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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.

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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.

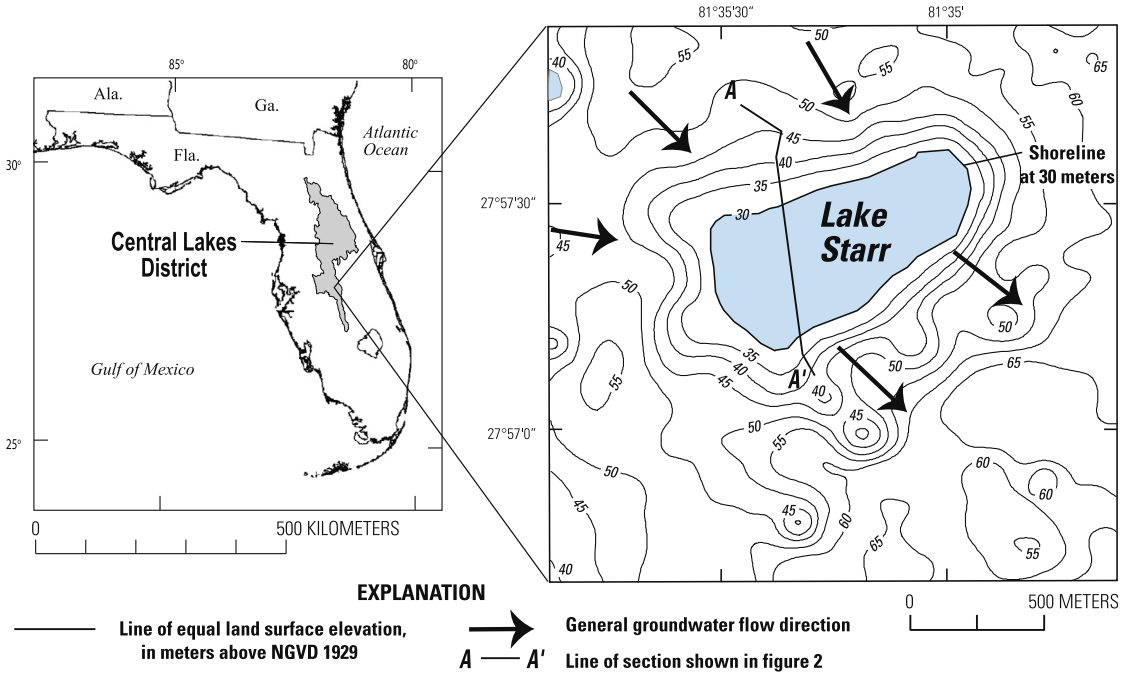

Fig. 1. Location of Lake Starr in Florida's Central Lake District, and detailed map of lake basin with topographic elevations and general groundwater flow directions.

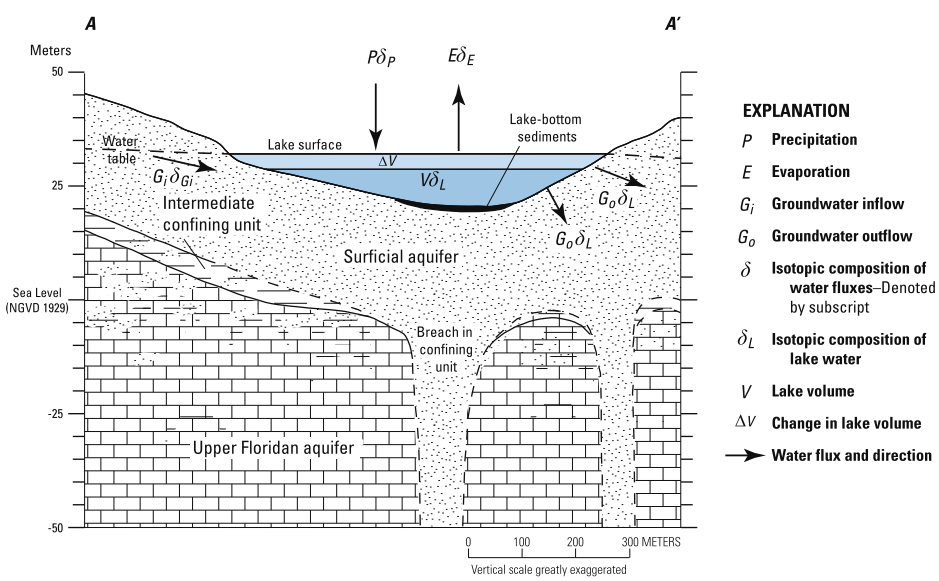

Fig. 2. Hydrogeologic cross section of Lake Starr and components of the lake isotope balance.

Seasonal rainfall patterns are overlain by climatic cycles of varying duration, including the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Multi-decadal Oscillation (AMO), all of which influence periods of high rainfall and drought (Enfield et al., 2001; Hagemeyer, 2007; Kelly and Gore, 2008; Obeysekera et al., 2011). Winter rainfall in central Florida is greater than normal during El Niño conditions (ENSO warm phase) and is less than normal during La Niña conditions (ENSO cool phase) (Hagemeyer, 2007). The study period corresponded to a warm phase of the AMO, but average rainfall measured at the lake was not above normal, as has been observed during other AMO warm phases (Kelly and Gore, 2008).

