2012

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Vitaly A. Zlotnik
University of Nebraska-Lincoln, vzlotnik1@unl.edu

John B. Ong
University of Nebraska-Lincoln

John D. Lenters
University of Nebraska-Lincoln, john.lenters@colorado.edu

Jens Schmieder
University of Nebraska–Lincoln, jens.schmieder@gmail.com

Sherilyn C. Fritz
University of Nebraska-Lincoln, sfritz2@unl.edu

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Quantification of salt dust pathways from a groundwater-fed lake: Implications for solute budgets and dust emission rates

Vitaly A. Zlotnik, John B. Ong, John D. Lenters, Jens Schmieder, and Sherilyn C. Fritz

Received 31 May 2011; revised 8 March 2012; accepted 9 March 2012; published 27 April 2012.

Emissions of salt dust from the shores of saline lakes significantly impact lake chemistry, air quality, transportation, human health, and climate. Quantitative methods for assessing these emissions, however, are still in the developmental stage. We investigate salt pathways from groundwater to dust using an approach that takes advantage of opportune conditions at a groundwater-fed, saline lake in the Nebraska Sand Hills region. The mass of salt in the lakeshore surface crust and soil was measured, as well as in the dust on the surrounding dune field. These data, together with information on the lake hydrology, show that dust emission is an important mechanism controlling lake salinity, even though a mere fraction of the salt crust is deflated each year under extant climatic conditions. Wind data collected at the lake site indicate high wind speeds capable of dust mobilization. Therefore, the physical and chemical bonding of salts in the crust is offered as the primary limiting factor for dust emission rates.


1. Introduction

[2] Shallow saline lakes are common in semi-arid and arid dune environments in North America, Africa, Asia, and Australia [Hammer, 1986; Yechieli and Wood, 2002]. Emissions of salt dust from such lakes occur through both natural and anthropogenic processes and have various effects on lake chemistry, air quality, transportation, human health, and climatic processes. Langbein [1961] estimated the mass of incoming solutes from surface runoff for several terminal lakes around the world and observed a deficit of mass over the lifetimes of these lakes. He hypothesized that much of this deficit of mass in the lake waters could be explained by the loss of salt through deflation, but a connection with sedimentological studies was not made in this pioneering study. Only after extensive research on the anthropogenic effects on Owens Lake, one of the largest and most studied dust sources in North America [Saint-Amand et al., 1986; Gill and Gillette, 1991; Cahill et al., 1996; Reheis, 1997; Smith et al., 1997; Tyler et al., 1997; Elmore et al., 2008], did the role of groundwater in salt dust emissions gain significant attention.

[3] In general, salt dust is part of the total dust flux, and the chemistry and solute budget of lake systems are defined by the complex interplay of surface and groundwater fluxes (as well as precipitation and evaporation). The range of wind velocities that mobilize various sizes of particulate matter and deflation rates has also been investigated [e.g., Gillette et al., 1980, 1982; Gill and Gillette, 1991]. These studies used methods such as dust traps [Reheis, 1997; Gillette et al., 2004; Pye and Tsoar, 2009], wind tunnels [Gillette et al., 1980; Houser and Nickling, 2001; King et al., 2011], piezoelectric impact sensors [e.g., Stout, 2004; Barchyn and Hugenholtz, 2010], and anemometer-coupled, wind-triggered video cameras [Reynolds et al., 2007] to measure dust emission. Remote sensing studies have provided insight into dust fluxes from playas on a global scale [Prospero et al., 2002], as well as conditions for dust mobilization [Gill, 1996]. Numerous qualitative observations have also been made in various lakes [Teller and Last, 1990; Rosen, 1994; Gosselin, 1997; Nimick, 1997; Bleed and Ginsburg, 1998]. A number of studies have confirmed Langbein’s [1961] conjecture that wet playas with shallow water tables are potent dust generators [Reynolds et al., 2007].

[4] To study the role of salt dust in total playa dust emission, Tyler et al. [1997] used groundwater solute inseepage estimates in conjunction with the following assumptions: (1) all solutes enter the lake under steady-state conditions, (2) the salt influx is purely advective and can be assessed by seepage velocity and total dissolved solids (TDS) in groundwater, (3) the lake is in equilibrium with the regional climate, and (4) the solute influx is equal to the dust emission rate. This approach was then applied to Owens Lake [Tyler et al., 1997] for assessment of salt fluxes.
Wood and Sanford [1995] studied the potential for salt dust emissions using groundwater chloride as a conservative tracer at Double Lake, a dry playa in Texas. They estimated annual chloride inseepage and compared these measurements with deflated and deposited downwind chloride mass. Assuming steady chloride mass in storage, they attributed the imbalance to infiltration of deposited salt dust back to the playa. Issues of playa equilibrium with the climate or potential imbalances that can be attributed to changes in salt storage were not considered.

Although deflation may not remove all of the salt that originates from groundwater seepage, salt dust removal represents a substantial fraction and useful indicator of total dust emission. Thus, it is important to trace salt from the solute phase to the solid phase (i.e., in the crust), which then becomes a pathway for salt dust emission from the lakeshore. Hydrologic factors, therefore, provide important constraints on the overall process of salt dust emission from saline lakes.

