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Research papers

Evaporation from a shallow, saline lake in the Nebraska Sandhills: Energy balance drivers of seasonal and interannual variability

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ABSTRACT

Despite potential evaporation rates in excess of the local precipitation, dry climates often support saline lakes through groundwater inputs of water and associated solutes. These groundwater-fed lakes are important indicators of environmental change, in part because their shallow water levels and salinity are very sensitive to weather and climatic variability. Some of this sensitivity arises from high rates of open-water evaporation, which is a dominant but poorly quantified process for saline lakes. This study used the Bowen ratio energy budget method to calculate open-water evaporation rates for Alkali Lake, a saline lake in the Nebraska Sandhills region (central United States), where numerous groundwater-fed lakes occupy the landscape. Evaporation rates were measured during the warm season (May – October) over three consecutive years (2007–2009) to gain insights into the climatic and limnological factors driving evaporation, as well as the partitioning of energy balance components at seasonal and interannual time scales. Results show a seasonal peak in evaporation rate in late June of 7.0 mm day^{-1} (on average), with a maximum daily rate of 10.5 mm day^{-1} and a 3-year mean July-September (JAS) rate of 5.1 mm day^{-1}, which greatly exceeds the long-term JAS precipitation rate of 1.3 mm day^{-1}. Seasonal variability in lake evaporation closely follows that of net radiation and lake surface temperature, with sensible heat flux and heat storage variations being relatively small, except in response to short-term, synoptic events. Interannual changes in the surface energy balance were weak, by comparison, although a 6-fold increase in mean lake level over the three years (0.05–0.30 m) led to greater heat storage within the lake, an enhanced JAS lake-air temperature gradient, and greater sensible heat loss. These large variations in water level were also associated with large changes in absolute salinity (from 28 to 118 g kg^{-1}), with periods of high salinity characterized by reductions in mass transfer estimates of evaporation rate by up to 20%, depending on atmospheric conditions and absolute salinity. Energy balance estimates of evaporation, on the other hand, were found to be less sensitive to variations in salinity. These results provide regional insights for lakes in the Nebraska Sandhills region and implications for estimation of the energy and water balance of saline lakes in similar arid and semi-arid landscapes.

1. Introduction

Saline, groundwater-fed lakes are important indicators of environmental change, in part because their size, water level, and salinity are very sensitive to weather and climate (Williams, 2002). In particular, open-water evaporation is typically a dominant component of the water budget for saline lakes, often greatly exceeding the average precipitation rate of the surrounding region (Winter, 1990, Winter et al., 2001). With little or no surface water outlet, saline lakes can also undergo disproportionately large changes in areal extent in response to small changes in precipitation, runoff, or evaporation (Micklin, 1992; Sahagian, 2000; Steenburgh et al., 2000). Langbein (1961) first hypothesized that the long-term balance of the salinity in a saline lake was mediated by its water level, which in turn was mediated by the long-term balance between water input and discharge by evaporation and often involved Aeolian salt dust removal (e.g., Zlotnik et al., 2012). Long-term monitoring of saline lakes is therefore crucial to determine seasonal patterns and to establish the relation among water levels, salinity,

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and evaporation rates. However, these intricate dynamics appear to be specific to each lake (Rimmer et al., 1999; Abbo et al., 2003), further substantiating the value of long-term observations.

Long-term observations in Lake Kinneret, a saline lake in the Jordan River watershed in Israel, have demonstrated that lake level plays an important role in the flux of solutes to the lake, especially at periods of high lake level (Rimmer and Gal, 2003). These researchers report a positive relation for both water and solute discharges with lake level, likely as a result of groundwater dynamics and high leaching of solutes during the rainy season. The influx of solutes is also positively correlated with rainfall on an annual basis (Rimmer and Gal, 2003). Similar observations, however, are rare throughout other saline lakes in the world and are particularly rare in the context of evaporation rates.

In North America, saline lakes play a prominent role in the landscape of the Great Plains region and, specifically, in the Nebraska Sandhills (NSH), the largest vegetated dune field in the western hemisphere and a critical recharge region for the High Plains and Ogallala aquifers (Scanlon et al., 2012). The NSH contain nearly 2000 interdunal lakes across an area of about 58,000 km^2 (Loope et al., 1995). The generally east-sloping landscape of the Sandhills includes a region of minimal slope in the west that contains shallow, endorheic or poorly draining, groundwater-fed lakes, many of which are saline (Bleed and Flowerday, 1998). Open-water evaporation is a dominant component of the energy and water balance of lakes in the NSH, yet most of the relevant research in this region has focused on evapotranspiration from dune areas (Billesbach and Arkebauer, 2012). As such, lake evaporation remains one of the most poorly quantified processes in climate and groundwater models for the NSH and similar regions (Chen and Hu, 2004; Evans et al., 2005; Radell and Rowe, 2008).

