Floating brine crusts, reduction of evaporation and possible replacement of fresh water to control dust from Owens Lake bed, California

D.P. Groeneveld [a,*], J.L. Huntington [b], D.D. Barz [a]

[a] HydroBio, Advanced Remote Sensing, Santa Fe, NM, United States
[b] Desert Research Institute, Reno, NV, United States

ARTICLE INFO

SUMMARY

Owens Lake, California, a saline terminal lake desiccated after diversion of its water source, was formerly the single largest anthropogenic source of fugitive dust in North America. Over 100 billion $m^{-3}\,yr^{-1}$ of fresh water are projected to be used for mandated dust control in over 100 km^2 of constructed basins required to be wetted to curtail emissions. An extensive evaporite deposit is located at the lake's topographic low and adjacent to the dust control basins. Because this deposit is non-dust-emissive, it was investigated as a potential replacement for the fresh water used in dust control. The deposit consists of precipitated layers of sodium carbonate and sulfate bathed by, and covered with brine dominated by sodium chloride perennially covered with floating salt crust. Evaporation (E) rates through this crust were measured using a static chamber during the period of highest evaporative demand, late June and early July, 2009. Annualized total E from these measurements was significantly below average annual precipitation, thus ensuring that such salt deposits naturally remain wet throughout the year, despite the arid climate. Because it remains wetted, the evaporite deposit may therefore have the potential to replace fresh water to achieve dust control at near zero water use.

© 2010 Published by Elsevier B.V.

1. Introduction

Owens Lake in Eastern California was formerly identified as the largest source of fugitive dust in North America caused by diversion of its water source to the City of Los Angeles (GBUAPCD, undated) (Fig. 1). During the past decade, a mammoth effort has been made to control this dust with the construction of wetting basins, an effort projected to cover about 103 km^2 and consume over 115 billion m^3 of water annually due to evaporation (LADWP, 2009) (Fig. 2). Reduction of the evaporative losses, while still controlling fugitive dust, is crucial because the water diverted for this usage, though important for dust control, further shorts other beneficial water use within the perennially water-short state of California. Little contribution for wetting occurs from direct precipitation since Owens Lake receives only about 85 mm yr^{-1} in an average annual temperature of about 15.5 °C (7 year average, north and south Owens Lake; CIMIS, undated).

Owens Lake is the terminus of the Owens River, and like other such terminal lakes accumulated large quantities of salt (Gale, 1915). Interception of its source of water caused it to desiccate by the late 1920s (Kahrl, 1982), stranding 70 million m^3 of evaporite deposit at its lowest topographic level (Alderman, 1983).

During intensive observations of the Owens's Lake bed over the past two decades, this evaporite deposit has not been observed to be a source of fugitive dust. Because of resistance to wind erosion, the water balance and evaporation (E) from this deposit became a focus to determine its potential to replace the huge volume of fresh water evaporated annually for dust control on adjacent portions of the lake bed.

Saline playas such as the Owens have been well studied in the literature often including quantification of evaporation (E). Many playas are subject to salt accumulation that reduces evaporation to extremely low levels, especially through the formation of crusts (Chen, 1992). For example Kampf et al. (2005) measured extremely low E rates (0–1.1 mm d^{-1}) from playa salt flats in Chile. Lee (1927) performed an experiment comparing evaporation of distilled water and Owens Lake brine of different densities, and found high sensitivity in the reduction of brine evaporation as the brine density increased. Tyler et al. (1997) calculated an average rate of groundwater discharge for the saline lake bed of Owens Dry Lake of about 100 mm yr^{-1}, approximately equal to precipitation. Similarly, Albertson et al. (1995) measured the energy balance over the Owens Lake bed and concluded that virtually all of the available net radiation was partitioned into sensible heat flux, indicating extremely low E.

Following complementary theory (Bouchet, 1963; Morton, 1978) low E results in high evaporative driving forces, i.e. inflated

* Corresponding author. Tel.: +1 505 992 0234; fax: +1 505 992 0274.
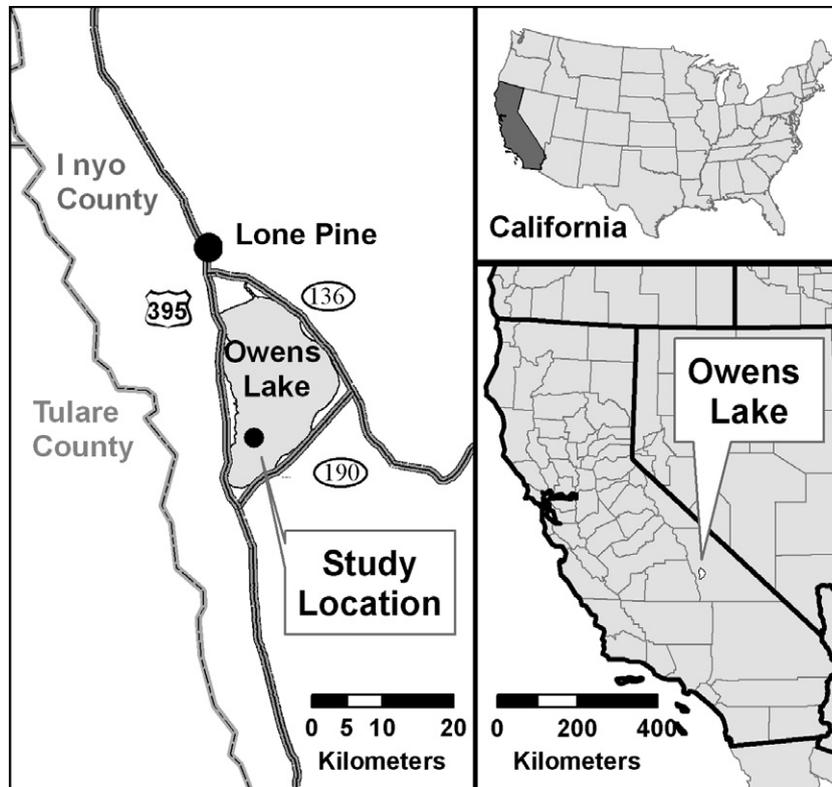E-mail address: David@HydroBioARS.com (D.P. Groeneveld).

