with a playa undergoing evaporation. The gradients in vapor density were very small and analysis of the humidity sensor sensitivity showed that it was not capable of accurately resolving the anticipated gradient. Although Malek et al. (1990) have reported Bowen ratio measurements of evaporation on playa surfaces, the technique, combined with the instrumentation used in this study, becomes subject to significant analytical error under conditions of very low evaporative fluxes. As a result, this method was not further explored in this study.

Eddy correlation measurements of all surface energy fluxes were conducted at two adjacent locations within the study area. Fig. 3 shows the components of the energy budget
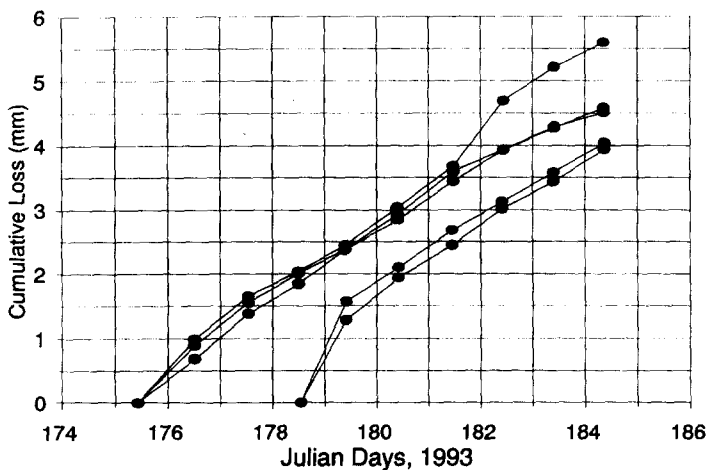

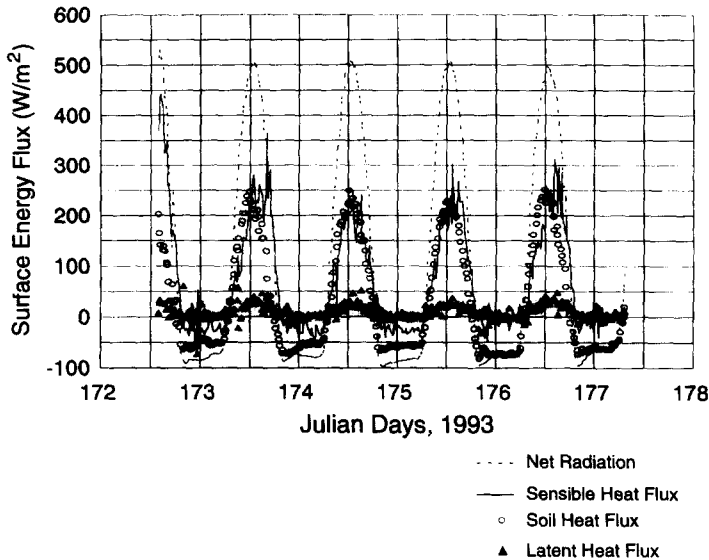Fig. 2. Cumulative water loss (in mm) from microlysimeters in the sand-dominated portion of the Owens Lake playa.

Fig. 3. Net radiation (R_n), sensible (H) and latent (LE) heat fluxes, and soil heat flux (G) as measured by eddy correlation technique in the sand-dominated portion of the Owens Lake playa.

for a representative 5 day period. As expected, the majority of available net radiation is converted to sensible heat from the playa surface and soil heat flux. Latent heat flux (evaporation) was small, reaching a maximum of 50 W m^{-2} shortly after noon each day. Periods of wind direction from ±40° upwind of the sensors were rare and were eliminated from the data. Average daily evaporation (6 day average) was 0.41 mm day^{-1}.

Fig. 4 shows the energy budget closure over the period shown in Fig. 3. Closure was generally less than 50 W m^{-2} over any 20 min period; however, several large excursions can be seen in the data. A significant portion of the closure error may be attributed to the
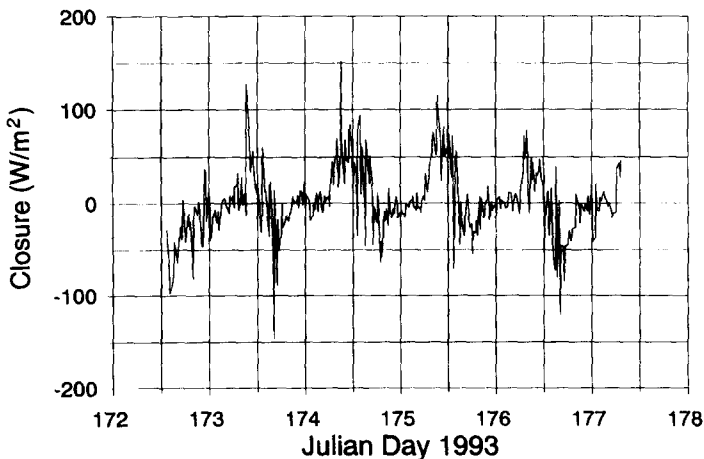

Fig. 4. Energy budget closure during summer 1993 at the sand-dominated portion of the playa.

measurement of soil heat flux. During the 5 day monitoring period, the two soil heat flux plate measurements differed by approximately 20%. In addition, both soil heat flux and net radiation represent essentially point measurements, whereas sensible and latent heat flux represent areally averaged quantities. This disparity in scales of measurement may lead to closure excursions over the short (20 min) averaging periods. When averaged over the entire 5 day monitoring period, however, the mean closure error was significantly reduced to 2.3 W m^{-2}.

