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The suitability of a simplified isotope-balance approach to quantify transient groundwater–lake interactions over a decade with climatic extremes

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SUMMARY

Groundwater inflow to a subtropical seepage lake was estimated using a transient isotope-balance approach for a decade (2001–2011) with wet and dry climatic extremes. Lake water $\delta^{18}O$ ranged from +0.80‰ to +3.48‰, reflecting the 4 m range in stage. The transient $\delta^{18}O$ analysis discerned large differences in semiannual groundwater inflow, and the overall patterns of low and high groundwater inflow were consistent with an independent water budget. Despite simplifying assumptions that the isotopic composition of precipitation (δ_P), groundwater inflow, and atmospheric moisture (δ_A) were constant, groundwater inflow was within the water-budget error for 12 of the 19 semiannual calculation periods. The magnitude of inflow was over or under predicted during periods of climatic extreme. During periods of high net precipitation from tropical cyclones and El Niño conditions, δ_P values were considerably more depleted in ^{18}O than assumed. During an extreme dry period, δ_A values were likely more enriched in ^{18}O than assumed due to the influence of local lake evaporate. Isotope balance results were most sensitive to uncertainties in relative humidity, evaporation, and $\delta^{18}O$ of lake water, which can limit precise quantification of groundwater inflow. Nonetheless, the consistency between isotope-balance and water-budget results indicates that this is a viable approach for lakes in similar settings, allowing the magnitude of groundwater inflow to be estimated over less-than-annual time periods. Because lake-water $\delta^{18}O$ is a good indicator of climatic conditions, these data could be useful in ground-truthing paleoclimatic reconstructions using isotopic data from lake cores in similar settings.

1. Introduction

Groundwater exchange can be an important part of a lake's water budget and can substantially impact a lake's chemical budget even when it is a relatively minor part of the water budget (Kenoyer and Anderson, 1989; Nakayama and Watanabe, 2008; Schwartz and Gallup, 1978; Stauffer, 1991). Indirect methods are required to quantify groundwater exchange (LaBaugh and Rosenberry, 2008). Water-budget methods typically compute net groundwater flow as a water-budget residual, but this approach cannot distinguish groundwater inflow from outflow. Numerical models that simulate groundwater-lake interactions have become increasingly sophisticated, but an accurate model requires detailed head data and hydrogeologic characterization of the lake basin for calibration. Using point measurement devices such as seepage meters and minipiezometers (Lee, 1977; Winter et al., 1988) to quantify groundwater exchange is challenging because of the difficulty in integrating those fluxes spatially and temporally.

Geochemical mass-balance methods provide an independent approach to define groundwater inflow, whereby the concentration of the solute or isotope in a lake can be related to groundwater inflow. This method has the advantage of integrating inflow spatially and temporally, but is complicated because the tracer must be conservative and be substantially different in concentration between the lake and groundwater (Dinçer, 1968; LaBaugh et al., 1997). Land-use activities within a lake basin can influence groundwater-solute concentrations to a degree that may make them difficult to use (Krabbenhoft et al., 1994; Sacks et al., 1998; Stauffer, 1985). The stable isotopes of the water molecule – deuterium (^2H) and oxygen-18 (^{18}O) – have the advantage of being conservative tracers contained in the water molecule itself, rather than a dissolved constituent that can undergo reactions and dispersion. In addition, ^2H and ^{18}O in water are minimally affected by land-use

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processes such as road salting or application of agricultural fertilizers, which can impact solute concentrations.

Isotope-balance approaches (Coplen, 2011) using δ^2H or δ^{18}O measurements of water have been used in numerous hydrologic studies to quantify groundwater inflow to lakes, with varying degrees of success (Dinçer, 1968; Krabbenhoft et al., 1990; LaBaugh et al., 1997; Sacks, 2002; Turner et al., 1984). Similar approaches have been used to investigate other lake processes, such as evaporation and residence time, as well as providing insights into paleoclimatology (Gibson et al., 2002; Gibson and Reid, 2010; Reddy et al., 2006; Steinman et al., 2010). Independent estimates of groundwater inflow to compare to isotope-balance derived estimates are often not rigorous and rely on short-term budgets; they rarely span periods of wet and dry extremes. Most isotope balance studies assume steady-state conditions (Krabbenhoft et al., 1994), which are simpler and more robust than a transient (i.e., nonsteady state) approach; yet a steady-state approach cannot distinguish variable rates of groundwater inflow due to differences in recharge and other physical factors. The majority of applications using a transient formulation of the isotope balance are in high latitudes or elevations, where lakes may not attain steady-state conditions because of short hydraulic residence times and large seasonal variability in meteorological and hydrologic conditions, such as spring snow melt (Gibson, 2002; Gurrieri and Furniss, 2004; Krabbenhoft et al., 1994; Stets et al., 2010; Tyler et al., 2007). Transient studies in other climates are rare (Sacks, 2002). The transient isotope-balance approach has the advantage of quantifying time-varying groundwater inflow, but because the uncertainty associated with the estimates can be large, a check against an independent determination of groundwater inflow is crucial.