The objective of this paper is to investigate the role of eolian salt transport in the solute budget of a groundwater-fed saline lake in the Nebraska Sand Hills (Figures 1a and 1b). We assess the potential for eolian salt transport by identifying salt-producing areas along the shoreline of Alkali Lake (Figure 1c), measuring the salt crust mass and salt dust distribution on the surrounding dunes, and analyzing the frequency distribution of local wind speeds. In addition, we compare these observations of annually emergent salt crust mass to the magnitude of solute inseepage to the lake to estimate the relative contribution of eolian salt transport to the long-term annual lake solute budget.

The Nebraska Sand Hills

The Nebraska Sand Hills (Figure 1) are the largest dune field in the Western Hemisphere, occupying an area of more than 50,000 km² atop the massive Ogallala Aquifer [Ahlbrandt et al., 1980; Loope et al., 1995]. Nearly 75% of the present-day precipitation (430–580 mm/a) takes place from April to September; 50% falls during May to July [Wilhite and Hubbard, 1998]. The grass-stabilized dunes, which attain heights of up to 130 m, emerged during extended mega-droughts when the groundwater table was deep [Loope et al., 1995; Miao et al., 2007]. Sustained eolian activity and dune movement occurred between about 9500 to 6500 years before present (YBP) and during the late Pleistocene. Evidence of significant droughts and eolian activity (obtained from sediment dating through optically stimulated luminescence) also exists for the periods 700–1000 YBP and 2300–4500 YBP [Miao et al., 2007; Mason et al., 2011]. This evidence is generally consistent with diatom-based analyses of lake levels [Schmieder et al., 2011]. Subsequent pluvial conditions led to an increase in groundwater recharge and a rise in the water table level, resulting in the steady seepage of groundwater into topographic depressions and the formation of hundreds to thousands of shallow lakes.

Regional groundwater in the High Plains aquifer flows eastward and creates numerous lakes in topographic depressions (Figure 1b). Although these lakes occasionally desiccate, they generally contain water more than 75% of the time, in contrast to playas in the southern High Plains that are wet in the rainy season only [Wood, 2002]. Estimated annual lake evaporation exceeds precipitation by 600 mm [Winter, 1986, 1990], indicating a significant net influx of water from groundwater. The salinity of natural lakes in the Nebraska Sand Hills ranges from freshwater (0.3 g L⁻¹) to hypersaline (>100 g L⁻¹), with pH ≈ 10 (Figure 1c). The underlying groundwater in the High Plains aquifer is fresh [Gosselin et al., 1994; Zlotnik et al., 2007], but geochemical modeling has shown that evaporation of groundwater in this region can produce lake solute compositions and pH values that are consistent with modern field observations [Gosselin et al., 1994]. Anecdotal accounts have noted the existence of salt dust clouds emanating from lakes in the semi-arid Nebraska Sand Hills [Gosselin, 1997; Joeckel and Ang

Figure 1. Map of the study area showing the (a) Nebraska Sand Hills, (b) spatial distribution of lakes, and (c) fresh and saline lakes in west-central Garden County, Nebraska.
Clement, 2005], but a quantitative assessment of the eolian salt transport in this region has not been undertaken.

3. Elements of Lake Hydraulics

[10] According to a commonly accepted classification [Born et al., 1979; Rosen, 1994], lakes that collect groundwater through the lakebed and evaporate to the atmosphere are called discharge lakes. Lakebeds that exhibit both groundwater discharge and recharge zones are referred to as flow-through lakes. Modeling studies indicate that the regime type is defined by the competition between the flushing effect of the regional groundwater flow and the magnitude of lake evaporation, as well as by factors such as precipitation, lake size, and hydrogeologic setting [Townley and Trefry, 2000; Zlotnik et al., 2009].

[11] We define $q = Q_{in} - Q_{out} = E - P$ as the net groundwater contribution to the lake water budget, where $Q_{in}$ is groundwater inseepage, $Q_{out}$ is outseepage, $E$ is evaporation, and $P$ is precipitation (all in units of L T$^{-1}$). In a steady-state, flow-through regime that neglects solute contributions (or loss) from precipitation and eolian transport, lake solute inseepage is simply balanced by the flushing of solutes from the lake via groundwater outflow. The concentration of lake solutes, $C_L$ [M L$^{-2}$], is then controlled by the dimensionless inseepage-to-outseepage ratio:

$$C_L = C_{GW} (Q_{in} / Q_{out}),$$

where $C_{GW}$ is the groundwater solute concentration [e.g., Sanford and Wood, 1991]. In a discharge regime (where $Q_{out} \approx 0$, $Q_{in} \approx q$), evaporating lakes become solute traps, and the solute mass per unit lake area, $M_F$ [M L$^{-2}$], accumulates linearly with time, $T_L$ [Zlotnik et al., 2010b], according to:

$$M_F = C_{GW} \cdot Q_{in} \cdot T_L.$$

The lake solute concentration can then be determined through

$$C_L = M_F / H = C_{GW} \cdot Q_{in} \cdot T_L / H,$$

where $H$ is the mean lake depth, and large fluctuations in lake level are assumed to be negligible.

[12] In addition to gravity-driven groundwater inflow/outflow, free convection in saturated sediments has also been noted to occur in sabkhas [Van Dam et al., 2009], marine environments [Stevens et al., 2009], and wetlands [Bauer et al., 2006]. Zlotnik et al. [2010a], however, showed that free convection processes are not prominent in lakes in the Nebraska Sand Hills. This has also been confirmed by geophysical studies [Ong et al., 2010; Ong and Zlotnik, 2011; Cardenas et al., 2010].