Fig. 1. Owens Lake study location map.

air temperatures and vapor pressure deficits. The estimated mean annual open water E rate calculated as 1.05 of ET_0 according to Allen et al. (1998) is about 1800 mm yr^{-1} calculated using local weather data (CIMIS, undated). ET_0 is a standard reference for the atmospheric potential for evaporation that was formulated for a grass canopy of unlimited fetch and water supply (Allen et al., 1998). Though classified as dry, the Owens Lake evaporite deposit is an area of about 50 km^2 that is perennially covered with aqueous brine, both exposed and beneath salt crusts. This deposit occupies about one-fifth of the bed of the former lake (Fig. 2).

Extremely low evaporation rates from brine with floating crusts were first identified by Tyler et al. (1997) using eddy correlation equipment over the evaporite deposit at Owens Lake. They reported a dramatic reduction of evaporation when a thin (<2 mm) floating crust was present. Our observation of the evaporite deposit at Owens Lake is that it forms floating surface salt crusts on the order of millimeter thicknesses covering aqueous brine, that, in turn overlies precipitated salts and saturated soils beneath. During summer periods of high evaporative demand these crusts quickly reform if broken or possibly dissolved by input of fresher water. Seasonal inflow of water or direct precipitation has been observed to reduce the salt concentrations to below saturation causing crusts to dissolve and expose open areas of brine. Unless, such inflow has recently occurred, the Owens Lake brine remains covered by salt crusts. Thicker crusts may occur, especially after prolonged periods of hot and dry weather (e.g., the entire summer) without precipitation or water inflow, eventually forming relatively hard, stable surface deposits. Even so, these salt crusts overlie supernatant brine that, in turn, overlies strata of precipitated salts.

Many researchers have concluded that the formation of salt crusts, decrease in saturation vapor pressure, and increased albedo are primarily responsible for reduced E in playa environments where shallow saline groundwater and brine are present (Harbeck, 1955; Kinsman, 1976; Allison and Barnes, 1985; Malek et al., 1990; Wood and Sanford, 1990). In salt solutions, water molecules are

bound in hydration sheaths around ions, reducing chemical activity and saturation vapor pressure (Kinsman, 1976). The resultant reduction in the vapor pressure gradient reduces the flux between the surface and the atmosphere. Vapor flux is also limited by diffusive and thickness characteristics of the brine crust (Thorburn et al., 1992). A basic understanding of these processes was judged to be critical for estimating components of the water budget for the Owens Lake evaporite deposit.

The objectives of this paper were to (1) evaluate the magnitude and primary processes responsible for reducing E at Owens Lake when salt crusts are present over brine, (2) develop hypotheses to guide further testing, (3) apply the measurements to calculate an approximate annual one-dimensional E from the evaporite deposit, and (4) compare this rate with the estimated E rate for fresh water to determine how much of the 115 billion m^3 yr^{-1} could be saved by substitution.

2. Study sites

Two study sites were chosen at a single location on the Owens Lake bed where past mining removed subsurface layers of sodium carbonate and left depressions that have filled with groundwater, subsequently concentrated to saturation by evaporation. This location is adjacent to, but not connected with, the main brine pool within the evaporite deposit and was chosen because it offered vehicle accessibility (Figs. 1 and 2).

Two sites were chosen for measurement because they represented two relative ages of floating crust. Site B crusts were evidently younger than Site A and appeared to be newly formed. Site B was located at the mouth of a ditch providing active inflow of groundwater to an open pond. Site A was located about 70 m from Site B and within the open brine pond that was continuously crusted (Fig. 3). During the morning field visit on July 1, 2009, leads of open brine had formed within 10 m of Site B suggesting that the crusts were dissolving, possibly due to groundwater inflow.
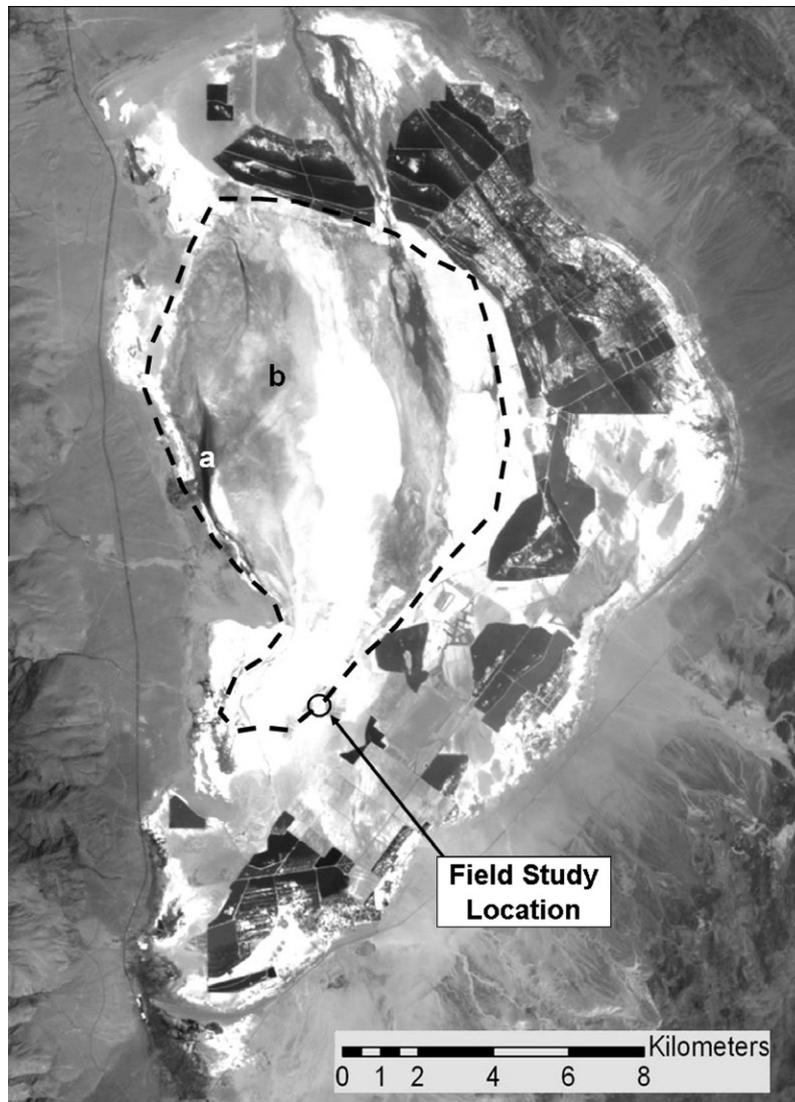
Fig. 2. May 2, 2009 Landsat TM 5 view of Owens Lake. The dotted line indicates the approximate extent of the evaporite deposit with "a" indicating groundwater inflow and "b" showing a thin crust atop supernatant brine. The dark polygons are basins flooded to control dust.