In a field setting, it is difficult to partition the sources of closure error without independent measurement of each of the energy components. Partitioning the closure error equally amongst the fluxes results in an uncertainty in latent heat flux of approximately 100%; however, sensible heat and soil heat flux were both generally much larger in absolute magnitude and probably contribute a greater proportion to the closure error. During the monitoring period, independent latent heat flux estimates were available from the microlysimeters to estimate the uncertainty in the eddy correlation estimates. During the same 5 day monitoring period, the mean microlysimeter evaporation was 0.52 mm day^{-1}, whereas the mean eddy correlation estimate was 0.41 mm day^{-1}. Assuming the lysimeter estimates to be accurate (their uncertainties owing to both replication and analytical accuracy were ±10% or less), the estimated eddy correlation latent heat flux uncertainty can be constrained to ±25%. The eddy correlation closure errors and their standard deviations in subsequent field seasons were very similar to those observed during summer 1993, suggesting that an uncertainty of ±25% in the mean eddy correlation derived evaporation is appropriate. Comparison of microlysimeter and eddy correlation estimates of evaporation from the SFIP site presented in the next section confirms that an uncertainty of ±25% represents a conservative estimate of the uncertainty in eddy correlation measured evaporative flux.

Chloride profiling can provide a long-term average groundwater discharge (evaporation) rate in playa sediments when solute transport is controlled by upward advection and downward diffusion. Chloride concentrations in the upper 0.9 m of the profile were calculated from dilution extracts of hand-augered core samples from two borings. Below 0.9 m, core samples could not be obtained, owing to the saturated and coarse nature of the sediments, and a drive-point piezometer was used to collect water samples for chloride analysis. Chloride concentrations from both borings showed high, but erratic, chloride concentrations above the water table and uniform concentrations below the water table. The uppermost samples showed chloride concentrations well in excess of solubility, confirming the presence of halite.

The chloride concentration profiles at the NFIP site did not display the anticipated exponential shape predicted by Allison and Barnes (1985) and were not amenable for analysis of long-term evaporation rate. The rather noisy profiles above the water table and uniform concentrations below suggest that transport mechanisms other than simple advection and diffusion are occurring in these sediments. The high saturated conductivity of the sands may allow rapid infiltration of the occasional rainfall event, destroying the profile shape in the near surface. In addition, erosion and deposition of sand and salt commonly occur in this area during dust storms, suggesting significant transport of chloride by mechanisms other than in the liquid phase. Below the water table, density-driven convection may be occurring, homogenizing the shallow groundwater profile.

Under such conditions, chloride profiling is not an appropriate technique to estimate long-term evaporation from the water table.

In summary, two techniques (microlysimeters and eddy correlation) were found viable for the sand-dominated areas. These two methods provided independent and consistent estimates of evaporation at the sandy soils at the NFIP site. Summer evaporation rates from the underlying groundwater were approximately 0.4–0.5 mm day^{-1} and are in general agreement with results from other playa studies.

6. Evaporation from the SFIP area (clay–crust dominated)

Measurements of evaporation were made at the SFIP study site representing the clay and salt crust portions of the playa in summer 1993. The surface conditions consisted of a thin (3–10 cm) friable salt crust underlain by lacustrine silts and clays. Evaporation pan, microlysimeters and chloride profiling were used during this period. Eddy correlation equipment was not available during summer 1993; however, eddy correlation measurements were made the following summer at the site under similar climatological conditions. The evaporation rate, as measured by evaporation pan, was very similar to that found at the NFIP site (14–26 mm day^{-1} vs. 17–27 mm day^{-1}), reflecting the similarity in climatic conditions at the two sites.

Six replicate microlysimeters were installed at two locations within the area. Care was taken to minimize disturbance of the surface crust during installation; however, the surface crust was inevitably broken up in the process. Fig. 5 shows the cumulative evaporation from the six microlysimeters. In all cases, the data show an initial high rate of evaporation lasting 1–2 days, followed by a period of lower, but steady, evaporation. The high initial rates most probably reflect the surface crust disturbance and rapid drying of near-surface material. The consistent slopes of the late-time data (0.23–0.35 mm day^{-1}) suggest control by the clay sediments in limiting evaporation. Therefore, the late-time rates may be most
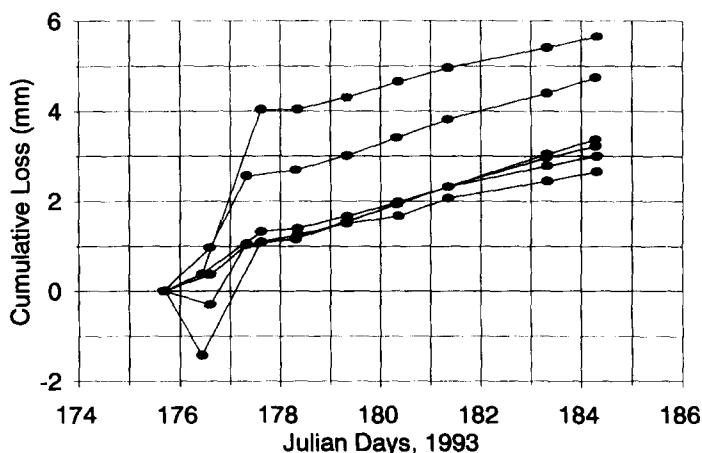

Fig. 5. Cumulative water loss (in mm) from microlysimeters at the clay-dominated portion of the Owens Lake playa.

indicative of the actual evaporation rate. The mean evaporation rate using the late-time rates from the six microlysimeters was 0.29 mm day^{-1}. The standard deviation of the six estimates was ±0.05 mm day^{-1}, identical to that found at the NFIP site; however, the mean daily evaporation rate at the clay–crust site was reduced by approximately 40%.