1.1.2. Water budget

Monthly and annual water budgets for a 15-year period were available for Lake Starr from a companion study (Swancar et al., 2000; Virdi et al., 2013; Supplementary data Tables A and B). For the present study, water budgets were re-computed for time intervals bracketing semiannual lake isotope samples for the period December 2001 to June 2011, and these intervals are referred to as isotope-balance periods. Groundwater inflow from the water budget was used to compare with isotope-balance estimates presented later in this paper, and was determined as the residual to the lake-water budget:

$$G_i = \Delta V - P + E + G_o + Q, \quad (1)$$

where G_i is groundwater inflow, ΔV is the change in lake volume, P is precipitation (rainfall), E is evaporation, G_o is groundwater outflow, and Q is direct withdrawal from the lake for lawn and citrus irrigation. Runoff, which occurs in the nearshore area following high rainfall events, was included with G_i (Virdi et al., 2013). Precipitation, evaporation, and lake stage were directly measured at the lake, and lake withdrawals were estimated from a relation with rainfall (Swancar et al., 2000). Groundwater outflow (G_o) was simulated daily for the period August 1996–July 2006 using a three-dimensional, variably-saturated groundwater flow model (Virdi et al., 2013). For the 60 months that extend beyond the modeled period (August 2006–July 2011), monthly groundwater outflow was estimated based on a regression using a polynomial equation relating monthly net groundwater flow ($G_i - G_o$) to groundwater outflow during the simulation period ($R^2 = 0.68$; standard error = 1.28 cm). All water-budget components are in linear units, and ΔV was normalized to average lake surface area for the time period of interest. Because G_i is a residual term, it incorporates uncertainties or errors in all of the other terms. Estimated errors in water-budget terms follow those presented in Swancar et al. (2000); the error for G_o was assumed to be 30% for the simulated period, and 40% for the regression period.

Seasonal and interannual variability in rainfall is the primary driver of the water budget. Rainfall was almost always greater than groundwater inflow for the semiannual isotope-balance periods, and both had considerable ranges (from less than 30 cm to more than 110 cm; Fig. 3; Table 1). Evaporation and groundwater outflow had less variability, and evaporation was always greater than groundwater outflow. The semiannual isotope balances typically correspond to two seasonal periods: June to December and December to June (Fig. 3; Table 1); the June-to-December periods were warmer and tended to be wetter than the December-to-June periods, as they encompassed most of the typical wet season (June to September). On average, rainfall accounted for 60% of water gains to the lake, and evaporation accounted for 70% of water losses. Groundwater inflow represented an average of 40% of water gains, and groundwater outflow made up 27% of water losses. Direct withdrawals from the lake for irrigation were minor, representing only 3% of losses. Rainfall exceeded evaporation for only 5 of the 19 isotope-balance periods, but groundwater inflow exceeded groundwater outflow for 12 of the 19 periods, illustrating the importance of groundwater inflow in maintaining the lake volume. Change in lake volume, normalized to average surface area, ranged from −81.4 to +123.2 cm, and most periods had a change in volume of more than 20 cm (Fig. 3; Table 1). Mean residence time for water in the lake was 2.2 years calculated using the outflows.

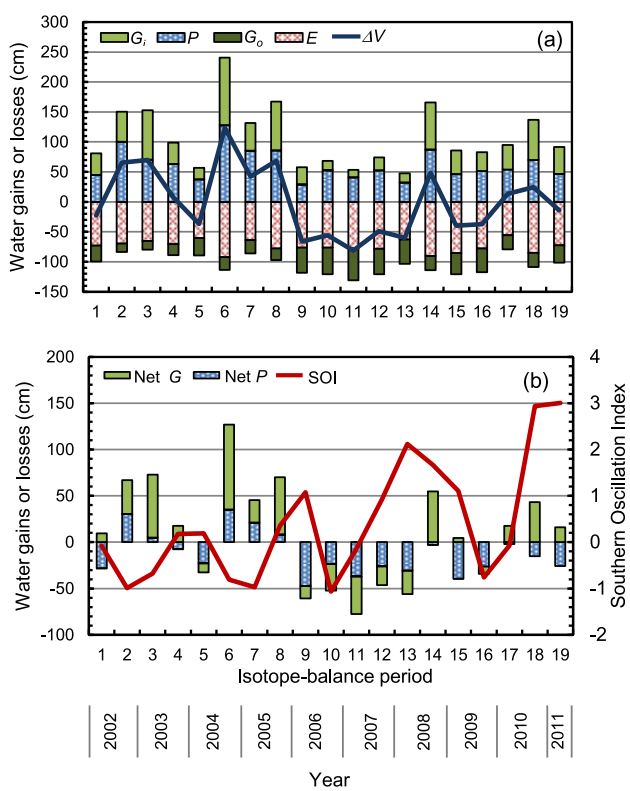

Fig. 3. Water budget of Lake Starr for each isotope-balance period: (a) showing precipitation (P), evaporation (E), groundwater inflow (G_i); groundwater outflow (G_o), and change in volume (ΔV); and (b) showing net precipitation (Net P), net groundwater flow (Net G), and the average Southern Oscillation Index (SOI).