4. Site Characteristics

[13] Alkali Lake, in Garden County, Nebraska (41°49’N, 102°36’W), has TDS values reaching ~120 g L$^{-1}$ (Figure 1c), which generally exceed that of neighboring lakes. Efflorescent salts are often observed along the lake-shore, as are wind-driven dust emissions (Figure 2). The lake surface area is 0.49 km$^2$ and is topographically closed by dunes, which rise approximately 30 m above the lake surface. The mean depth of the lake averages ~0.3 m but often shows pronounced seasonal variability (e.g., from nearly dry in late summer to ~0.4 m or more in spring and early summer). Interannual variability can also be considerable, with maximum observed lake levels of around 0.75 m during spring 2010 and 2011.

[14] The lake shoreline includes a wetland section to the north, a relatively steep 0.5-m bank to the west, a sandy/grassy beach along the southern and eastern shores, and a conduit in the southeastern section that connects to a smaller crescent-shaped pond during high-water stands. The conduit is often covered by a salt crust, giving a snow-like appearance to the area, similar to the salt crust that forms along other portions of the lake during the dry season (Figure 2b). We filmed an episode of salt dust emission and transport along this conduit that occurred in May 2008, and a still image from this video is shown in Figure 2c.

[15] Winter [1986, 1990] estimated $q = E - P = 600$ mm yr$^{-1}$ for lakes in this region. A more accurate determination of the water balance for Alkali Lake is currently under investigation. Application of equation (1) using $C_L = 100$ g L$^{-1}$ and $C_{GW} = 0.2$ g L$^{-1}$ [Zlotnik et al., 2007] yields $Q_{in} / Q_{out} = 500$. This extremely low outflow-to-inflow ratio of 0.2% indicates that water outseepage from Alkali Lake is negligible relative to other components of the water balance. Even this very low estimate for $Q_{out}$, however, is likely to be overestimated considering that equation (1) was derived by neglecting eolian salt losses. In fact, direct seepage analyses by Ong and Zlotnik [2011] and geophysical studies by Ong et al. [2010] and Cardenas et al. [2010] indicate the presence of only upward groundwater fluxes within Alkali Lake, rather than outseepage. This provides strong support for the characterization of Alkali Lake as a discharge lake.

5. Methodology

[16] The methods that were employed in this study include: (1) collection of beach salt crust, sand substrate (directly beneath the salt crust), and upper soil sediment in the dune area during dry weather conditions (when the salt crust emerged); (2) collection and analysis of local wind velocity data; (3) measurement of salt in the lake solute, crust, and dust to assess the importance of eolian processes in the lake salinity dynamics; and (4) comparison with hydrologically derived rates of solute seepage into the lake.

[17] Samples of crust and substrate were collected by pushing a hollow, thin cylinder (with a bottom area of 91.6 cm$^2$) into the crust at four lakeshore locations and along the southeastern conduit of Alkali Lake. The salt crusts had roughly the same thickness in each area of deposition and were easily separated from the damp substrate. At each location, three samples were taken within a 1 m radius to assess the variability of the crust mass. Substrate material was collected immediately below the sampled salt crust by inserting a cylinder to a depth of 3.8 cm. This sample size provided adequate lateral and vertical averaging of salt and soil masses but was also shallow enough to represent the bulk density of the top soil layer.
only [see Wang et al., 2009a]. In addition to the lakeshore sites, samples of dune soils were collected in the vicinity of Alkali Lake to assess the prevalence of salt dust in the surrounding dunes. These samples were collected along eight radial transects (separated by roughly 45°) at distances of 10, 100, 200, 400, and 800 m away from the lake (Figure 3). Each sample was mixed with 1 L of distilled water and sonicated for 20 minutes. Similar to Nickling and Ecclestone [1981], the TDS of leached solute was assessed using a regression equation between electrical conductivity (EC; in mS cm⁻¹) and TDS (in g L⁻¹), namely TDS = 0.67 EC. This relationship was established by Zlotnik et al. [2007] for lakes and groundwater in the area. Data on areal salt density (discussed below) are reported for the top 3.8 cm of substrate and/or dune soil (in kg m⁻²) and are shown in Figure 3. Ordinary kriging methods using Surfer® software were employed for interpolation and integration of areal salt dust mass. Data on water table elevation were collected from an array of 39 piezometers, and these measurements were then interpolated around Alkali Lake [Ong, 2010].

Wind velocity data were obtained from a floating weather station that was deployed near the center of Alkali Lake in late June 2007 (and operated through early November 2009). Wind speed and direction were measured using a propeller anemometer (R.M. Young marine model 05106) mounted at a height of ~2.7 m above lake level. Data were recorded at a measurement interval of 10 s and averaged to hourly and daily mean values. Maximum daily wind gusts were also recorded. For the purposes of this study, we focus on the 1-year period from November 1, 2008 to October 31, 2009, which provides a continuous series of hourly wind data over a complete annual cycle.

Finally, the mass of salt in the waters of Alkali Lake was estimated (from lake solute concentration, surface area, and mean depth), and the mass of annual solute inseepage was assessed using methods similar to Wood and Sanford [1995], Tyler et al. [1997], and Zlotnik et al. [2010a]. This annual solute influx was then compared with the observed mass in the salt crust to assess the potential role of salt crust deflation in the lake solute balance.