Eddy correlation estimates taken the following summer (1994) under similar climatic conditions showed a mean daily evaporation rate of 0.34 mm day^{-1}, very close to the microlysimeter estimates the previous summer. The surface crust conditions remained friable. No precipitation had been recorded at Keeler, California, 10 km northeast of the
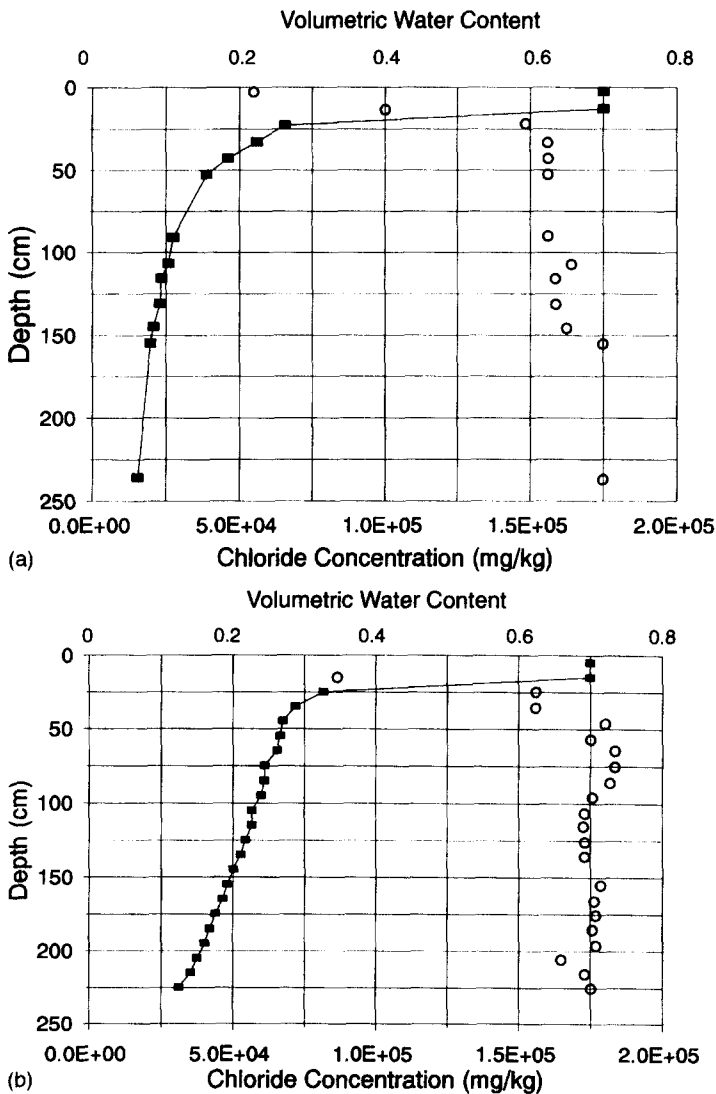

Fig. 6. Chloride concentrations (solid squares) in pore waters from the SFIP study area (clay-dominated areas) in (a) Boring B1 and (b) Boring B2. Open circles represent measured volumetric water contents.

study site, for 67 days before the measurement period and the last precipitation event was followed by hot and windy conditions.

Soil water chloride concentrations were analyzed from 1:1 dilutions of near-surface soils and from pore water squeezed from core samples to a depth of 2.35 m from two auger holes adjacent to the microlysimeters. Fig. 6(a) and Fig. 6(b) show the chloride concentration in pore waters vs. depth from these two borings. Chloride concentrations exceed solubility limits in the upper 0–150 mm only and showed a gradual decline with depth.

Estimates of soil tortuosity and porosity were made on two samples from Boring B1 (0.5 m and 1.45 m depth) and three samples from Boring B2 (0.55 m and two replicates at 1.55 m). Tortuosity ranged from 0.11 to 0.60 and was consistent with the high porosities of the lacustrine sediments. Porosity was estimated from gravimetric analysis of water content. For the cores analyzed, the correction of porosity for soluble salts in the pore waters was not significant. Table 1 shows the measured boron diffusion coefficients, estimated tortuosities, porosities and calculated effective chloride diffusion coefficient at the average annual field temperature (15°C).

The evaporation rate for each boring was calculated following Ullman (1985), using the average effective chloride diffusion coefficient from the samples in each boring and the slope of the soil water chloride profile. The minimum chloride concentration was assumed to be that of the deepest sample depth, and sodium chloride saturation was assumed at the land surface. The calculated evaporation rates from the two borings were 0.046 mm day^{-1} and 0.056 mm day^{-1} (17 mm year^{-1} and 21 mm year^{-1}), respectively, well below that observed by both the microlysimeters and eddy correlation methods.

The solute profiling technique has been proposed to provide a long-term average analysis of evaporation (Ullman, 1985), and is relatively insensitive to short-term fluctuations. The eddy correlation and microlysimeter methods are, by nature, real-time measurements of flux; however, the lack of recent precipitation during the study periods implies that these techniques were resolving the net groundwater flux only. As will be shown in further sections, seasonal variation in evaporation is not sufficient to reduce the average rate to that estimated by the chloride profile measurements.