There were two distinct periods of rainfall surplus and deficit over the 9.5 years (Fig. 3b; Table 1), which correspond to differences in ENSO conditions (represented by the El Niño-Southern Oscillation Index, SOI, averaged over the isotope-balance periods; National Oceanic and Atmospheric Administration, 2012). The first 4 years of the study (late 2001 to late 2005) were characterized by above average rainfall (total rainfall surplus of 97.5 cm compared to the long-term average) and negative to very small positive SOI values (average −0.3), indicating neutral to mild El Niño conditions. This period was also characterized by the most active hurricane season of the study (August–September 2004, when three hurricanes passed over the lake; Florida Department of Environmental Protection, 2004; Wang et al., 2005). The latter 5.5 years (late 2005 to mid 2011) were characterized by below average rainfall (rainfall deficit of 127.5 cm), and overall positive SOI (average + 1.0), indicating predominantly La Niña conditions. No statistically significant relations were apparent between water-budget terms and climatic indices averaged over the isotope balance periods, although total dry season rainfall (October–May) at this site was significantly correlated to the SOI.

Extremes in precipitation were recorded at Lake Starr during the 9.5-year period over which semiannual water budgets were defined (December 2001–July 2011) when compared with 90 years of rainfall data (1921–2011; using data from Mountain Lake before 1996 as a surrogate for Lake Starr). Three years were in the lowest 90th percentile for rainfall (2006, 2007, and 2009), and two years were in the top 10th percentile (2004 and 2005). Three months had the lowest rainfall measured for that month (March 2001, May 2008, and October 2010), whereas one month had the highest rainfall measured (December 2002). The highest daily rainfall on record for September, as well as the third highest on record for any month, occurred on September 26, 2004 (19.8 cm) during Hurricane Jeanne.

2. Methods

Samples from Lake Starr were collected semiannually for δ^2H and δ^{18}O analysis (usually in December and June) between December 2001 and June 2011. Samples were collected from about 10 cm below the surface near the center of the lake. Lake Starr is typically well mixed, and earlier isotope sampling indicated that aerial and vertical stratification was minimal (Sacks, 2002). Isotope samples were also collected from the lake at more variable time intervals between April 1996 and July 2000, including monthly samples between January 1999 and July 2000 (Sacks, 2002; Sacks et al., 1998). To avoid bias when these earlier data were used to define averages and trend lines, years with more frequent data were filtered to include only two samples per year. All samples for isotope analysis were unfiltered and collected in glass bottles with polyseal caps.

Table 1
Water budget components, rainfall surplus, and the average Southern Oscillation Index (SOI) for isotope-balance periods for Lake Starr; unless otherwise noted units in cm per period (irregular time intervals); variables defined in Eq. (1).

Isotope- balance period	Begin date (mo/day/yr)	End date (mo/day/yr)	ΔV	P	E	G_i	G_o	Q	Net P[a]	Net G[b]	Rainfall surplus[c]	SOI (dimensionless)
1	12/19/2001	6/24/2002	−22.7	44.7	73.0	36.2	26.7	4.0	−28.3	9.6	−9.0	−0.08
2	6/24/2002	12/16/2002	65.4	100.0	69.7	50.6	14.0	1.5	30.3	36.6	21.9	−0.99
3	12/16/2002	6/23/2003	69.8	70.3	65.5	82.5	14.4	3.1	4.8	68.1	12.0	−0.68
4	6/23/2003	12/23/2003	7.4	62.9	70.4	36.0	18.3	2.7	−7.5	17.6	−8.6	0.18
5	12/23/2003	6/4/2004	−36.8	37.4	60.2	19.2	29.0	4.1	−22.8	−9.8	0.4	0.19
6	6/4/2004	12/28/2004	123.2	127.6	92.5	113.1	21.2	3.4	35.1	91.9	34.9	−0.81
7	12/28/2004	6/23/2005	42.4	85.0	63.9	46.4	22.3	2.8	21.1	24.2	27.7	−0.97
8	6/23/2005	12/28/2005	68.3	85.7	77.6	81.4	19.5	1.7	8.1	61.9	13.8	0.36
9	12/28/2005	6/29/2006	−66.3	29.0	76.4	28.5	42.1	5.4	−47.3	−13.6	−28.3	1.08
10	6/29/2006	12/21/2006	−55.7	52.7	76.2	15.5	44.4	3.3	−23.5	−29.0	−16.2	−1.07
11	12/21/2006	6/28/2007	−81.4	41.0	77.9	12.4	53.2	4.0	−36.9	−40.8	−18.2	−0.14
12	6/28/2007	12/27/2007	−49.1	52.3	78.3	22.1	42.4	2.7	−26.0	−20.4	−21.0	0.92
13	12/27/2007	6/3/2008	−60.0	32.2	63.0	15.2	40.4	4.1	−30.7	−25.2	−9.5	2.12
14	6/3/2008	12/29/2008	48.8	87.3	90.4	78.5	23.6	3.1	−3.1	54.9	−0.4	1.67
15	12/29/2008	7/10/2009	−39.9	46.1	85.6	39.8	35.3	4.8	−39.5	4.5	−18.0	1.11
16	7/10/2009	1/19/2010	−37.4	51.4	77.8	31.7	39.3	3.3	−26.4	−7.6	−16.6	−0.76
17	1/19/2010	6/14/2010	13.6	53.8	55.8	41.2	23.6	2.0	−2.0	17.6	12.2	−0.07
18	6/14/2010	12/22/2010	24.4	69.9	85.0	67.0	23.8	3.7	−15.1	43.2	−15.0	2.94
19	12/22/2010	6/20/2011	−13.9	46.8	72.5	44.7	28.8	4.2	−25.6	16.0	3.3	3.01

[a] Net precipitation: $P - E$.
[b] Net groundwater: $G_i - G_o$.
[c] Amount that precipitation was greater than (+) or less than (−) long-term average precipitation at Mountain Lake NWS site (1921–2011), located 1.8 km southwest of Lake Starr.