Fig. 3. Images from brine sampling at Site 2. Counter clockwise, starting from upper left is Site A with fiberglass ring emplaced into the floating brine crust that has healed completely after one hour, the chamber is shown atop the fiberglass ring during a measurement of Site B, and a fiberglass ring is in situ in Site A on the edge of a large salt encrusted pond.

The Owens Lake evaporite deposit is dominated by Na with the anions, listed in order of increasing concentration, Cl, SO_4, and CO_3. The SO_4 and CO_3 are locked into precipitates that are bathed in, and capped by brine dominated by Na (Alderman, 1983). Like the evaporite deposit, the deposits at the study location consisted of precipitated Na_2CO_3 and Na_2SO_4 species of variable thickness with a supernatant layer of brine dominated by NaCl. It is atop this supernatant brine that thin salt crusts form that are the subject of this paper.

3. Methods and materials

A portable chamber technique was chosen as the means to measure E. Such chambers were originally developed for agricultural research (Musgrave and Moss, 1961; Reicosky and Peters, 1977; Puckridge, 1978; Pickering et al., 1993). Static chambers, which are closed to the atmosphere, allow a rate of surface flux gas or vapour to be calculated by measuring the rate of change in humidity over short time periods. The use of static chambers for measuring evapotranspiration (ET) in arid shrublands has gained popularity (Garcia et al., 2008; Stannard and Weltz, 2006; Arnone and Obrist, 2003; Obrist et al., 2003) due to relatively low cost and the ability to measure discrete subject surfaces and plants. Additionally, static chambers are especially advantageous where fetch requirements needed for eddy correlation or Bowen ratio techniques are not attainable. Potential alteration during measurements of temperature, vapor pressure, and wind speed inside the chamber was pointed out by Wagner and Reicosky (1992). However, more recent studies suggest these alterations have minor effect when measurements are taken over time intervals of a few minutes or less (Feeney Hall, 1996; Stannard and Weltz, 2006; Garcia et al., 2009). Additionally, the static chamber seems well suited for estimating E from non-vegetated surfaces because temperature and vapour pressure effects on stomatal conductance can be ignored.

The static chamber used was a half-sphere made from 9.5 mm thick Plexiglass similar to the chamber described by Stannard (1988). Total height of the chamber was 0.44 m, with a volume of 0.171 m^3. Two small 12-volt computer processor fans were installed inside the chamber to provide well-mixed conditions for representative measurement of relative humidity (RH) and air temperature T_a. A Campbell Scientific CS215-L RH and temperature sensor was fitted inside the chamber at 0.32 m above ground surface. Fiberglass rings of the same inner diameter as the chamber (86.4 cm) were constructed to embed within the delicate surface crust to support the chamber (Fig. 3). A cross section of each ring is the shape of an inverted "L" with the lip to the outside to support the chamber during measurement. For each measurement, the vertical wall of the ring was pushed through the brine crust and embedded in the precipitated salts below the 5–30 mm thick supernatant brine.

Measurements of RH, T_a, and time in seconds were obtained with a Campbell Scientific CR200 data logger over a two minute period after placement of the chamber atop the ring. RH and T_a measurements were used to calculate the vapor density (ρ_a) that was graphed against time. With the chamber in place over time the vapor density inside the chamber increases as E occurs, the vapour pressure gradient is reduced and the resultant rate of E is reduced. To avoid this effect the E rate was calculated using the maximum slope of the ρ_a time series during the two minute measurement period following methods in Stannard (1988). This maximum slope uniformly occurred at the beginning of the measurement period and was calculated by linear regression using a minimum of 20 points. The rate of E was calculated by Eq. (1) according to Stannard (1988).

$$E = 3.6 \, MVC/A \tag{1}$$

where E is evaporation rate (mm h^{-1}), 3.6 is a conversion factor to yield mm h^{-1}, M is the maximum slope of the vapour density time series, B is the volume of the chamber and ring above the brine (0.192 m^3), C is a unitless calibration factor for the chamber, and A is the area covering the ground surface.