The chloride profile method is controlled by the near-surface shape of the concentration profile and assumes only upward advection and downward diffusion of salts. Theoretically, the solute concentration should approach solubility limits (if halite exists) at or near the land surface. Extrapolation of regression analysis for both borings falls far

Table 1
Measured and predicted effective diffusion coefficients for the SFIP site

Core ID	Core boron concentration (mg l^{-1})	Experimental D_{boron}^{*} (m^2 s^{-1})	τ	Porosity	Predicted $D_{chloride}^{*}$ (m^2 s^{-1})
B1 (0.5 m)	620	1.1×10^{-10}	0.11	0.63	1.7×10^{-10}
B1 (1.45 m)	180	3.7×10^{-10}	0.38	0.70	6.0×10^{-10}
B2 (0.55 m)	1300	4.8×10^{-10}	0.49	0.71	7.7×10^{-10}
B2 (1.55 m)	470	5.6×10^{-10}	0.60	0.72	9.4×10^{-10}
B2 (1.55 m)	470	5.8×10^{-10}	0.51	0.72	8.1×10^{-10}

D_0 (boron) is 0.98×10^{-9} m^2 s^{-1} (22°C); D_0 (chloride) is 1.58×10^{-9} m^2 s^{-1} (15°C).

short, however, of reaching the expected surface concentrations. Evaporation and diffusion should lead to an exponential shape of the chloride profile. Examination of the data in Fig. 6(a) and Fig. 6(b) shows that the chloride profile from Boring B2 deviates significantly from the theoretical profile shape, and the estimated evaporation rate from this boring must be viewed with skepticism. This fact, combined with the poor agreement between observed and regressed surface chloride concentration, suggests that other processes may be affecting the shape of the chloride profiles.

In the near surface, several other processes can lead to a more diffuse solute profile and therefore an underestimate of the evaporation rate. Strong thermal gradients will produce daily and seasonal liquid fluxes in excess of that owing to evaporation. Osmotic gradients, which are most severe in the upper 100 cm, will tend to reduce surface concentrations and enrich deeper soil waters. Friedman et al. (1997) have suggested that density-driven convection may have displaced pore waters in the central portion of Owens Lake to a depth of 10 m over the last 100 years. Although the sediments are composed primarily of silt and clay, the hydraulic conductivity of the sediments appears to be larger than would be predicted from particle size analysis. Observation of piezometer recovery following sampling in the lacustrine sediments suggests hydraulic conductivities in the range of 10^{-7} m s^{-1}, which may be sufficient to support a downward density-driven counter flux. Oxidized fractures were also observed in both borings to depths of 2.35 m, which may have facilitated mobilization of surface salts to much greater depths. One or all of these processes may be responsible for the non-ideal shape of the profiles and the resulting low rates of evaporation calculated. Ullman (1985) reported similar rates from halite-crusted surfaces using data from the upper 1 m. However, the salt crust at the SFIP site is friable and porous, unlike that found in halite-dominated crusts, and should permit greater atmospheric exchange and hence evaporation. Similar conditions to those found at the SFIP site were reported by Malek et al. (1990) in western Utah. Long-term evaporation rates in western Utah, as measured by Bowen ratio, suggested evaporation rates of 229 mm year^{-1}, closer in magnitude to that measured at this site by both microlysimeters and eddy correlation.

In summary, microlysimeters and eddy correlation methods yielded independent and similar estimates for daily evaporation at this site. Soil chloride profiling suggested much lower evaporation rates but may be sufficiently affected by other soil water processes to make its use at best a limiting lower bound for evaporation flux. Based on the results of this work, it is suggested that the chloride profile estimates be considered a lower bound of the evaporative flux, and other independent methods be used to provide a more accurate representation of the actual flux.

7. Evaporation from open-water surfaces (brine pool site)

Permanent, open water only exists on Owens Lake along the western margin of the basin, fed by groundwater discharge, marginal springs and occasional runoff from tributaries and the Owens River. Except where it enters the lake, the lake water exists as a brine saturated in sodium salts of chloride, carbonate and sulfate. The extent of this brine pool fluctuates seasonally and also responds to snowpack conditions in the surrounding mountains. Extreme precipitation and runoff events can produce a much

larger open-water surface; however, these events are very rare and short lived. During the summer of 1993, evaporation measurements via eddy correlation were made on a small spit along the western shore (Fig. 1), which was surrounded by mixed open water and brine-saturated evaporites. Instruments were directed southward, the predominant wind direction. The extent of the brine pool in the southerly direction was approximately 0.5–2 km depending on the orientation. The sensor platform was situated on evaporites with approximately 20–50 mm of overlying brine. Measurements of net radiation, sensible and latent energy fluxes were made along with brine temperature.

Fig. 7 shows the net radiation, sensible and latent energy fluxes measured over the period 29 June–1 July. In contrast to the results from the playa surfaces, the latent heat flux was a significant component of the energy budget, with rates exceeding 600 W m^{-2}. Sensible heat flux, as anticipated from an open-water body, was much smaller. It is interesting to note that during conditions of high wind in the late afternoon, latent heat flux often exceeded net radiation. These strong advective conditions, combined with the fairly small upwind fetch from the southwest, produced a significant 'oasis effect' and evaporation was enhanced by dry, hot winds blowing from the surrounding arid shoreline. Evaporation from the brine pool was estimated to be 3.6 mm day^{-1} on 30 June and 5.5 mm day^{-1} on 1 July. The higher evaporation rate on 1 July was due to stronger afternoon winds.