Isotope samples were analyzed by the U.S. Geological Survey (USGS) Reston Stable Isotope Laboratory in Reston, Virginia. Hydrogen isotope ratios were determined using a hydrogen equilibration technique (Coplen et al., 1991), and oxygen isotope ratios were determined using a carbon dioxide equilibration technique (Epstein and Mayeda, 1953). Results are reported in δ notation relative to Vienna Standard Mean Ocean Water-Standard Light Antarctic Precipitation (VSMOW-SLAP). The laboratory-reported 95-percent confidence interval for analytical uncertainty is 2 permil (‰) for δ^2H and 0.2‰ for δ^{18}O measurements. Duplicate analyses, however, indicate that accuracy was considerably better than this, and reproducibility was within ±1.2‰ and ±0.07‰ for δ^2H and δ^{18}O, respectively.

The isotope balance equation for Lake Starr is defined as:

$$\Delta(V\delta_L) = P\delta_P - E\delta_E + G_i\delta_{Gi} - G_o\delta_L - Q\delta_L, \quad (2)$$

where δ is the isotopic composition of the lake water (δ_L), precipitation (δ_P), evaporation (δ_E), and ground-water inflow (δ_{Gi}); other terms are as defined for Eq. (1) (Fig. 2). For this study, δ^{18}O is used in the isotope balance to estimate groundwater inflow, rather than δ^2H, because of the better relative analytical accuracy of δ^{18}O. The isotopic composition of Q and G_o are assumed to equal that of the lake, and water-budget terms remain in linear units. Following Krabbenhoft et al. (1990), the water-budget Eq. (1) is rearranged to solve for G_o, which is then substituted into Eq. (2) and rearranged to solve for G_i:

$$G_i = \frac{P\delta_P - E\delta_E - (P - E - \Delta V)\delta_L - \Delta(V\delta_L)}{(\delta_L - \delta_{G_i})}. \quad (3)$$

When calculated this way, both G_o and Q cancel out and, thus, do not need to be estimated. Eq. (3) was solved for 19 semiannual isotope-balance periods corresponding to the time between lake samples. Of the variables in Eq. (3), P, E, ΔV, and δ_L were directly measured at the lake.

The assumption was initially made that the isotopic composition of precipitation (δ_P) and groundwater inflow (δ_{Gi}) were constant throughout the study period. Both were sampled at Lake Starr between 1999 and 2000 as part of an earlier study (Sacks, 2002), but no samples were collected at the lake after that. Data for δ_P were also available from three other sites in west-central Florida for different time periods between 1996 and 2005 (Kish et al., 2010; Metz and Sacks, 2002; Sacks et al., 1998), with the most distant site located 95 km west of the lake. All δ_P samples were composited approximately monthly, and were sealed from the atmosphere between rainfall events. The volume-weighted mean (VWM) δ_P of all samples from these sites and Lake Starr was used as the initial value for the isotope balance. The assumption was also made that δ_{Gi} was equal to δ_P. Earlier sampling of shallow groundwater with an inflow gradient near the lake found that δ_{Gi} was similar to VWM δ_P (Sacks, 2002; Sacks et al., 1998).

The variable δ_E is the most difficult term to estimate for the isotope balance, as it cannot be measured directly. According to theory originally developed by Craig and Gordon (1965), evaporation occurs as both equilibrium and kinetic (nonequilibrium) fractionation processes (Clark and Fritz, 1997; Gonfiantini, 1986; Zimmerman and Ehhalt, 1970). Water vapor is in isotopic equilibrium with the lake water in a very thin boundary layer directly overlying the water surface, where relative humidity is 100%. Above this is a transition zone where molecular diffusion, which is a kinetic fractionation process, transports water vapor from the boundary layer to the well-mixed open air column. Lighter isotopes of water vapor (^{1}H and ^{16}O) are transported faster than heavier isotopes. Using nomenclature from Krabbenhoft et al. (1990), the isotopic composition of evaporating water (δ_E) can be defined as:

$$\delta_E = \frac{\alpha^*\delta_L - h\delta_A - \varepsilon}{(1 - h + 0.001\Delta\varepsilon)}, \quad (4)$$

where δ_A is the isotopic composition of atmospheric moisture (A); α^* is the equilibrium isotope fractionation factor at the temperature of the air–water interface (calculated from the average lake-surface temperature (T_0), and relations presented by Majoube, 1971) for $1/\alpha$; h is relative humidity normalized to average T_0 (vapor pressure of the air divided by the saturation vapor pressure at T_0), expressed as a fraction, calculated daily, and averaged over each balance period; ε is the total isotopic fractionation factor equal to $1 - \alpha^* + \Delta\varepsilon$; and $\Delta\varepsilon$ is the kinetic isotopic fractionation factor estimated as 14.2 $(1 - h)$ for δ^{18}O (Gonfiantini, 1986). Variables α^*, h, ε, and $\Delta\varepsilon$ are

functions of air temperature, T_0, and relative humidity, all of which were measured over the study period at Lake Starr.

The value of δ_A used here (−14.01‰) was from an earlier study of Lake Starr (Sacks, 2002), whereby a steady-state value for δ_A was back-calculated from an independent water-budget estimate of groundwater inflow along with measured values of other hydrologic, climatic, and isotopic variables in Eq. (3). This groundwater inflow value was used in Eq. (3) to calculate δ_E, which was then used in Eq. (4) and rearranged to solve for δ_A. Other estimates of δ_A – from either sampled values or values of δ_A calculated assuming isotopic equilibrium with rainfall – were greater than the back-calculated value and resulted in unrealistic groundwater inflow estimates that were higher than water-budget results (Sacks, 2002).