The calibration factor C is usually several percent greater than unity and accounts for adsorption of water on the hydrophilic Plexiglass™, response time of the chamber, sensor errors, incomplete mixing (Stannard, 1988), and also is likely a function of the chamber dimension. C is calculated by comparing the calculated evaporation rate to a known evaporation rate occurring inside the chamber. Previous studies report C to range from 1.037 to 1.136 (Stannard and Weltz, 2006; Garcia et al., 2008). Garcia et al., (2008) found C to equal 1.037 for a larger sized static chamber (0.5 m^3) also made of Plexiglass™. Other researchers have disregarded calibration entirely when using larger chambers (1 m^3) made of Lexan™ (Prater et al., 2006) and significantly larger chambers (16.4 m^3) made of woven semi-transparent polyethylene (Arnone and Obrist, 2003; Obrist et al., 2003). We chose to use a C value of unity because the several percent correction afforded by this factor is negligible given the uncertainty in measurement and calibration.

Measurements began by emplacing the fiberglass rings and allowing the crusts to reseal prior to measurement. Though generally occurring within 15 min during midday, each ring was left in place for at least one hour prior to measurement. Measurements at each site were midday on June 18, 2009, midday and evening on June 30, 2009, and at dawn on July 1, 2009. All measurements with the chamber were conducted under clear skies.

A brine sample was obtained for analysis from Site A on June 18. Sites A and B had crusts that were formed over supernatant brine. The June 18 measurement was made at Site B over brine with the crust physically removed.

Before emplacing the chamber, the surface temperature of the crust or brine surface was obtained using a calibrated hand-held infrared thermometer with the emissivity set to 0.95.

Reference evapotranspiration (ET_0) was computed at each site as a measure of the atmospheric demand for evaporation. The ET_0 was computed using the standardized Penman–Monteith equation for a grass reference surface (Allen et al., 2005) chosen to provide a common denominator for transfer of these results to other sites that may have different site specific net radiation and ground heat flux and atmospheric demand. This concept of a common denominator is the basis for transferability of the ET_0 fraction (commonly referred to as a crop coefficient) to estimate crop ET across the globe (Allen et al., 1998). This ratio provides standardization, since the applying the fraction of ET_0 elsewhere must use the same equation that was used to develop the ET_0 fraction. Therefore, we chose the most commonly used standardized form of the ET_0 equation to compute the reference ET fraction.

Fractions of reference ET_0 (ET_0F) were expressed by dividing the measured static chamber evaporation rate by the time-appropriate hourly ET_0 calculated from data obtained at a nearby total station (CIMIS undated). ET_0 provides a simple estimate for shallow open water evaporation when multiplied by a factor of 1.05 (Allen et al., 1998). Since the intent of this work is to compare measured E through the floating salt crust to open water, the ET_0F values calculated will be relative to 1.05 ET_0. To distinguish this shallow open water reference, these will be designated ET_0' and $ET_0'F$.

Only two sites were measured for this paper because of the extreme fragility of the sub-millimeter thin crust that prevented rapid measurement repetition for each site. Although multiple sites would add statistical variability of crust conductance over space the magnitude of the E measured was extremely small in relation to the E of shallow open water (ET_0') and multiple measurements would not greatly improve the quality of the comparison for deter-

mination of relative E in this dynamic brine/saltcrust system. Our overall objective was simply to compare the calculated magnitude of E for fresh water to the magnitude of the measured E through the salt crusts, an objective that was answerable with only a few carefully conducted measurements.

Repeated replacement of the dome to obtain additional measurements were observed to induce cracking around the edges of the fiberglass ring and floating brine crust that compromised the integrity of the measurements by boosting the apparent E obtained. While the high midday evaporative demand would have allowed resealing within about 15 min, broken crusts during morning and evening measurements were not observed to reform during the approximate 1.5-h period of the field visits, likely due to the low evaporative demand. This was observed and compared during measurement visits when the crust was purposely broken with only finger pressure.

4. Results and discussion

Table 1 reports laboratory analysis results (Rio Tinto, 2009). The brine sampled at Site A was dominated by NaCl but contained components of Na_2SO_4 and Na_2CO_3 with a density of 1.272 g cm^{-3}. Compared to the antecedent aqueous solution, the proportion of NaCl in the floating brine crust was concentrated by a factor of over three. The measured concentration of salt species approximates that reported by Alderman (1983) for the average brine within and atop the evaporite body. The brine in the study location can, therefore, be regarded as representative of the larger evaporite body. Brine densities may be variable depending upon temperature controlled salt solubility (Fig. 4) that greatly affect NaSO$_4$ and NaCO$_3$ but have little effect upon NaCl concentrations (IUPAC-NIST, undated).
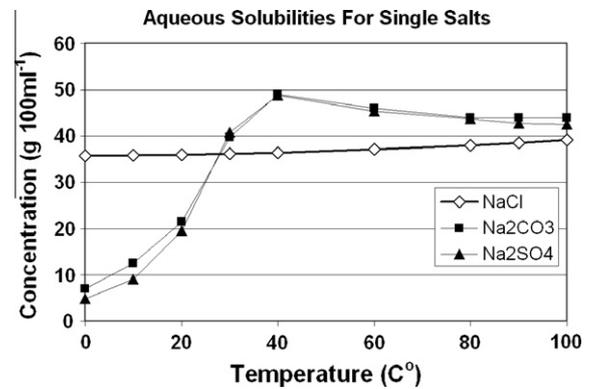
Table 2 reports E measurements and related parameters and shows that E rates from crusted brine were extremely low, about two orders of magnitude below the estimated ET$_0'$ representing open water. E values represent the measurement obtained with the chamber, while the ET$_0'$ represent average hourly values from CIMIS (undated). Midday temperatures of the brine crust at Sites A and B were very high (55.5 and 58.9 °C). Although these temperatures seem excessive they are much lower than the surface temperatures of Owens Lake brine reported by Saint-Amand et al. (1987) to reach about 74 °C.