8. Summary of techniques

Direct comparisons of all techniques at the NFIP site showed good agreement between evaporation estimates using microlysimeters and eddy correlation. Difficulties were
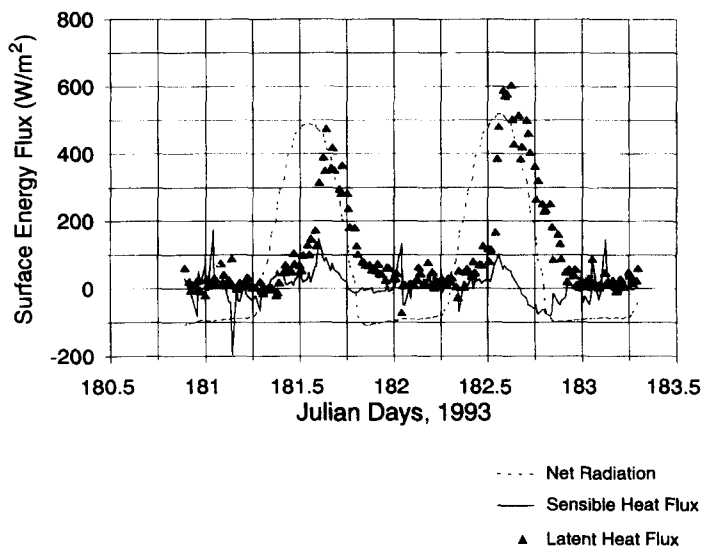

Fig. 7. Net radiation (R_n), latent (LE) and sensible (H) heat flux from the brine pool area recorded during summer 1993. (Note that latent heat flux exceeds net radiation during the late afternoon of Day 182 owing to strong advective conditions.)

encountered with some of the microlysimeters owing to soil loss (and gain) from wind transport across the lysimeter surfaces. Because of the friable nature of the salt-cemented crust, some disturbance of the crust was inevitable during lysimeter installation and appears to be reflected by higher rates of evaporation directly following installation. As expected, pan evaporation rates were several orders of magnitude larger than measured evaporation from the playa surface, which would result in very low and insensitive pan coefficients. Chloride profiling was not applicable to the coarse-textured and windblown sediments found at the NFIP and may have been influenced by convective mixing in the saturated zone. Bowen ratio estimates were not reliable, owing to the small gradients in vapor density and limited sensitivity of vapor density measurements.

At the SFIP study site, microlysimeters were less prone to error, as a result of less sand transport occurring at the southern end of the playa. Microlysimeter evaporation rates were slightly lower than observed at the NFIP site, probably the result of the extensive salt crust found at the SFIP. Chloride profiling resulted in lower estimates of evaporation than either microlysimeters or eddy correlation and appears to be significantly influenced by transport mechanisms beyond groundwater evaporation.

Because of the presence of open water in the brine pool, eddy correlation was the only method that could be tested. Eddy correlation estimates of evaporation from the brine pool are in general agreement with previous open-water estimates (Lee, 1912; W. McClung, personal communication, 1994). For continued estimates of evaporation from the three study areas, eddy correlation was chosen to be most generally applicable and, based on comparison with the independently measured microlysimeters, appeared to provide representative measurements over a large spatial scale and with sufficient accuracy for water budget estimates.

9. Seasonal variation of evaporation

Based on the 1993 summer results, evaporation monitoring was conducted in spring, summer and autumn 1994 to determine the seasonality of evaporation and to develop annual estimates of total groundwater evaporative loss from Owens Lake. An additional set of measurements was made during spring 1995 at the SFIP study area only. Measurements were not made during the 1994–1995 winter owing to unusually wet conditions, which impeded access to the study areas, but were made in early 1996 under warm but calm conditions.

During each season, eddy correlation measurements were made for several days at each of the study sites described previously. Precipitation preceded summer and autumn measurement periods by at least 15 days and was not significant (1 mm or less). Spring measurements may have been influenced by prior precipitation, with 3 mm falling 1 day before the 1994 measurements and 19 mm falling 21 days before the 1995 measurements. An additional study area at the southernmost portion of the lake was also included, where artificial dunes had been created as part of the dust mitigation testing. Evaporation estimates from this area were similar to those measured in the sand-dominated areas. The eddy correlation technique was chosen based on its earlier success, field portability and reliability under harsh conditions. The reliability of the equipment was surprising and

only one short (1.5 days) failure period was noted over the 30 cumulative days of measurement when a major dust storm obscured the open-path hygrometer and broke one of the fine-wire thermocouples.