6. Results

6.1. Salt Distribution and Total Mass

Locations of crust-covered areas near Alkali Lake were consistent over the study period from 2005 to 2009. Salt crusts are typically found to emerge in spring or early summer. A sample Landsat-5 TM image (Figure 2a) shows extensive deposits of salt crusts as highly reflective pixels around the lakes, and this image is used as a base map for illustrating the locations of crust samples collected in the study area on 21 March 2009. Different mineral crystal forms were observed on the surface. Massive, grainy, encrusting, and coral-like salt forms were the most common (Figure 2d), but ephemeral elongated, prismatic flakes (Figure 2e) were also occasionally found along the lake margins. Based on the crystal habits, these two forms were
identified as thenardite and mirabilite, respectively. Typically, the salt crust had a thickness of \( \frac{1}{2} \) mm. Table 1 shows the areal salt mass density of crust and substrate, calculated as the mass of salt per unit area of cylindrical sample. The coefficient of variation for each cluster of samples is relatively small.

[21] The sand substrate along the lake margins exhibits high equivalent pore solute concentrations in various areas (Table 1), which were computed from the total salt mass in the top 3.8-cm layer, assuming water-saturated soil with a porosity of 0.30 ± 0.05, which is common for lacustrine sand (i.e., less sorted than dune sand). These concentrations were observed to result in precipitation of salt crusts when the lake shoreline receded and evening air temperatures dropped below \( \frac{1}{2} \) °C.

[22] Areal salt dust density at 40 locations and water table elevations along the radial transects around Alkali Lake are shown in Figure 3. Highest areal salt dust densities were typically found in the vicinity of the lake (up to \( \frac{1}{2} \) kg m\(^{-2}\)) and in topographic lows where the water table is 1–2 m below the ground surface. A “background” areal salt dust density of 0.012 ± 0.08 kg m\(^{-2}\) (Table 2) was determined from the mean value of the areal salt dust density measurements at the far ends of the radial dune transects (excluding transect GG, which ends in a wetland). In addition, a spatial map of the salt dust distribution in the dune soil (Figure 4) was constructed by interpolating all point measurements of salt mass (using Surfer® software). From this map, an overall areal-mean salt density of 0.028 kg m\(^{-2}\) was determined (i.e., a factor of \( \frac{1}{2} \) larger

Table 1. Summary of Salt Mass Samples Collected in the Crust and Substrate at Various Locations Near Alkali Lake

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Number of Samples</th>
<th>Salt in Crust</th>
<th>Salt in Substrate*</th>
<th>Equivalent Solute Concentration (g L(^{-1}))</th>
<th>Area of Crust (m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (main Alkali Lake)</td>
<td>3</td>
<td>1.3 ± 0.2</td>
<td>0.16</td>
<td>1.9 ± 0.4</td>
<td>3.3 · 10(^3)</td>
</tr>
<tr>
<td>L1 (southeast end of Alkali Lake)</td>
<td>6</td>
<td>0.93 ± 0.3</td>
<td>0.29</td>
<td>1.0 ± 0.5</td>
<td>7.1 · 10(^3)</td>
</tr>
<tr>
<td>C (southeast conduit of Alkali Lake)</td>
<td>3</td>
<td>2.4 ± 0.5</td>
<td>0.22</td>
<td>1.9 ± 0.9</td>
<td>2.7 · 10(^3)</td>
</tr>
<tr>
<td>W (Wilson lake)</td>
<td>6</td>
<td>0.30 ± 0.04</td>
<td>0.14</td>
<td>0.9 ± 0.24</td>
<td>4.9 · 10(^4)</td>
</tr>
<tr>
<td>L2 (southern unnamed lake)</td>
<td>9</td>
<td>0.96 ± 0.6</td>
<td>0.63</td>
<td>1.5 ± 0.7</td>
<td>2.8 · 10(^4)</td>
</tr>
</tbody>
</table>

*Salt mass in the substrate was measured to a depth of 3.8 cm. Equivalent solute concentration assumes a porosity of 30 ± 5%.

\( ^b \)Coefficient of variation.
than the background value; Table 2). A previous study of
dune sand properties in the Nebraska Sand Hills [Wang et al., 2009a] indicates that the bulk density of the top
5 cm of soil is in the range of 1.50 ± 0.01 g cm⁻³. Together with a density of 2.65 g cm⁻³ for dune sand,
yields a total porosity of 0.43, which is consistent with other values found in the literature [e.g., Pye and Tsoar, 2009]. This value for porosity was used to deter-
mine equivalent solute concentrations for water-saturated sand in the top 3.8-cm dune soil layer, yielding 1.7 g L⁻¹ and
0.7 g L⁻¹ for areal-averaged and background levels of salt
dust, respectively (Table 2). These values vastly exceed the typical local groundwater concentration of 0.2 g L⁻¹ [Zlotnik et al., 2007].

[23] The total salt masses measured in the crust, substrate, and surrounding dune soils are summarized in Table 2. A lake solute mass of 1.3⋅10⁵ kg was determined from the observed lake area (4.9⋅10⁵ m²), water depth (0.5 m), and TDS (52 g L⁻¹), which were all measured on the same date as the soil survey (21 March 2009). Salt crusts on the beach of Alkali Lake occupied an area of 3.3⋅10⁵ m², and the total salt mass contained in the crusts was estimated at 4.4⋅10⁵ kg. This value is likely to be underestimated, because it neglects efflorescent salt that was present on vegetation in the adjoining wetland. The substrate for the same area contained 6.3⋅10⁵ kg of salt in the top 3.8 cm.