Several types of sensitivity analyses were performed for the isotope balance. Input parameters to Eqs. (3) and (4) were varied for a low and high groundwater inflow scenario so that relative sensitivities could be compared. In addition, the best-fit values of δ_P and δ_A were determined so that G_i matched water-budget results for cases when isotope-balance groundwater inflow results were outside of the range of the water-budget error. For that analysis, it was assumed that δ_A was in isotopic equilibrium with rainfall, given air temperature and relations from Majoube (1971). Lastly, for periods that had isotope-balance groundwater inflow results that were within the water-budget error, the range was determined over which values of δ_P, δ_{Gi}, and δ_A could independently vary and still remain within the water-budget error.

3. Results

3.1. Isotopic data

The isotopic composition of water from Lake Starr varied inversely with lake stage for the period of record (1996–2011; Figs. 4 and 5; Supplementary data Table C). Values of $\delta^{18}O$ ranged from +0.80 to +3.48‰, with an average value of +2.21‰. Lake water was most enriched in ^{18}O (δ values greater than +2.5‰) when the lake was at its lowest stage (below 30.5 m), and was most depleted in ^{18}O (δ values less than +1‰) when the lake was at its highest stage (above 32.5 m). For isotope-balance periods, lake-water $\delta^{18}O$ values for the end sampling date were significantly correlated with lake stage, rainfall amount, groundwater inflow and outflow, rainfall surplus, and the SOI. Change in $\delta^{18}O$ between balance periods ranged from −1.53‰ to +1.03‰ and also had significant correlations with the rainfall amount, change in lake volume, groundwater inflow and outflow, and rainfall surplus; best relations were with rainfall amount and change in lake volume (R^2 = 0.84 and 0.70, respectively; p < 0.001, Fig. 5). Values of

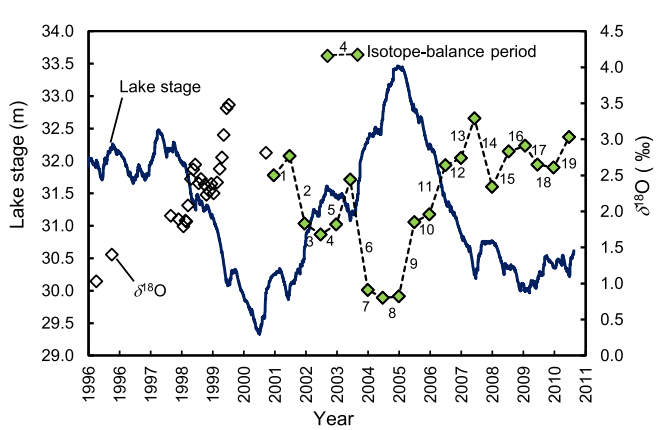

Fig. 4. Lake stage and oxygen-18 composition ($\delta^{18}O$) of water from Lake Starr (1996–2011).

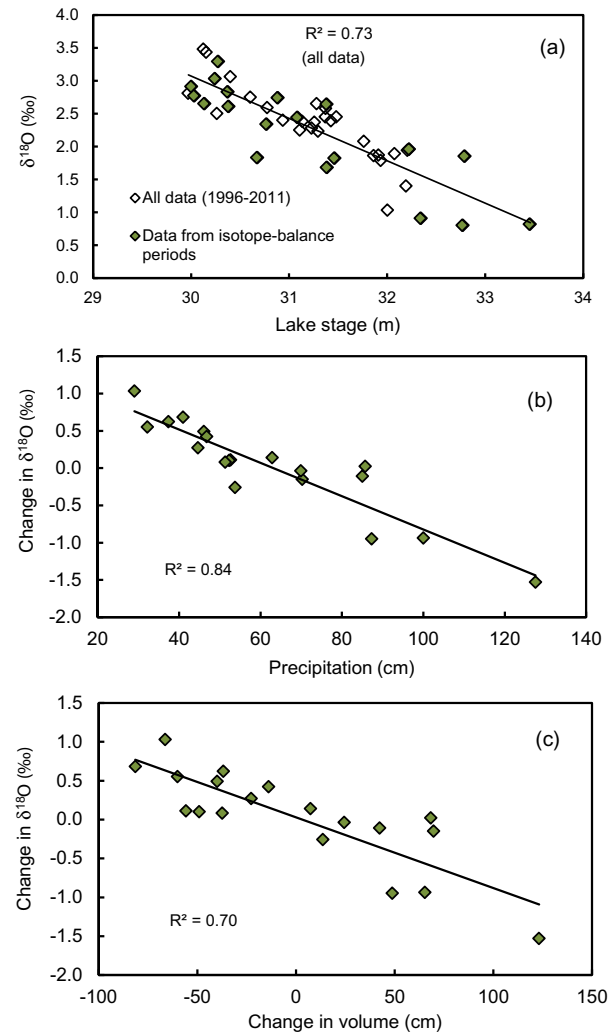

Fig. 5. Relation between (a) $\delta^{18}O$ and lake stage, and between change in $\delta^{18}O$ and (b) precipitation and (c) change in volume, for semi-annual isotope-balance periods at Lake Starr.

δ^2H followed a similar trend with lake stage (R^2 = 0.79) and ranged from +2.8 to +18.5‰, with an average value of +11.3‰ (Supplementary data Table C).