Fig. 8 shows the daily average evaporation rate as a function of season of measurement from the three study areas. Evaporation from the NFIP site appears to steadily decline from the initial measurements in summer 1993 and may reflect the prolonged drought and subsequent decline of the water table in this area. In contrast, evaporation from the SFIP site (clay–crust dominated) shows similar summer rates in 1993 and 1994. This insensitivity to drought may be related to the continued high water contents maintained in these clay soils well above the water table. The SFIP site also shows highest evaporation rates during spring periods (0.5 mm day^{-1}), when near-surface soil moisture may be at its highest. During these periods, the overlying salt crust is less desiccated and may also maintain better hydraulic contact with the underlying sediments. Malek et al. (1990) postulated that loss of contact between the overlying salt crust will impede evaporation by effectively forming a mulch over the soil. During both spring measurement periods, no decline in evaporation rate was observed through the period of measurement, suggesting that precipitation before the measurement dates had little influence on the evaporation rates. Winter evaporation rates were slightly higher than those recorded during the autumn months, although they are similar. The winter measurement period was characterized by warmer than average daytime temperatures, which may have slightly increased the
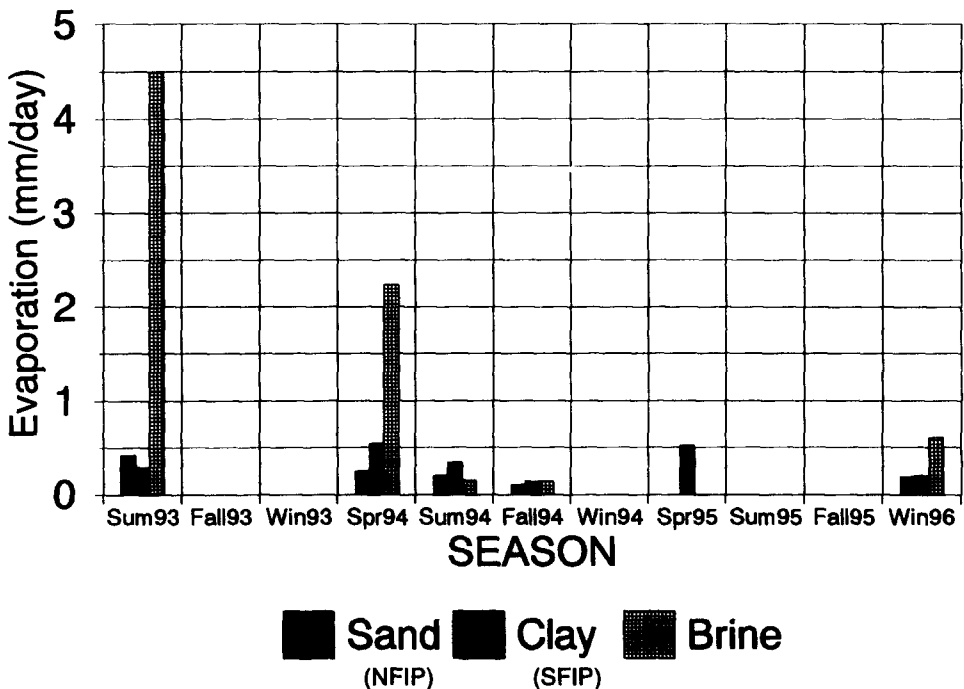

Fig. 8. Summary of seasonally measured evaporation rates from the three dominant surface conditions on Owens Lake.

evaporation rates. However, wind conditions were uncharacteristically calm, with maximum daily wind speeds rarely exceeding 1 m s^{-1}, which may tend to reduce the evaporative flux.

The measurements of evaporation from the brine pool show several important features. As expected, rates in spring 1994 are below those in the previous summer, owing to lower temperatures and decreased net radiation. However, evaporation in the following summer and autumn are much lower than would be expected from an open saline water body. This dramatic reduction in evaporation was due to a thin (less than 2 mm) floating salt crust that had formed across the entire extent of the brine pool. This membrane-like film was dry to the touch, yet could be easily broken. This salt crust was also present during the autumn 1994 measurements. Both periods of measurements were characterized by calm conditions, which allowed the crust to remain intact and effectively cut off evaporation. Such crusts occasionally occur (Friedman et al., 1976), but generally break up and sink during windy conditions. Although these conditions occasionally occur, they appear to have been accentuated by the prolonged drought, which considerably reduced the size of the brine pool. Winter evaporation rates over the brine pool averaged 0.6 mm day^{-1}, almost an order of magnitude below that measured during the summer months.

Yearly estimates of groundwater evaporation from the three dominant surface areas were extrapolated from the data shown in Fig. 8. Yearly average evaporation was taken as the arithmetic average of the four seasonal rates for each area. For both the NFIP and SFIP areas, autumn rates were well below those measured in the spring, implying that evaporation is more strongly controlled by groundwater conditions rather than potential evaporation. Groundwater levels tend to decline in late summer and autumn, owing to evaporative demand, and therefore it is conceivable that winter rates may actually exceed autumn rates.

The coincidence of prolonged drought with the measurement period appears to have affected evaporative flux in both the NFIP area and the brine pool. Consecutive summer measurement of evaporation at both sites showed a considerable decrease owing to drought conditions. For this reason, summer evaporation rates from 1993 were used to estimate the yearly evaporation from the NFIP area to produce a more representative average annual evaporation. At the brine pool site, autumn rates were assumed to be equal to those measured in spring 1994, when open water was extensive.

Using this approach, the seasonally adjusted annual evaporation rate from the sand-dominated areas represented by the NFIP site was 88 $\pm$ 22 mm year^{-1}. The clay–crust-dominated regions typified by the SFIP site were calculated to have an evaporation rate of 104 $\pm$ 26 mm year^{-1}. Yearly evaporation from the brine pool surface was calculated to be 872 $\pm$ 218 mm year^{-1}.

10. Annual groundwater and salt fluxes

One of the important data requirements for dust mitigation efforts is an estimate of the total yearly evaporation from Owens Lake and the yearly salt flux to the playa surface. Efforts are currently underway to develop an overall water budget for the lake basin to determine the availability of water resources for dust mitigation purposes. As the lake bed

represents the principal sink for groundwater in the basin, it is crucial that accurate estimates of evaporative loss be known. Given the large size of the lake, we must extrapolate our local-scale measurements to obtain a preliminary estimate of yearly total groundwater evaporation.