### 6.2. Wind Velocity and Climatic Conditions

[24] Figure 5a shows a histogram and cumulative fre-
nce of hourly mean wind speeds collected at the lake-
based weather station for the period November 1, 2008 to
October 31, 2009. A wind rose diagram of the predominant
wind directions during this time (Figure 5b) displays a
bimodal behavior in the wind direction distribution, with a
tendency for prevailing winds to be either from a north-
westernly (NW) or south-southeasterly (SSE) direction. NW
winds are generally found to occur during autumn and
winter and/or immediately following the passage of cold
fronts (during any season). SSE winds, on the other hand,
are more common during the spring and summer, often in
the warm sector of an extratropical cyclone. As is typical
for midlatitude regions, the seasonal variability and
monthly range in wind speed at Alkali Lake (Figure 5c)
show spring and autumn to be the windiest times of year,
as well as the most variable. July was found to be the
calmest and least variable month, although hourly wind
speeds still occasionally exceeded 8 m s⁻¹. Seasonal pat-
terns of monthly mean rainfall and air temperature at
Alkali Lake (Figure 5d) are also typical for this region,
with summer convection contributing significant precipi-
tation in June and July, but in the presence of very warm
temperatures and high evaporative demand. Precipitation
during the coldest months falls primarily in the form of
snow.

[25] The mean wind speed measured at Alkali Lake was
4.5 m s⁻¹, with a median value of 4.0 m s⁻¹ and maximum
value of 18.8 m s⁻¹ (Figure 5a). Synoptic land- and satellite-
based studies using wind data collected at 10-m height
indicate that the wind velocity associated with dust-raising
events ranges from ~7 to 13 m s⁻¹ [Gillette et al., 1980;
Cahill et al., 1996; Prospero et al., 2002]. This information
is occasionally provided in a histogram format as well [e.g.,
Helgren and Prospero, 1987]. The frequency distribution
for Alkali Lake shows that wind speed measured at a height of
2.7 m exceeds values of 7 m s⁻¹ and 13 m s⁻¹ approxi-
ately 19% and 1% of the time, respectively (Figure 5a),
with the windiest months being the period October to May
(Figure 5c). Wind speed measurements at a height of 10 m
would obviously exceed these values with even greater frequency. Thus, while it is clear that numerous factors influence dust emissions, wind speeds at Alkali Lake are frequently strong and should not, therefore, impose a major constraint on dust emissions at this site.

7. Discussion

7.1. Salt Accumulation Over Centennial Time Scales

Radiocarbon dates, optical age dates, and diatom analysis from 3-m cores collected near the center and western edge of Alkali Lake show lacustrine sediment deposition beginning at around 14,000 YBP [Ong, 2010; Zlotnik et al., 2010a]. The diatom analysis indicates that the lake originally was dominated by a relatively diverse freshwater flora and remained fresh for a period of time, before alkalinity increased under evaporative conditions. Diatoms were obliterated in the upper meter of sediment column, likely due to the high alkalinity, with pH > 9 [Ryves et al., 2001]. Compared to the neighboring freshwater lakes that have sediment deposits up to 15 m thick, the lakebed deposits at Alkali Lake – representing the last 9,300 years – are only 0.85 m thick. This suggests that a substantial amount of sediment was deflated during the Holocene and is indicative of shorter (or fewer) pluvial periods during this time.

Under the present climatic conditions, Alkali Lake is a discharge lake, and water level fluctuations are typically ~0.4 m. The seepage rate, $Q_{in}$, is balanced by evaporation and precipitation according to: $Q_{in} = q = E - P = 0.6$ m yr$^{-1}$. Using a conservative estimate of groundwater concentration ($C_{GW} = 0.2$ g L$^{-1}$), the annual solute delivery into the lake is approximately $0.12$ kg m$^{-2}$ yr$^{-1}$ (from equation (2), using $T_L = 1$ yr). With a lake area of $0.49 \times 10^6$ m$^2$, this leads to a rate of salt mass influx from groundwater of almost $6 \times 10^4$ kg yr$^{-1}$.

Extensive age dating of dune sands in the Sand Hills shows that eolian activity and dune movement dominated the area from ~9500 to 6500 yr BP [Miao et al., 2007]. Significant droughts also mobilized dunes at ~700–1000 yr BP and 2300–4500 yr BP. Thus, Alkali Lake is likely to have gone through at least three phases during which the lakebed was completely dry for extended periods. These dates help to constrain the current “age” of Alkali Lake (i.e., since last drying up) and suggest that the present pluvial episode may be as long as $T_L = 700, 2300, or 6500$ years. We use these ages to assess the potential accumulated salt mass and lake concentration that would occur over time, assuming that the lake remained a discharge lake throughout this period. The results are summarized in Table 3 and show that the estimated concentrations – regardless of lake age – vastly exceed the modern TDS value of ~50–100 g L$^{-1}$ (and even the value of solute saturation at typical ambient temperatures). This indicates that – even in a period as short as the past 700 years – salt influx to Alkali Lake has
exceeded salt accumulation within the lake. Thus, salt loss processes such as eolian transport [Langbein, 1961] cannot be ignored, especially in the latter stages of lake chemistry evolution, when solute concentrations increase. In the next section, we examine this potential for eolian transport in greater detail.