For the four rainfall sites in west-central Florida, the VWM δ_P was −18.7‰ and −3.73‰ for δ^2H and $\delta^{18}O$, respectively. Values from individual samples ranged from −7.94‰ to −0.45‰ (Supplementary data Table D). For wet season rainfall (June–September), there was a statistically significant inverse relation between rainfall amount and $\delta^{18}O$ (R^2 = 0.49, n = 20, p < 0.001). The average isotopic composition of shallow groundwater near Lake Starr was similar to the VWM δ_P (−20.0‰ and −3.91‰ for δ^2H and $\delta^{18}O$, respectively; data from 1996 to 2000; Sacks et al., 1998; Sacks, 2002), with $\delta^{18}O$ values from 19 samples ranging from −4.82‰ to −2.66‰. On a graph of δ^2H against $\delta^{18}O$, rainfall data plot along a local meteoric water line (MWL) (Fig. 6) whose slope is statistically indistinguishable from global meteoric water lines defined by Craig (1961) and Rozanski et al. (1993) (samples collected between 1996 and 2005; significance level, α = 0.05).

Isotopic data from Lake Starr fall along an evaporation trend line, which is offset from the MWL (Fig. 6). The intersection of the evaporation trend line and the MWL represents the average isotopic composition of inflow waters to the lake, which should approximate VWM δ_P. However, the intersection of these lines fell

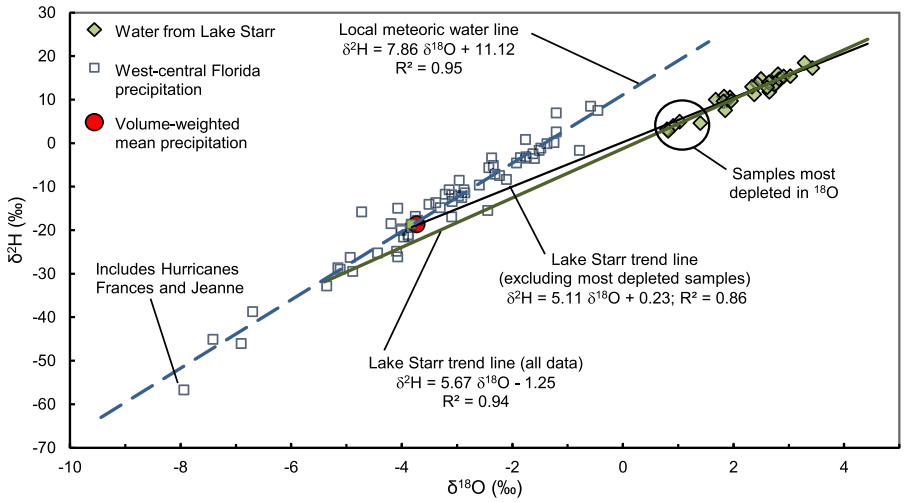

Fig. 6. δ^2H plotted against δ^{18}O for Lake Starr, and for precipitation in west-central Florida from several sites between 1996 and 2005, including the volume-weighted mean value; Lake Starr evaporation trend lines shown both including and excluding the five lake samples that were most depleted in ^{18}O.

at a point considerably more depleted in ^{2}H and ^{18}O than VWM δ_P (δ^2H and δ^{18}O values of −33.3‰ and −5.65‰, respectively). The slope of this evaporation trend line is controlled by five lake samples that are the most depleted in ^{2}H and ^{18}O (δ^2H and δ^{18}O values less than +5.0‰ and +1.5‰, respectively) (Fig. 6). These samples were from periods following high rainfall events when rainfall likely was depleted in ^{2}H and ^{18}O compared to VWM δ_P. Excluding these most depleted lake samples results in an evaporation line that intersects the MWL at an intercept more similar to VWM δ_P (δ^2H and δ^{18}O values of −20.0‰ and −3.96‰, respectively) (Fig. 6). Differences in these intercepts are evidence that inflow waters significantly depleted in ^{2}H and ^{18}O compared to VWM δ_P influenced the isotopic composition of the lake during parts of the study. This depleted rainwater also recharged the groundwater, further influencing the isotopic composition of lake water by way of groundwater inflow.

3.2. Isotope balance estimates of groundwater inflow

Isotope-balance estimates of groundwater inflow (G_i) ranged from −18.2 to 186.3 cm, compared to water-budget results of 12.4 to 113.1 cm (Fig. 7; Table 2). Median isotope-balance G_i was 48.5 cm, which was slightly higher than median water-budget G_i (39.8 cm). Overall, periods of low and high groundwater inflow corresponded, and there was a good relation between results from the two methods (R^2 = 0.81) (Fig. 8). Isotope-balance G_i was within the error bounds of water-budget G_i for more than half the isotope-balance periods (12 of 19). One additional period (no. 10) was very close to the high end of the water-budget range (within 5 cm or 13%). Small negative groundwater inflow, which is a mathematical artifact, was computed for three balance periods (Table 2); these periods had low water-budget G_i (<25 cm). Groundwater inflow was significantly overestimated by the isotope balance for three periods (Fig. 7).