The study areas were chosen to represent the three major surface conditions found on the lake bed, sand dominated, clay–salt crust dominated and brine covered. Areas were delineated from 1:72 000 scale aerial photographs taken in 1976 and supplemented by core data from soil investigations and piezometer installations by the Great Basin Air Pollution Control District. Piezometer depths ranged from 1.2 to 10 m. Fig. 9 shows those areas of the lake in which the surface conditions were dominated by sandy soils, approximately 133 km^2. On the surface, the sand-dominated areas ranged from sand dunes to salt-cemented sand similar to that found in the NFIP study area. These areas were assigned
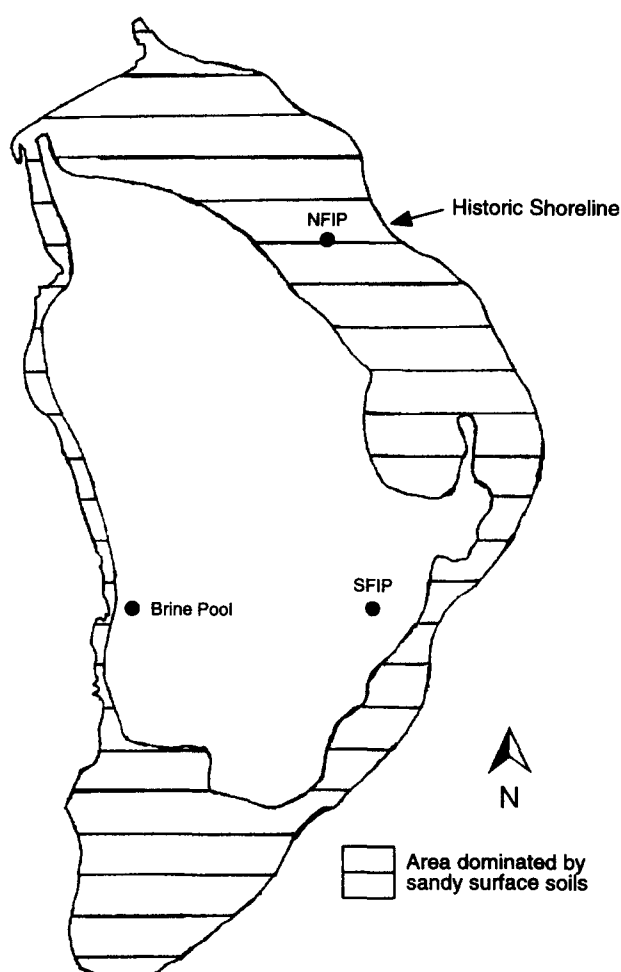

Fig. 9. Area of Owens Lake dominated by sand-covered areas.

a yearly evaporation rate of 88 $\pm$ 22 mm year^{-1}, corresponding to the yearly mean measured at the NFIP site. Using this rate and the sand area (133 km^2), the estimated yearly groundwater loss from these areas is 11.7 $\times$ 10^6 $\pm$ 2.9 $\times$ 10^6 m^3.

The brine pool has four principal sources of water: direct groundwater discharge, discharge from marginal springs along the western shore of the lake, surface and shallow subsurface flows from the Owens River, and precipitation. The brine-covered areas of the lake vary seasonally and significantly annually, owing to increased spring discharge, precipitation during winter months, infiltration of surface flows, and the flat topography. This yearly fluctuation in the brine elevation primarily inundates clay-dominated areas.

The brine evaporation rates measured in this study can be compared with historical records of brine pool recession to test their validity. Since the 1950s, the brine pool elevation seasonally has varied approximately 0.3 m from 1082.9 m in early spring (February) to 1082.6 m by early June. Area and volume relations developed by Blevens et al. (1976) show that such yearly fluctuations result in brine area and volume decreases from approximately 76 km^2 to 20 km^2 and 17.3 $\times$ 10^6 m^3 and 2.5 $\times$ 10^6 m^3, respectively. The resulting volume of water evaporated during this roughly 4 month (February–May) recession period using bathymetry data is 14.8 $\times$ 10^6 m^3. Using the measured evaporation rate of 2.23 $\pm$ 0.56 mm day^{-1} during the period of brine pool recession (February–May) and an average open-water area of 50 km^2 (midpoint of the recession area) over a period of evaporation of 4 months, the mean calculated evaporation volume is 13.4 $\times$ 10^6 $\pm$ 3.4 $\times$ 10^6 m^3, which spans that estimated from bathymetric data (14.8 $\times$ 10^6 m^3) and provides confidence in the measured evaporation rates.

During the summer months, the brine pool generally remains at its low stand (20 km^2) and gradually expands during the late autumn and winter in response to reduced evaporation and winter precipitation. The volume of water lost during this 8 month period (June–January) from the brine pool surface was estimated using a seasonally weighted evaporation rate (2.7 $\pm$ 0.68 mm day^{-1}) and an assumed brine pool area of 20 km^2, the low stand area of the pool. The constant area assumption will result in a slight underestimate of the actual volume lost; however, it is important to note that 70% of the water is lost during the summer months of this 8 month period (June–January), when the brine pool remains at its low stand. The volume of water lost from the brine pool during this 8 month period was estimated to be 12.8 $\times$ 10^6 $\pm$ 3.2 $\times$ 10^6 m^3. The total evaporated volume for the brine pool is the sum of the 8 month and 4 month periods (26.2 $\times$ 10^6 $\pm$ 6.6 $\times$ 10^6 m^3).

In contrast to the measurements on the playa, the volume of water evaporated from the brine pool has a contribution from precipitation inherent in its estimate. Using an annual average precipitation of 150 mm for the western portion of the lake bed (Blevens et al., 1976) and the seasonally adjusted brine area, the resulting precipitation volume is 4.5 $\times$ 10^6 m^3. Therefore, the total yearly mean volume of water evaporated from the brine pool is reduced to 21.7 $\times$ 10^6 m^3. This figure represents the sum of direct groundwater discharge, spring discharge, and surface or shallow subsurface runoff which directly enters the brine pool.