7.2. Annual Dust Cycle

[29] Alkali Lake undergoes an annual cycle of wetting and drying, typical of perennial shallow lakes in the western Sand Hills and in accordance with the regional climate (e.g., Figure 5d). Each summer, the wet lake area decreases, while the water table declines slightly but remains at shallow depths. The fluctuating salt-encrusted margins are important “launch pads” for eolian salt deflation. Our own observations from 2005–2009 show that the annual cycle of deflation has three phases:

[30] 1. During the winter and early spring, lake levels tend to increase due to reduced temperatures and evaporation, as well as increased in-seepage (in association with spring snowmelt and rain; Figure 5d). Windy conditions prevail during this time (Figure 5c) and are conducive for the creation of efflorescent salts along the lake shoreline. On warm days, the minerals dehydrate in the daytime along dry beaches, resulting in an appearance that resembles snow-covered terrain. Mirabilite (Na2SO4·10H2O) can rapidly dehydrate with temperature fluctuations and occasionally changes into a white powder, thenardite (Na2SO4). Over a few cycles, the minerals become “fluffy,” and the salt crust easily separates from the substrate. Strong alternating NW and SSE winds during frontal passages produce spectacular views of wind-blown dust.

[31] 2. Late spring and summer thunderstorms bring precipitation and minor overland flow to the lake. After rain events, a new salt-silt-clay crust is formed, and salts are bonded to the silts and clays. Proceeding into the hot July–September period, the lake shoreline recedes, salt-laden beaches become wider, and the lake is often reduced to small, shallow pools. The desiccation of crust and abrasion by saltating particles occurs. Capillary mechanisms still provide a supply of shallow groundwater to the surface, but total areal evaporation from the lake margins and the smaller water surface is limited, despite generally warm surface temperatures. Wind speeds tend to be lowest, however, during these three months (Figure 5c), and so a smaller volume of salt dust is removed.

[32] 3. During late fall (October to November), wind speeds intensify (Figure 5c) just as the lake level reaches its typical seasonal minimum. Dust emissions become more frequent as the prolonged dry periods and strong variations in temperature mechanically desiccate the hard salt crusts. Saltation of dune sand abrasives and removes loose salt material. A cemented crust with less salt and more clay emerges after the loosely attached salts are removed. Dust production is then curtailed unless this crust becomes broken. During this time of year, fluffy mineral crusts are rare, but more dust may be emitted as a result of abrasion.

[33] Lakes in the western Sand Hills have a broad range of salinity and shoreline characteristics, and so this translates to similar variability in dust and salt emissions. Some beaches are not as pronounced as those of Alkali Lake and, therefore, do not generate as much dust, particularly during the spring. In these cases, only the hard crust can generate dust emissions from the dry playa when water levels recede by late summer and early fall. The chemistry of Sand Hill lakes is dominated by Na, K, and CO3 [Gosselin et al., 1994]. In various ambient conditions, thenardite (Na2SO4) and mirabilite (Na2SO4·10H2O) are the dominant mineral precipitates, while bloedite (Na2Mg[SO4]2·4[H2O]), halite (NaCl), burkeite (Na2CO3·SO3), and calcite (CaCO3) are minor constituents [Joeckel and Ang Clement, 2005]. The limited amount of halite is related to the groundwater geochemical path [Gosselin et al., 1994].

[34] These patterns are apparent in other lakes and playas throughout the world, although their significance and deflation patterns vary. Amongst the most studied playas, Owens (dry) Lake and Mono Lake [Saint-Amand et al., 1986; Cahill et al., 1996; Gill et al., 2002] generate the largest dust storms during the late winter and spring, but sizable dust emissions also occur during the summer and fall. Halite, trona, and mirabilite form at temperatures below ~18°C and above 10°C [Saint-Amand et al., 1986]. Reynolds et al. [2007, p. 1820] measured dust emissions in Mojave Desert playas and found the major contribution to be from efflorescent salts. The deflation style is defined by groundwater conditions beneath the playa (water level and chemistry), soils, average temperatures, and climate patterns (precipitation and diurnal temperature variations) [e.g., Reynolds et al., 2007, Figure 12]. The semi-arid western Sand Hills lakes receive more annual precipitation (~430 mm) than Owens Lake and Mono Lake, which are both located in or near the arid Mojave Desert (~130 mm). Mean temperatures and diurnal fluctuations are comparable, however, differing by just a few °C. All of the lakes mentioned above have high alkalinity (pH~10).

7.3. Role of Salt Crust in the Lake Solute Balance

[35] The total salt mass in the shoreline crust (4.4·10^5 kg) comprises about 3.3% of the lake solute mass (Table 2). If one considers a scenario in which the entire salt crust mass is removed annually through eolian deflation, but balanced by solute replacement from lake water, then the lake would be devoid of salt after ~30 years (i.e., in the absence of solute replenishment from groundwater in-seepage). However, even the previously calculated solute in-seepage rate of 5.9·10^5 kg·yr^-1 would not be able to compensate for such large eolian salt losses. Thus, a hypothesis of complete eolian removal of the salt crust on an annual basis is not plausible. On the other hand, if eolian deflation is simply...
assumed to balance the input of solutes from groundwater inseepage, then only ~13% of the shoreline salt crust mass would need to be deflated from Alkali Lake on an annual basis (i.e., 5.9-10^9 kg·yr^{-1}/4.4-10^9 kg·yr^{-1}). This deflation would generate 59 metric tons of dust per year from a lake with an area of ~0.5 km^2, yielding an emission rate of ~120 t·km^{-2}·yr^{-1}. (This calculation considers crust as the major pathway of salt from the lake).