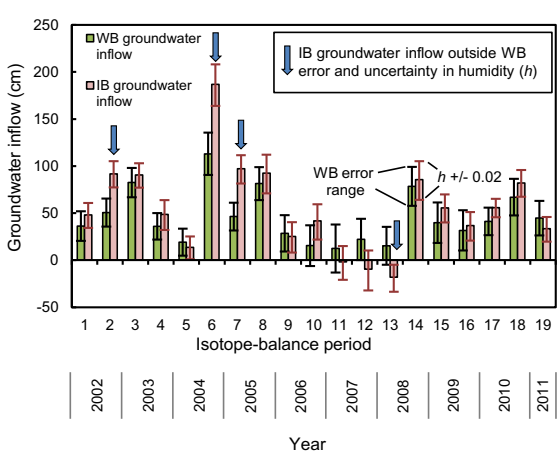

Fig. 7. Water-budget (WB) and isotope-balance (IB) groundwater inflow, illustrating the error range for the water budget and the influence of uncertainty in humidity values on isotope-balance groundwater inflow.

Uncertainties in input variables used to compute isotope-balance G_i impact the resultant inflow values to varying degrees. Results were most sensitive to h, E, and, δ_L (Eqs. (3) and (4); Fig. 9). The relative uncertainty was considerably more pronounced when groundwater inflow was low (<25 cm; Fig. 9). Reasonable uncertainties in h (±0.02), E (±10%), or δ_L (±0.1‰) could easily account for discrepancies between water-budget and isotope-balance results for three periods with low water-budget G_i (nos. 10–12), including two of the three periods with negative results (Fig. 7). For the other period with negative inflow (no. 13), the value can be explained by combining small uncertainties in multiple terms, which together can result in a negative value. However, it could also be related to other factors (discussed below). Uncertainty in h, E, and δ_L could not explain the discrepancy between isotope-balance and water-budget G_i results for three of the periods (no. 2, 6, and 7; Table 2).

Using a standard sensitivity analysis to assess uncertainties in the terms δ_P and δ_A, which were initially assumed constant, was more difficult because they were not measured for individual periods; hence, their range of expected values was not well known. Instead, δ_P and δ_A were adjusted together (assuming isotopic equilibrium between liquid and gas phases in the atmosphere) to achieve a match to water-budget results for the seven balance periods that were outside of the water-budget error. Adjusted values of δ_P ranged from −5.46‰ to −2.81‰ (compared to the initial value of −3.73‰), and adjusted values of δ_A ranged from −14.91‰ to −12.58‰ (compared to the initial value of −14.01‰). Periods with low SOI (<−0.80), indicative of El Niño conditions and high rainfall, had adjusted δ_P and δ_A values that were more depleted in ^{18}O than initial values (Fig. 10). Conversely, dry periods when the SOI was positive, indicating La Niña conditions, had adjusted δ_P and δ_A values that were more enriched in ^{18}O than initial values (Fig. 10).

Table 2
Isotopic and climatic variables used to compute groundwater inflow (G_i) to Lake Starr using the isotope-balance approach, and isotope-balance (IB) G_i compared to water-budget (WB) G_i and estimated error; variables defined in Eq. (4); δ_P and δ_{Gi} assumed to equal −3.73‰; δ_A assumed to equal −14.01‰.

Isotope-balance period	Begin date (mo/day/yr)	End date (mo/day/yr)	Initial lake δ^{18}O (‰)	Final lake δ^{18}O (‰)	T_0[a] (°C)	h[b] (ratio)	α^* (ratio)	$\Delta\varepsilon$ (‰)	ε (‰)	δ_E[c] (‰)	IB G_i (cm)	WB G_i (cm)	Error WB G_i (cm)
1	12/19/2001	6/24/2002	2.50	2.77	23.63	0.650	0.990590	4.97	14.38	−7.51	48.1	36.2	15.8
2[d]	**6/24/2002**	**12/16/2002**	**2.77**	**1.83**	**27.83**	**0.656**	**0.990926**	**4.88**	**13.96**	**−7.13**	**91.4**	**50.6**	**14.9**
3	12/16/2002	6/23/2003	1.83	1.68	23.01	0.661	0.990539	4.82	14.28	−9.54	90.3	82.5	15.5
4	6/23/2003	12/23/2003	1.68	1.82	27.18	0.675	0.990875	4.62	13.75	−7.76	48.5	36.0	14.0
5	12/23/2003	6/4/2004	1.82	2.44	21.58	0.668	0.990422	4.71	14.29	−8.38	13.6	19.2	14.2
6[d]	**6/4/2004**	**12/28/2004**	**2.44**	**0.91**	**27.32**	**0.683**	**0.990886**	**4.50**	**13.61**	**−7.42**	**186.3**	**113.1**	**22.5**
7[d]	**12/28/2004**	**6/23/2005**	**0.91**	**0.80**	**22.35**	**0.686**	**0.990485**	**4.46**	**13.97**	**−11.04**	**96.8**	**46.4**	**14.8**
8	6/23/2005	12/28/2005	0.80	0.82	27.21	0.694	0.990877	4.35	13.47	−9.51	92.1	81.4	17.5
9	12/28/2005	6/29/2006	0.82	1.85	23.05	0.670	0.990543	4.68	14.14	−10.25	25.0	28.5	19.4
10	6/29/2006	12/21/2006	1.85	1.96	27.10	0.688	0.990869	4.43	13.56	−6.41	41.6	15.5	21.6
11	12/21/2006	6/28/2007	1.96	2.64	22.95	0.688	0.990534	4.43	13.89	−6.25	−1.9	12.4	25.5
12	6/28/2007	12/27/2007	2.64	2.74	27.63	0.706	0.990910	4.18	13.27	−2.38	−9.7	22.1	22.0
13[d]	**12/27/2007**	**6/3/2008**	**2.74**	**3.29**	**22.51**	**0.689**	**0.990499**	**4.42**	**13.92**	**−4.07**	**−18.2**	**15.2**	**20.1**
14	6/3/2008	12/29/2008	3.29	2.34	26.49	0.682	0.990820	4.51	13.69	−4.18	85.4	78.5	20.7
15	12/29/2008	7/10/2009	2.34	2.83	23.47	0.641	0.990577	5.09	14.52	−8.17	55.5	39.8	21.5
16	7/10/2009	1/19/2010	2.83	2.91	25.90	0.657	0.990773	4.86	14.09	−5.87	36.5	31.7	21.4
17	1/19/2010	6/14/2010	2.91	2.65	22.18	0.646	0.990471	5.02	14.55	−7.64	55.8	41.2	14.7
18	6/14/2010	12/22/2010	2.65	2.61	27.57	0.624	0.990905	5.33	14.43	−8.07	81.9	67.0	19.4
19	12/22/2010	6/20/2011	2.61	3.03	22.83	0.649	0.990525	4.99	14.46	−7.23	33.3	44.7	18.3