The remaining evaporation from the lake dominated by a clay–crust surface was calculated from the measured average rate for the area of 104 $\pm$ 26 mm year^{-1}. The clay-dominated area varies in size from 67 km^2 during high brine pool stand to 127 km^2 at low stand. However, groundwater discharge may continue to occur under

inundated conditions, as all deep wells completed on the lake bed show artesian conditions when corrected for density variations (Lopes, 1986). Therefore, it may be appropriate to assume that flux continues throughout the year over the entire clay-dominated portions of the lake, including the areas seasonally inundated by the brine pool. Under these conditions, the yearly flux is estimated to be $13.2 \times 10^6 \, m^3 \, year^{-1}$.

Table 2 summarizes the areas and yearly evaporated volumes from Owens Lake. The yearly volume of water evaporated from Owens Lake (sand area + clay–crust area at minimum brine pool) is $24.9 \times 10^6 \pm 6.2 \times 10^6 \, m^3$ and represents primarily direct groundwater discharge. The total volume of water lost from the lake surface is $46.6 \times 10^6 \pm 12.8 \times 10^6 \, m^3$. This volume is derived from direct groundwater discharge as well as spring and surface water inflows into the brine pool. Lopes (1986) estimated total subsurface inflows to the lake to be $39.6 \times 10^6 \, m^3 \, year^{-1}$. Using the estimated evaporative flux of $46.6 \times 10^6 \, m^3 \, year^{-1}$, the water budget closure is within 18%. Recent analysis (E. Jacobson, personal communication, 1996) showed a closure ranging from 3 to 29% using the above estimate of evaporation combined with new information on groundwater, spring discharge and surface-water inflows to the lake basin.

The evaporation volumes calculated above can also be used to estimate the yearly salt flux to the playa surface derived from evaporation of the groundwater. Salts must precipitate during transition to vapor-phase transport in the uppermost portion of the soil profile; however, occasional wetting of the profile following precipitation allows the salts to migrate to the surface and form an efflorescent, powdery crust. Significant dust storms are then often seen after these rainy periods (B. Cox, personal communication, 1994).

The yearly salt flux to the playa surface is controlled by both the evaporation rate and underlying groundwater salinity. The underlying groundwater chemistry varies dramatically across the lake, with total dissolved solids concentrations ranging from several hundred milligrams per kilogram near the margins to in excess of $300\,000 \, mg \, kg^{-1}$ in the brine pool. Using an average groundwater concentration of $30\,000 \, mg \, kg^{-1}$, as found at depth in the SFIP area, and the mean evaporation rates, the mass of salt brought to the Owens Lake playa may be as high as $7.5 \times 10^8 \, kg \, year^{-1}$. As surface evaporite deposits do not appear to be accumulating over much of the playa, it is

Table 2
Estimated evaporation rates and yearly water loss from Owens Lake

Surface condition	Seasonally adjusted evaporation rate (mm day^{-1})	Estimated surface area (km^2)	Yearly water loss (m^3)
Sand dominated (NFIP)	0.24 (0.06)	133	11.7×10^6 (2.9×10^6)
Clay–crust (SFIP)	0.29 (0.08)	127	13.2×10^6 (3.3×10^6)
Open water (brine pool)[b]	2.7[b] (0.68)	20	12.8×10^{6a} (3.2×10^6)
Brine pool fluctuation[c]	2.23[c] (0.56)	50 (varies from 20 to 80 km^2)	13.4×10^6 (3.4×10^6)

Uncertainties are shown in parentheses.
[a] Includes precipitation volume.
[b] Seasonal average of summer, autumn and winter rates.
[c] Spring rate only.

reasonable to assume that much of this mass of salt is carried from the playa surface by dust storms. Sampling of airborne dust in the area has shown that 20–70% of the dust is soluble salts, with the remainder being insoluble lacustrine sediments. Therefore, the annual loading of dust from both salt and sediments to the atmosphere from Owens Lake may range from 1×10^6 to 3.8×10^6 t year^{-1}.

11. Summary and conclusions

Several techniques to measure evaporation were compared at Owens Lake in eastern California. The eddy correlation method was found to be generally most suited for routine evaluation of the low fluxes observed. Microlysimeter estimates correlated well with eddy correlation estimates, although some difficulties were encountered with the microlysimeters during conditions of eolian transport and erosion.

Both the Bowen ratio technique and pan lysimeters were found to be insensitive to the low evaporative fluxes from the groundwater. Chloride profiling methods, developed by Ullman (1985) and Allison and Barnes (1985), were found to under-predict actual evaporation when compared with both eddy correlation and microlysimeters. The source of this discrepancy is probably due to additional osmotic and thermal fluxes in the upper 0.5–1.0 m of the soil profile, which produce a more diffuse profile than would be predicted from simple molecular diffusion alone. Although the method is simple, it is likely to provide a minimum estimate of groundwater evaporation, with actual rates being two to four times the estimated rate.

Yearly mean evaporation rates from the Owens Lake playa ranged from 88 to 104 mm year^{-1}, in general agreement with other water balance studies on playa surfaces. Brine-covered areas showed much higher yearly mean evaporation rate (872 mm year^{-1}); however, the evaporation rate was strongly controlled by the presence or absence of a floating salt crust, which can form under strong evaporating conditions.

The volume of water lost to evaporation (excluding precipitation) was estimated to be $46.6 \times 10^6 \pm 12.8$ m^3 year^{-1}, with approximately 50% of this loss from the open-water surfaces on the western margin of the lake. Evaporation from the dust-producing playa area of the lake was approximately 25×10^6 m^3 year^{-1}. Combining this evaporation rate with an assumed chemistry of the underlying groundwater suggests that 7.5×10^8 kg year^{-1} of soluble salts are deposited at or near the soil surface of the playa. As no permanent evaporite deposits are forming in these areas today, this flux of salts appears to be removed during high wind periods and maintains Owens Lake's distinction of being one of the major sources of dust in North America.

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