[36] Fed by groundwater, Alkali Lake accumulated solutes during the last pluvial episode, which was at least 700 years long according to radiometric and optical age dates [Zlotnik et al., 2010a; Mason et al., 2011; Schmieder et al., 2011]. Therefore, the lake solute budget is not in a steady state on centennial time scales, and not all solute inseepage is balanced by loss processes (e.g., salt dust emission), as is sometimes assumed [Wood and Sanford, 1995]. Groundwater-based solute inseepage represents an upper bound on the annual salt dust emission rate, which amounts to roughly 13% of the emerged crust mass. Wind data collected at the lake site indicate high wind speeds capable of dust mobilization.

Therefore, the physical and chemical bonding of salts in the crust is offered as the primary limiting factor for dust emissions. Since the field data in this study were collected during years with typical hydroclimatic conditions, they are likely to be representative for purposes of determining the potential deflation rate for Alkali Lake. During wet years, these rates would be reduced, while drier, windier years would yield higher salt dust emissions.

7.4. Salt Dust on Dunes as Manifestation of Dust Emissions From Lake

[37] Salt accumulates in the dune field surrounding Alkali Lake due to the entrapment of eolian dust, as well as the vertical upward flux of solutes in areas of shallow groundwater (Figure 3). Even the “background” value of equivalent solute concentration along the dune surface is 0.7 g·L^{-1} (Table 2), which is 2–3 times greater than the TDS of ambient groundwater. At depths of 1–2 m, the water table commonly influences the magnitude and direction of vertical fluxes of water and solutes [Wang et al., 2009b]. It is likely that locations closest to the lake experience a superposition of both upward solute flux and salt dust deposition. However, numerous locations at elevations greater than 5 m above the water table showed elevated salt dust mass. Additions of eolian dust derived from nearby Wilson Lake (Figure 3) may be responsible for some of the high salt concentrations along transect C-C', which lies more than 5 m above the water table and has salt concentrations greater than the background value of ~0.012 kg·m^{-2}. However, the TDS value of 11 g·L^{-1} for Wilson Lake is significantly lower than the TDS value of 53 g·L^{-1} for Alkali Lake (measured on March 21, 2009). Similarly, the adjacent crust area near Wilson lake is only 4.9·10^4 m^2, which is much smaller than the crust area surrounding Alkali Lake (Table 1). Therefore, it is safe to assume that the emission of salt dust is also much smaller. In addition, a steep dune slope borders Wilson Lake along transect C-C' (Figure 3), which likely would obstruct dust transport, leaving Alkali Lake as the major source of dust. This is corroborated by the overall decrease in areal salt dust density with radial distance from the shore of Alkali Lake. Higher salinity on topographic highs can only partially be attributed to evaporation from the water table, with the majority being the result of eolian deposition.

[38] An interesting observation on salt distribution can be made using the results of Nickling and Ecclestone [1981], who examined the propensity of dune sand for dust emissions at different areal salt mass densities. Applying highly constraining conditions for dust emissions by depositing some of the most binding salts to the soil (namely NaCl and KCl; through wet spraying and drying, while ignoring abrasion by saltating particles), they found an increase of the critical shear velocity with salt mass per unit soil mass. The critical shear velocity varies in proportion to exp (0.1027·S), where S is salt mass per unit soil mass, in mg·g^{-1}. We calculated S using both the “background” and “average” equivalent solute concentrations of 0.7 g·L^{-1} and 1.7 g·L^{-1} for lake dune soil, respectively (Table 2). For a soil porosity of 0.43 and sand density of 2.65 g·cm^{-3}, the corresponding salt dust mass densities are S = 0.2 mg·g^{-1} (background) and S = 0.5 mg·g^{-1} (average). The above exponential relationship for critical shear velocity indicates a slight effect of salt mass on dust mobility for both the background dune soil (~2% greater shear velocity required) and the average salt concentrations (~5%). Only near the lake margins, where S values are higher by an order of magnitude (S ~5 mg·g^{-1}), does the impact on critical shear velocity become large (i.e., a ~70% increase). Considering that the wind speed data at our site were collected at a height of 2.7 m and there is a sizable fraction of wind speeds greater than 7–13 m·s^{-1}, wind is still not likely to be a limiting constraint on dust emissions from dune surfaces near Alkali Lake. However, the Nickling-Ecclestone model suggests that salt bonding in soil is an important factor to consider for salt dust mobility, particularly as one moves closer to the lakeshore and the surrounding crust areas.

7.5. Implications of Past and Future Climate Change

[39] Our analysis of the salt balance of Alkali Lake, which is based on hydrologic considerations and sediment age dating, has assumed 100% discharge conditions (\(Q_{\text{out}} = 0\)) and a steady-state groundwater inseepage rate, \(Q_{\text{in}}\). However, strong evidence for widespread drought in the Sand Hills at various times during the Holocene [Miao et al., 2007] suggests that significant changes in \(P - E\), groundwater recharge, and \(Q_{\text{in}}\) may have existed in the past. It is also possible that the loss of lake solutes through groundwater outseepage was not always negligible, particularly during wet periods.

[40] Although future projections of climate change have varying degrees of uncertainty, some studies have predicted a decrease in recharge to the Ogallala aquifer of more than 20% [Rosenberg et al., 1999]. In such a scenario, the groundwater table would likely drop, and many of the lakes in the Sand Hills would receive less groundwater inseepage (or none at all). This change could cause many lakes to eventually dry up. Under such conditions, lakes would become playas, and dust emissions would increase, resulting in a negative salt budget. On the other hand, more recent studies are less certain of such large changes [Milly et al., 2008] and instead suggest only mild changes in groundwater recharge and associated salt dust emissions. Nevertheless, despite uncertainties in the magnitude of change, it is important to be cognizant of the impacts of non-stationary
conditions (such as climate change) on the overall lake solute budget.