Understanding the role of evaporation in the energy, water, and solute balance of saline lakes first requires quantification of the relevant processes. Lake evaporation is commonly estimated using eddy covariance, mass transfer, or energy balance techniques. (For method comparison and review, see Drexler et al., 2004 and Rosenberry et al., 2007.) Among them, eddy covariance is an accurate, but intensive technique that is effective over a wide range of lake sizes, including large, deep lakes whose heat storage term would otherwise be difficult to quantify (Blanken et al., 2000, 2011). The Bowen ratio energy budget (BREB) method, on the other hand, has proven reliable for estimating lake evaporation from small lakes, so long as the heat storage term is properly quantified (Lenters et al., 2005; Winter et al., 2003). In addition, mass transfer techniques are often employed once one of the other two methods has been applied long enough to develop reliable transfer coefficients (Tanny et al., 2008; Liu et al., 2012; McGloin et al., 2014).

A few studies have used the BREB method in the NSH to estimate terrestrial evapotranspiration (ET), which has been shown to be much higher in wet, interdunal areas compared to upland dune areas (Billesbach & Arkebauer, 2012; Healey et al., 2011). These studies highlight the disproportionately higher water losses that occur in wet portions of the otherwise dry Sandhills landscape. These previous studies provide some insight into the regional energy and water balance of the *terrestrial* landscape in the NSH. To the best of our knowledge, however, no direct measurements of *open-water* evaporation have been reported for the NSH region, and limited understanding of such processes can be derived from previous studies of the much drier surrounding landscape.

Our objective here is to quantify and analyze open-water evaporation rates for a typical saline lake in the NSH. Using the BREB technique, we provide new insights into the climatic factors that drive lake evaporation and energy balance partitioning at seasonal and interannual time scales. Given the significant role that the NSH region occupies for one of the most agriculturally productive regions of the world, this information is necessary to constrain the primary drivers of water and solute balances and to accurately estimate evaporation and recharge rates across this region.

2. Methods

2.1. Site description

This study was conducted at Alkali Lake, a saline lake in the western margin of the Sandhills (41.82° N, −102.60° W; Fig. 1). Alkali Lake has a surface area of roughly 50 hectares that varies widely seasonally and annually. Lake area, depth, and volume are strongly controlled by temporal dynamics of the various water budget components. Among them, evaporation and groundwater in-seepage are dominant. According to existing classifications of lakes with substantial groundwater components to the water balance, it is a groundwater discharge lake (Zlotnik et al., 2010), as also clearly shown by geophysical techniques (Ong et al., 2010; Befus et al., 2012). Average water depth at Alkali Lake is 0.2 m, but ranges from 0.1 to 1.2 m. Overland flow entering the lake is limited, given the high permeability of the sandy soils and dunes that surround it. The lake water is dominated by sodium (Na) and potassium (K) anions and has been found in a previous study to have a pH of 10.4 and salinity ranging from 36.9 to 78.9 parts per thousand (McCarraher, 1977). Lake chemistry in the western Sandhills is largely influenced by evaporative concentration of groundwater (Bleed and Flowerday, 1998).

2.2. Instrumentation and monitoring

A buoy constructed from the hull of a Hobie Bravo catamaran sailboat (Hobie Cat Company, Oceanside, CA) was deployed near the center of Alkali Lake in June 2007 and remained on the lake for the duration of this study (2007–2009). Variables measured on the buoy include downward and upward shortwave radiation (pyranometer model CMP21, Kipp & Zonen, Delft, The Netherlands), downward and upward longwave radiation (pyrgeometer model CGR4, Kipp & Zonen, Delft, The Netherlands), air temperature and relative humidity (model HMP45C, Vaisala, Helsinki, Finland), electrical conductivity/salinity (multi-parameter sonde model YSI 600R, Fondriest, Fairborn, OH), two estimates of bulk surface water temperature (from the YSI 600R sonde and a HOBO U22-001, Onset, Bourne, MA), surface water "skin" temperature (model SI-111, Apogee, Logan, UT), barometric pressure (model CS100, Campbell Sci., Logan, UT), wind speed and direction (model 05106, RM Young Company, Traverse City, MI), and rainfall (model TE525MM, Texas Electronics, Dallas, TX).

All meteorological and YSI sonde variables at the buoy were sampled every 10 s using a data logger (model CR1000, Campbell Sci., Logan, UT), while bulk water temperature from the HOBO sensor was sampled every 10 min. Additionally, two pressure transducers (HOBO U20 Titanium Water Level Data Logger, Onset, Bourne, NA) were installed near the eastern and western ends of the lake to measure water level and temperature at 20-min intervals. An additional sonic-ranging water level gage was deployed on the buoy on June 29, 2009 to provide supplementary measurements of lake level (model SR50, Campbell Sci., Logan, UT). Locations of the instrumented buoy and pressure transducers are shown in Fig. 1. Bulk water temperature at the buoy was smoothed to hourly and 3-hourly (centered) running means in order to obtain more robust estimates of the daily change in lake heat content. The IRT-derived surface temperature measurements were used for any calculations that required measurements of the lake "skin" temperature (e.g., saturation vapor pressure and outgoing longwave radiation) and were carefully quality controlled through systematic intercomparison with the four independent sources of bulk