The midday sample with the crust removed showed a rate that was 1.104 of the calculated ET$_0'$, an extremely high rate due to exposing the brine to atmospheric conditions by removing the floating saltcrust. With the high temperature of the brine (54 °C), a disequilibrium was created by removing the crust that had prevented atmospheric exchange of latent heat flux that would otherwise cool the brine. The high temperature of the exposed brine under this disequilibrium caused an increase in vapor pressure, and hence E (Harbeck, 1955; Myers and Bonython, 1958; Kinsman, 1976). According to data presented in Oroud (1994), a salt solution density of 1.27 g cm^{-3} would yield an ET$_0'$F rate approximately 53% of fresh water. The high measured E rate of the exposed brine was inflated 10% over ET$_0'$ due to non-equilibrium conditions and advective effects from quickly exposing the heated brine to the atmosphere.

Fig. 4. Temperature-dependent single-salt solubility for dominant salt species found in Owens Lake brine.

Crust breakage can naturally occurs in high winds that may expose leads of open brine. This process has been noted to create "salt boats" that float on the open brine and move about during high winds (Lamos, 2009). Precipitated salt crystals tend to float in surface tension as was observed for floating crystal islands on the order of centimeters across, that first reformed before completely filling to form a continuous crust. These floating crystal islands were observed to dimple the brine surface, thus implicating the role of surface tension. Small amounts of dissolved Na_2SO_4 and Na_2CO_3 (Table 1) that are much heavier than NaCl ions may also help to raise the density of the remaining brine to assist in floating the thin salt crusts as water is removed by evaporation in the process of forming the floating crusts.

4.1. Diurnal Differences in E and ET$_0'$F

Despite very low E, a marked diurnal E response is visible for Sites A and B, generally following the ET$_0'$ demand (Fig. 5). This suggests that temporal variation in brine E is driven by the temporal variation in atmospheric conditions, specifically in the vapour pressure gradient. This is illustrated by inspecting variables in a steady state solution of Fick's law for vapour flux (cm day^{-1}) through porous media given by Gardner (1958). For an abrupt transition zone from liquid to vapor for a mulch that protects the surface, represented in this case by a salt crust:

$$E = D_V(\rho_s - \rho_a)/L\rho_w \tag{2}$$

where D_V is the diffusion coefficient for water vapor movement (cm^2 d^{-1}), ρ_s is the saturation vapor density (g cm^{-3}) of the brine fluid, ρ_a is actual vapour density (g cm^{-3}) at the upper surface of the crust, L is the thickness of the crust (cm), and ρ_w is the density of water (g cm^{-3}).

By inspecting Eq. (2), it is evident that the E rate is inversely proportional to the thickness of the crust. Site B had consistently higher E rates than Site A, even though both sites were affected by the same ET$_0'$ throughout the day (Fig. 5). Site B had a noticeably thinner crust (~0.5 mm) than site 2 (~1.0 mm) and the thinner crust at Site B is likely a primary cause for higher E when compared to Site A. To a lesser extent, spatially discrete crust diffusion coefficients may have induced saturation vapour pressure differences

Table 1
Analysis results in weight percent for brine and crust sampled at Site A.

	Na_2CO_3	$NaHCO_3$	NaCl	Na_2SO_4	Na_2O	Insoluble	Total salts	Water
Brine	5.5	0.1	20.3	5.5	3.2	0.0	34.5	65.48
Crust	0.8	2.0	66.2	7.4	1.2	0.1	77.6	22.43

Table 2
Evaporation, ET$'_0$F and surface temperature of brine samples.

| Site	Surface crust condition	Date 2009	Time (PST)	Slope of vapour ρ gm^{-3} s^{-1}	E (mm h^{-1})	ET$'_0$ (ET$_0$·1.05) (mm h^{-1})	ET$'_0$F	Surface T °C
A	~1 mm, translucent	30-June	13:35	0.0027	0.003	0.998	0.003	55.5
A	~1 mm, translucent	30-June	17:55	0.0010	0.001	0.336	0.004	43.9
A	~1 mm, translucent	1-July	5:40	0.0013	0.002	0.063	0.024	24.1
B	~0.5 mm, translucent	30-June	14:11	0.0167	0.020	0.998	0.020	58.9
B	~0.5 mm, translucent	30-June	18:05	0.0074	0.009	0.336	0.026	45.9
B	~0.5 mm, translucent	1-July	5:49	0.0097	0.011	0.063	0.182	26.5
B	Artificially removed	18-June	13:13	0.7072	0.835	0.756	1.104	54.0
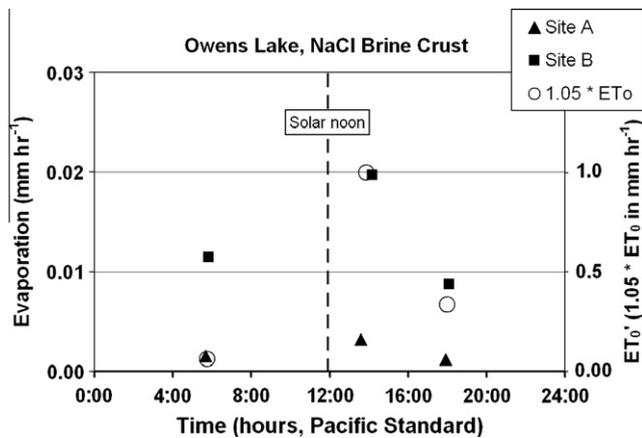
Fig. 5. Evaporation and ET$'_0$ estimates through a diurnal cycle.

to contribute to differences in E between the two sites. This is suggested by the approximate 2× difference in crust thickness, but consistently >5× E rates at site Site B indicate that some factor other than crystal thickness may have influenced the diffusion coefficients for the two crusts such as salt crystal packing. This is a subject that should be explored with a data set designed specifically to answer these questions. Before approaching this problem with additional field study, though, a method to accurately quantify the thickness of the fragile floating crust is needed.