8. Summary and Conclusions

[41] Groundwater seepage can supply a substantial mass of naturally occurring solutes to lakes on centennial or millennial time scales. In discharge lakes, these solutes are trapped and become highly concentrated. As the lake area cyclically expands and recedes, precipitated salt crusts along the lake shoreline evolve partially into dust, which can then become airborne. This hydrologic mechanism was hypothesized by Langbein [1961], demonstrated by Wood and Sanford [1995], and extensively studied in sedimentology in terms of its surficial manifestations [e.g., Gill, 1996; Reynolds et al., 2007]. However, a methodology for quantifying eolian salt transport from shallow lakes is still in the developmental stages. Our field study of Alkali Lake, a saline, discharge lake in the Nebraska Sand Hills region, illustrates this groundwater / land surface / atmosphere “conveyor” of dust.

[42] Salt dust production in this semi-arid climate, with an annual mean precipitation of ~400 mm, undergoes similar seasonal phases to those found in more arid climates: (1) a winter and early spring phase where precipitated minerals and dehydrated salts cover beaches with snow-like crust and dust; (2) a rainy spring-summer phase where uniform and cohesive crusts are created; and (3) a late summer-fall phase, where receding lakeshores exhibit desiccated salt crust and are deflated through abrasion by saltating dust sand. These salt dust emissions are hypothesized to contribute to the spatial variability of lake salinity in the western Nebraska Sand Hills.

[43] We used hydrologic and sedimentological analysis of annual salt accumulation to constrain potential rates of salt dust emission from Alkali Lake. The evaporative concentration of groundwater in-seepage delivers salt at a rate of ~5.9×10^4 kg yr^-1, or about 59 metric tons of salt annually through a lakebed area of ~0.5 km^2. Radiometric and optical age dating and diatom analysis of a lake sediment core indicate increasing lake salinity, but at multi-centennial to near-millenial timescales. For such lakes, or lakes in approximate steady-state conditions, the rate of solute delivery can be balanced with eolian deflation (assuming no loss of solute to groundwater recharge) to set an upper limit for salt dust emission rates under modern climatic conditions. Based on the solute delivery rate for Alkali Lake, this maximum dust emission rate amounts to ~120 t km^-2 yr^-1.

[44] We assessed the areal density of salt crust masses along the shores of Alkali Lake during a typical year (early spring of 2009). A total mass of 4.4×10^5 kg of efflorescent salt crust was found on the beaches of the lake. Based on the estimates shown above, modern groundwater in-seepage of solutes supplies ~13% of this mass annually. Thus, the availability of salt crust along the beaches of Alkali Lake is not a limiting factor for salt dust emissions. The presence of ubiquitous salt dust in spring, the summer desiccation of salt crusts, and the large local supply of abrasive sand facilitate eolian deflation. A sizable amount of airborne salt dust (1.5×10^5 kg) has been found in the lake vicinity in a thin soil layer (3.8 cm) at distances of up to 800 m from the lake-shore. The occurrence of high wind speeds and the mechanical properties of salt are also important for controlling eolian deflation. Locally measured hourly mean wind speeds for a typical year show significant potential for dust emissions at the site. Therefore, we propose that the physical and chemical bonding of salts with soils is likely to be the primary limiting factor for dust emission rates in this region.

[45] This study represents the first attempt to quantify the significant potential for small, shallow lakes to generate salt dust in the semi-arid climate of the Nebraska Sand Hills. In the future, additional in situ field techniques (such as the use of portable wind tunnels) may improve the measurement of salt dust emission rates and their variability across space and time.

[46] Acknowledgments. This study was funded by National Science Foundation grant EAR-0609982 to Z. Zlotnik, S. Fritz, and J. S. Swinehart, and the Sand Hills Biocomplexity Project (DEB-0322067) at U. Nebraska-Lincoln (UNL). Additional funding for site instrumentation was provided by the UNL Water Resources Research Initiative. The authors thank J. S. Swinehart (UNL) for his contributions to the fieldwork and sediment age dating, M. Koepsel, N. Powers, and M. French (Crescent Lake National Wildlife Refuge, U.S. Fish and Wildlife Service) for assistance with logistics, M. Peters for access to the field site, R. Kettler and L. Galvez (both at UNL) for laboratory support, S. L. Jones (UNL) for field assistance, R. M. Jacobell (UNL), N. D. Smith (UNL) and M. Sweeney (University of South Dakota) for preliminary review, and the Editor, the Associate Editor, reviewers T. Barchyn and M. Reheis, and one anonymous reviewer for insightful and constructive reviews.

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S. C. Fritz, J. B. Ong, J. Schmieder, and V. A. Zlotnik, Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, 214 Bessey Hall, Lincoln, NE 68588-0340, USA. (sfritz2@unl.edu; jbong@huskers.unl.edu; jens.schmieder@gmail.com; vzlotnik1@unl.edu)

J. D. Lenters, School of Natural Resources, University of Nebraska-Lincoln, 723 Hardin Hall, 3310 Holdrege St., Lincoln, NE 68583-0987, USA. (jlenters2@unl.edu)