In this paper, we present groundwater inflow results from a transient isotope balance for a seepage lake in central Florida that has a detailed water budget. Isotope balances were computed for approximately 6-month periods over the 9.5-year study period (December 2001 to June 2011), which includes a range of climatic extremes from drought to excessive rainfall. Simplifying assumptions are made that the isotopic composition of precipitation, groundwater inflow, and atmospheric moisture are constant for all calculation periods; these estimates are based on results from regional or short-term data from earlier studies. The sensitivity of the approach to these and other terms in the isotope balance equation is explored. Isotope-balance derived estimates of groundwater inflow are compared to groundwater inflow computed from a detailed water budget. Differences between the two methods are used to assess the suitability of these simplifying assumptions and to explore potential causes for deviations, as well as to guide future studies. In addition, results from this study document changes in the isotopic composition of a subtropical lake over a decadal time-scale with varying climatic conditions, which is rare in the literature.

1.1. Background

Lake Starr, a lake selected to be representative of the many seepage lakes in central Florida, has been the focus of long-term research to understand lake evaporation losses and groundwater-lake interactions (Lee, 2000; Swancar and Lee, 2003; Swancar et al., 2000; Virdi et al., 2013), which are often the least well quantified fluxes in a lake-water budget. Annual and monthly lake-water budgets span a 15-year period (August 1996–July 2011). Groundwater inflow and outflow were also quantified for a 10-year period by Virdi et al. (2013) using a three-dimensional variably-saturated flow model of the lake and basin. An earlier study (Sacks, 2002), used a steady-state isotope-balance approach to estimate groundwater inflow to a population of Florida lakes, including Lake Starr, over a consistent time period. Lake Starr continued to be sampled semiannually for δ^2H and δ^{18}O for the next decade after that study, and these additional data made it possible to estimate groundwater inflow using a transient formulation of the isotope-balance approach.

1.1.1. Site description

Lake Starr is one of many seepage lakes in the mantled karst terrain of the Central Lake District of Florida (Fig. 1) (Brooks, 1981; Palmer, 1984; White, 1970). This region is characterized by thousands of lakes, many of which are seepage lakes with no surface water inflows or outflows, where groundwater inflow can be a substantial part of the water budget (Deevey, 1988; Palmer, 1984; Sacks, 2002). Lake Starr is 54 ha in area with mean and maximum depths of 4.9 and 9.8 m, respectively, at stage 31.7 m above NGVD 1929. Lake stage fluctuated about 4 m during the 15-year water-budget study (1996–2011), from 29.4 to 33.5 m above NGVD 1929. Topography varies about 47 m from the lake bottom to the highest hill defining the topographic basin (Fig. 1). Soils in most of the basin are excessively drained permeable sands, which are typical of relict beach ridges (Griffith et al., 1997; Natural Resources Conservation Service, 2008; White, 1970). Single family residences ring the lake perimeter, and upper parts of the basin are planted in commercial citrus groves.

Lakes in this region have a karst origin, where the overburden subsided or collapsed into voids in the underlying limestone. A sandy surficial (water-table) aquifer overlies the intermediate confining unit, which is a semi-confining unit in the study area and is discontinuous beneath the lake (Fig. 2); this unit separates the surficial aquifer from the carbonate-rock Upper Floridan aquifer (Swancar et al., 2000). The deeper aquifer is the source for nearly all domestic and irrigation water supply in the basin, and withdrawals from it increase leakage from the lake (Swancar and Lee, 2003; Virdi et al., 2013). Lake Starr is a "flow-through" lake, with groundwater entering the lake from the surficial aquifer along the north and west margins, and lake water leaking into the surficial aquifer on the southeast margin (Figs. 1 and 2; Swancar et al., 2000; Virdi et al., 2013). Groundwater outflow (i.e., lake leakage) also occurs in the deeper parts of the lake, particularly where lake sediments are thin, driven by a downward head gradient from the lake to the Upper Floridan aquifer (Swancar et al., 2000). High recharge events cause water-table mounding in nearshore areas, resulting in groundwater flow reversals where areas of typical groundwater outflow become areas of inflow. Recharge in these nearshore areas is rapid and efficient and can approach 100% (Swancar and Lee, 2003; Swancar et al., 2000).

The climate in central Florida is humid subtropical. Annual average air and lake-surface temperatures at Lake Starr are 22.1 and 25.1 °C, respectively, and average relative humidity is 80% at 2 m above the lake surface (data from August 1996 to July 2011). Long-term average rainfall at Mountain Lake, which is 1.8 km southwest of Lake Starr, is approximately 130 cm yr^{-1} (August 1921–July 2011; National Climatic Data Center, 2012). Average rainfall measured at Lake Starr for the 15-year period with the detailed water budget (August 1996–July 2011) was 122.8 cm yr^{-1} and ranged from 88 to 191 cm yr^{-1} for individual years. Lake evaporation, which averaged 147.5 cm yr^{-1}, exceeded rainfall in 13 of 15 years. Groundwater inflow exceeded groundwater outflow for 10 of the 15 years, helping to offset the negative net precipitation (precipitation minus evaporation). June to September is the typical wet season, when 60% of the rainfall usually occurs; rain during this season is derived from local convective thunderstorms and occasional tropical storms and hurricanes. During the remainder of the year rainfall usually is less intense and has a continental influence.