The diurnal differences in E and ET$'_0$F suggest opportunities for future study. An example is E that decreased significantly during the early morning, but not proportionately to ET$'_0$, thus inducing a striking increase in early morning ET$'_0$F (Fig. 5). This may be due to mechanisms that include: (1) thinning of the crust due to lowering concentrations of salts due to groundwater inflow, (2) changes in D_V due to thinner floating crusts resulting from partial dissolution induced by solubility-temperature relationships that affect brine solution concentrations, or (3) condensation from the atmosphere.

The mechanisms affecting ET$'_0$F require considerable additional work to derive which mechanism dominates under what conditions. Groundwater influences can be rejected as a controlling influence in these diurnal comparisons, though, because the relative magnitude of changes in ET$'_0$F from midday to early morning were the same for both sites and Site A was clearly located away from the direct influence of groundwater flow.

Temperature-controlled dissolution of the floating NaCl crust possibly affecting D_V during the early morning measurements is plausible given that the temperature of the brine was 24–26 C (Table 2), a temperature sufficient to greatly reduce the solubility of the NaSO$_4$ and NaCO$_3$ in the brine measured from samples collected during midday (Table 1 and Fig. 4). Small quantities of Na$_2$SO$_4$ and Na$_2$CO$_3$ would precipitate from the brine, thus slightly lowering solution saturation levels and inducing partial dissolution of the floating crust. This aspect can be tested with time-series

sampling of brine chemistry and density paired with additional E measurements.

During non-saturated atmospheric conditions salt crusts can adsorb water vapour from the atmosphere into the crusts, and depending on the topography, wetting by the condensed water can occur even though the relative humidity of ambient air is not unity (Kinsman, 1976; Thorburn et al., 1992). The decrease in saturation vapor pressure of a saline solution is proportional to its activity, β, which is defined as the ratio of the saturation vapour pressure over a saline solution compared to that of freshwater exposed to the same temperature (Oroud, 1999). Asmar and Ergenzinger (1999) developed an empirical relationship between saline water densities and activity coefficients using data reported by Salhotra et al. (1985) and Oroud (1994), where the relationship is reported to be independent of the ionic composition and accounts for negative temperature feedbacks and buoyancy effects. This relationship is

$$\beta = -30.285 + 77.650\rho - 62.712\rho^2 + 16.300\rho^3 \qquad (3)$$

where ρ is the fluid density (g cm^{-3}).

Researchers have suggested that the density of a saline solution is far more significant in determining the activity coefficient than the solution temperature or chemical composition (Turk, 1970; Calder and Neal, 1984; Salhotra et al., 1985). Applying this relationship to the measured density at Site A of 1.27 g cm^{-3} results in an activity coefficient of 0.57 (i.e. lowering the saturation vapour pressure by 43%). The equilibrium water vapour pressure would then be achieved at a relative humidity of 57% leading to condensation over the brine surface. Continuous measurement of RH during 6/30 and 7/1 was not performed at the study sites; however the maximum relative humidity from CIMIS South Owens Lake Station of 55% occurred between 200 and 400, approximately 2 h before the morning measurements of E at sites 2 and 3. Calculation of the activity of brine simply provides a benchmark that shows that borderline conditions existed for condensation of atmospheric water over brine. Because the measurements were obtained over precipitated salts in a crust that contained over twice the amount of salts as the brine (Table 1) the correspondingly lower activity of the salt crust could have fostered condensation that would then be available for evaporation given an increase in evaporative energy with fan mixing during the measurements. This offers another hypothesis for higher morning E than the evening measurements at both sites in a mechanism to be the subject of future study.

4.2. Basal water use for brine replacement of fresh water for dust control

The values of ET$'_0$F obtained for Site A in Table 2 can be used to estimate an approximate annual E for comparison to E of shallow fresh water used for dust control, taken to be ET$'_0$. Although E rates through crusted brine were comparatively low for both sites, Site B was judged to be transitional to the thicker more stable crust at Site A, given that it was located within a zone influenced by groundwater inflow and its crusts were much thinner. Thus, E rates

for Site A are judged to be better representative of annual flux rates expected for salt deposits created to replace fresh water within the wetting basins. Such sites would have the open exposed characteristics apparent for Site A as shown in Fig. 3.

Estimating annual E from a hypothetical evaporite deposit established for dust control was intended for comparison to annual precipitation to answer whether the deposit will remain saturated only with precipitation inputs. Using the $ET_0'F$ values for Site A (Table 2), the $ET_0'F$ for afternoon and evening that averaged 0.0035 can be taken to represent daylight hours, while the value for early morning, not yet influenced by solar radiation or diurnal drop in ET_0', was almost a magnitude higher, 0.024. Multiplying the average of the two, 0.014, chosen to represent a 24-h $ET_0'F$, with the approximate annual average ET_0' of 1800 mm yr^{-1} yields an estimate of 25 mm yr^{-1}. This total is less than one-third of the average annual precipitation (CIMIS, undated).

From this simple annualization of E, it is apparent that were salt from the existing Owens Lake deposit used to replace fresh water for dust control, the resulting deposits would tend to remain saturated, perpetually wetted by water supplied from precipitation. Temperature and precipitation inputs, however, make this a dynamic process with the crust going into and out of solution according to saturation conditions. A conceptual model is: (1) after receiving sufficient direct precipitation the brine would drop below saturation and floating saltcrusts would dissolve; (2) high rates of E would then rapidly remove water; (3) the brine would again become saturated inducing floating crusts to reform, and (4) E would again drop to extremely low rates. Under either exposed or crusted brine the system would remain wetted, thus, preventing release of dust. Due to the high ET_0' of the Owens Lake climate, periods with exposed brine are expected to be relatively short lived and associated only with direct precipitation or surface water inflow and the expected surface condition is brine covered with salt crust.

Maintaining the saturated state of the lake bed surface is a requirement for the shallow flooding dust control measure (GBUAPCD, 2008). Given that the brine crusting retains the salt deposits in a perpetually wet condition, once salt deposits are successfully established for dust control, they would not require further addition of water. Although a supply of fresh water would be required to dissolve and transport the salts from the source deposit into the wetting basins, after this initial supply, complete (100%) water conservation appears possible. Brine losses through infiltration are expected to be negligible over much of the clayey lake bed environment. However, were infiltration losses to occur over time, a minor amount of brine could be added to recharge the NaCl. Fortunately, the existing source deposit has been well quantified and can serve as a model to guide establishment and maintenance of salt deposits within the dust-control wetting basins.

5. Conclusions

Floating salt crusts that cover NaCl-dominated brine are the expected surface condition for the natural evaporite deposit at Owens Lake. These floating crusts reduce evaporation to levels less than precipitation, thus ensuring that the evaporite body remains wetted at all times. Moving salts from an existing evaporite deposit to the dust control basins may, therefore, offer a viable replacement for the fresh water used for dust control on the dry lake bed. Using the adjacent non-dust-emissive natural evaporite deposit as a model, salt deposits created in the dust control basins could be engineered to contain equivalent layers: precipitated salts of $NaSO_4$ and $NaCO_3$, below, capped by a layer of NaCl-dominated brine. Salt crusts would form atop this supernatant brine layer to reduce annual E to less than annual precipitation, thus ensuring that the engineered salt deposits would also remain wet and non-emissive. Once established, the natural properties of salt deposits modeled upon the natural deposit may enable complete dust control with near zero additional fresh water.

References

Albertson, J.D., Parlange, M.B., Katul, G.G., Chu, C., Stricker, H., Tyler, S., 1995. Sensible heat flux from arid regions: a simple flux variance method. Water Resources Research 31, 969–973.

Alderman, S.S., 1983. Geology of the Owens Lake evaporite deposit. In: Sixth International Symposium on Salt, Salt Institute, Alexandria, Virginia, pp. 75–83.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, 300 pp.

Allen, R.G., Walter, I.A., Elliot, R., Howell, T., Itenfisu, D., Jensen, M., (Eds.), 2005. The ASCE Standardized Reference Evapotranspiration Equation. American Society of Civil Engineers Environmental and Water Resource Institute, 59 pp. <http://www.kimberly.uidaho.edu/water/asceewri/>. (accessed 11.02.10).

Allison, G.B., Barnes, C.J., 1985. Estimation of evaporation from the normally "dry" Lake Frome in South Australia. Journal of Hydrology 78, 229–242.

Arnone, J.A., Obrist, D., 2003. A large daylight geodesic dome for quantification of whole-ecosystem CO_2 and water vapour fluxes in arid shrublands. Journal of Arid Environments 55, 629–643.

Asmar, B.N., Ergenzinger, P., 1999. Estimation of evaporation from the Dead Sea. Hydrological Processes 13, 2743–2750.

Bouchet, R.J., 1963. Evapotranspiration feelle et potentielle, signification climatique. Int. Assoc. Sci. Hydrol., Gentbrugge, Belgium, Publ. No. 62, pp. 134–142 (in French).

Calder, I.R., Neal, C., 1984. Evaporation from saline lakes: a combination equation approach. Hydrologic Sciences Journal 29, 89–97.

Chen, X.Y., 1992. Evaporation from a salt-encrusted sediment surface: field and laboratory studies. Australian Journal of Soil Research 30, 429–442.

CIMIS, undated. California Irrigation Management Information System. Station 183, North Owens Lake and 189, South Owens Lake. California Department of Water Resources. <http://wwwcimis.water.ca.gov/cimis/welcome.jsp> (accessed 06.07.09).

Feeney Hall, M.P., 1996. Investigation of Spring and Seep Discharge at Owens Lake, California. University of Nevada, Masters Thesis 3755, 117 p.

Gale, H.S., 1915. Salines in the Owens, Searles and Panamint Basins, southeastern California. US Geological Survey Bulletin 580, 251–323.

Garcia, C.A., Johnson, M.J., Andraski, B.J., Halford, K.J., Mayers, C.J., 2008. Portable Chamber Measurements of Evapotranspiration at the Amargosa Desert Research Site near Beatty, Nye County, Nevada, 2003-06. US Geological Survey Scientific Investigations Report 2008–5135, 10 p. <http://pubs.usgs.gov/sir/2008/5135/index.html> (accessed 11.10.09)

Garcia, C.A., Andraski, B.J., Cooper, C.A., Stonestrom, D.A., Johnson, M.J., Michel, R.L., Wheatcraft, S.W., 2009. Transport of tritium contamination to the atmosphere in an Arid Environment. Vadose Zone Journal 8, 450–461.

Gardner, W.R., 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science 85, 228–232.

GBUAPCD, undated. Great Basin Unified Air Pollution Control District. Website Description of Owens Lake and the Dust Control Program. <http://www.gbuapcd.org/owenslake/index.htm> (accessed 08.07.09).

Harbeck, G. E., 1955. The Effect of Salinity on Evaporation: US Geological Survey Professional Paper 272-A, pp. 1–6.

IUPAC-NIST, undated. International Union of Pure and Applied Chemistry, National Instute of Standards and Technology Solubility Database, Verion 1.0. NIST Standard Reference Database 106. <http://srdata.nist.gov/solubility/index.aspx> (accessed 07.03.10). Data compiled in Wikipedia Solubility Table <http://en.wikipedia.org/wiki/Solubility_table> (accessed 07.03.10).

Kahrl, W.L., 1982. Water and Power. University of California Press, Berkeley, California. 574 pp..

Kampf, S.K., Tyler, S.W., Oriz, C.A., Muñoz, J.F., Adkins, P.A., 2005. Evaporation and land surface energy budget at the Salar de Atacama, Northern Chile. Journal of Hydrology 310, 236–252.

Kinsman, D.J., 1976. Evaporites: relative humidity control of primary mineral facies. Journal of Sediment Petrology 46, 273–279.

LADWP. 2009. Los Angeles Department of Water and Power. Annual Owens Valley Report, May 2009. <http://www.inyowater.org/> (accessed 10.09.09).

Lamos, P., 2009. Personal Communication Regarding Behavior of Crusts Atop Aqueous Brine. Superintendent, Owens Lake Operations, Rio Tinto Minerals.

Lee, C.H., 1927. Discussion of "Evaporation on reclamation projects" by I.E. Houk. Transactions of the American Society of Civil Engineers 90, 340–343.

Malek, E., Bingham, G.E., McGurdy, G.D., 1990. Evapotranspiration from the margin and moist playa of a closed desert valley. Journal of Hydrology 120, 15–34.

Morton, F.I., 1978. Estimating evapotranspiration from potential evaporation: practicality of an iconoclastic approach. Journal of Hydrology 38, 1–32.

Musgrave, R.B., Moss, D.N., 1961. Photosynthesis under field conditions in a portable, closed system for determining the rate of photosynthesis and respiration of corn. Crop Science 1, 37–41.

Myers, D.M., Bonython, C.W., 1958. The theory of recovering salt from sea-water by solar evaporation. Journal of Applied Chemistry 8, 207–219.

Obrist, D., Delucia, E.H., Arnone, J.A., 2003. Consequences of wildfire on ecosystem CO_2 and water vapor fluxes in the Great Basin. Global Change Biology 9, 63–574.

Oroud, I.M., 1994. Evaluation of saturation vapour pressure over hypersaline water bodies at the southern edge of the Dead Sea Jordan. Solar Energy 53, 497–503.

Oroud, I.M., 1999. Temperature and evaporation dynamics of saline solutions. Journal of Hydrology 226, 1–10.

Pickering, N.B., Jones, J.W., Boote, K.J., 1993. Evaluation of the portable chamber technique for measuring canopy gas exchange by crops. Agricultural Forest Meteorology 63, 239–254.

Prater, M.R., Obrist, D., Arnone III, J.A., DeLucia, E.H., 2006. Net carbon exchange and evapotranspiration in postfire and intact sagebrush communities in the Great Basin. Oecologia 146, 595–607.

Puckridge, D.W., 1978. A comparison of evapotranspiration measurements of crop communities using lysimeters and assimilation chambers. Australian Journal of Soil Research 16, 229–236.

Reicosky, D.C., Peters, D.B., 1977. A portable chamber for rapid evapotranspiration measurements on field plots. Agronomy Journal 69, 729–732.

Rio Tinto. 2009. Rio Tinto Minterals. Samples analyzed in cooperation for this project courtesy of Mr. Paul Lamos, Superintendent, Owens Lake Operations.

Saint-Amand, P., Gaines, C., and Saint-Amand, D., 1987. Owens Lake, an ionic soap opera staged on a nitric playa. Centennial field Guide Volume 1. Cordilleran Section of the Geological Society of America, pp. 145–150. <http://www.gsajournals.org/perlserv/?request=get-specialpub-toc&isbn=0-8137-5401-1> (accessed 04.07.09).

Salhotra, A.M., Adams, E.E., Harleman, D.R., 1985. Effects of salinity and ionic composition on evaporation analysis of Dead Sea evaporation pans. Water Resources Research 21, 1336–1344.

Stannard, D.I., 1988. The use of a hemispherical chamber for measurement of evapotranspiration. US Geological Survey Open-File Report 88-452. 18pp.

Stannard, D.I., Weltz, M.A., 2006. Partitioning evapotranspiration in sparsely vegetated rangeland using a portable chamber. Water Resources Research 42, W02413. doi:10.1029/2005WR004251.

Thorburn, P., Glenn, R.W., Woods, P.H., 1992. Comparison of diffuse discharge from shallow water tables in soils and salt flats. Journal of Hydrology 136, 253–274.

Turk, L.J., 1970. Evaporation of brine: a field study on the Bonneville Salt Flats. Water Resources Research 6, 1209–1215.

Tyler, S.W., Kranz, S., Parlange, M.B., Albertson, J., Katul, G.G., Cochran, G.F., Lyles, B.A., Holder, G., 1997. Estimation of groundwater evaporation and salt flux from Owens Lake, California, USA. Journal of Hydrology 200, 110–135.

Wagner, S.W., Reicosky, D.C., 1992. Closed-chamber effects on leaf temperature, canopy photosynthesis, and evapotranspiration. Agronomy Journal 84, 731–738.

Wood, W.W., Sanford, W.E., 1990. Ground-water control of evaporite deposition. Economic Geology 85, 1226–1235.