[a] Average lake surface temperature.
[b] Average relative humidity normalized to lake surface temperature.
[c] Calculated using Eq. (4).
[d] IB period (marked in bold) has IB G_i that significantly differs from WB G_i (considering WB error and uncertainty in h of ±0.02).

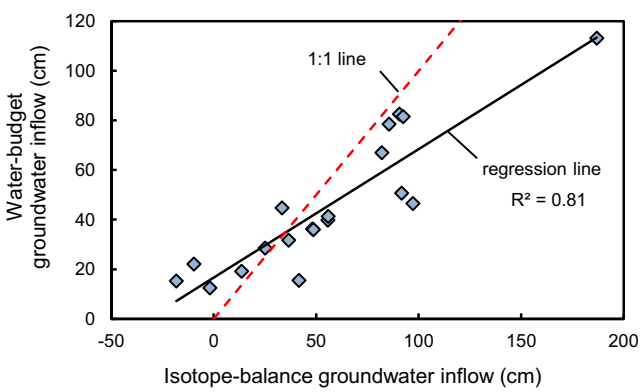

Fig. 8. Comparison between water-budget and isotope-balance groundwater inflow.

The three periods with the greatest difference between water-budget and isotope-balance results were characterized by the highest surplus rainfall and net precipitation of the study (>20 cm for both variables; Table 1), and corresponded to lows in the SOI (<−0.80; Fig. 3; Table 1). In addition, three hurricanes passed over the lake during one of these periods (August and September 2004; period no. 6); rainfall from these hurricanes accounted for 41 cm, or 32%, of the total rainfall for that balance period, including the highest daily rainfall measured during the study (19.8 cm). The analysis above indicated that values of δ_P for these three periods would need to be considerably more depleted in ^{18}O than the regional mean (between −5.5‰ and −5.0‰, compared to −3.73‰) to match water-budget results. These values, although more negative than the mean, are still within the observed range of δ^{18}O for rainfall in the region (Fig. 6). Rainfall collected at a site 60 km northwest of Lake Starr over a 38-day period that included the 2004 hurricanes was the most depleted in ^{18}O of the rainfall samples collected in west-central Florida during the study period (−7.94‰, Fig. 6; Supplementary data Table D). The VWM δ_P from this alternate site for the entire balance period (δ^{18}O −5.32‰) was similar to the value derived in the analysis above (−5.45‰).

The period with the most negative groundwater inflow (no. 13) was within a La Niña cycle that was characterized by drought conditions. Although uncertainty in multiple input variables could explain the negative value, it could also be explained by values of δ_P and δ_A that were more enriched in ^{18}O than initial assumptions. This period corresponded to a time that included extremely low rainfall for the month of May (0.19 cm for May 2008; a 90-year low). This lack of rainfall occurred when lake evaporation was at its annual high, resulting in that month having the most negative net precipitation of the study. The above analysis indicated that δ_A may have been considerably more enriched in ^{18}O (−12.58‰) than the originally assumed value (−14.01‰). Note that if the value of δ_A is fixed at this high value and the value of δ_P is allowed to vary, δ_P could have a large range in possible values and still be within the water-budget error, including the original VWM δ_P. Thus, variability in δ_A dominates our calculated results. One plausible explanation is that drought conditions during this period were favorable for significant amounts of local lake evaporate to influence δ_A, enriching it in ^{18}O compared to ambient δ_A. During periods of drought, many lakes in central Florida are more enriched in ^{2}H and ^{18}O (for example, Lake Starr δ^{18}O > +3‰, Fig. 4; Sacks, 2002) compared to δ^{18}O of seawater (approximately +0.5‰ to +1.5‰ for surface water from the adjacent Atlantic Ocean and Gulf of Mexico, respectively; National Aeronautics and Space Administration, 2012; Yobbi, 1992). Thus, the resultant lake evaporate should be significantly more enriched in ^{2}H and ^{18}O during droughts than evaporate originating from seawater, assuming other climatic variables are similar. Data are not available on how δ_A varies over a lake during extreme dry periods; however, preliminary estimates suggest that if 10–20% of water vapor were derived from enriched lake evaporate, the resultant δ_A would be in the range of −12.5‰.

For the 12 periods that had agreement between isotope-balance and water-budget results, groundwater inflow estimates were relatively insensitive to variations around the initially assumed values of δ_P, δ_{Gi}, and δ_A. These values could vary within a relatively

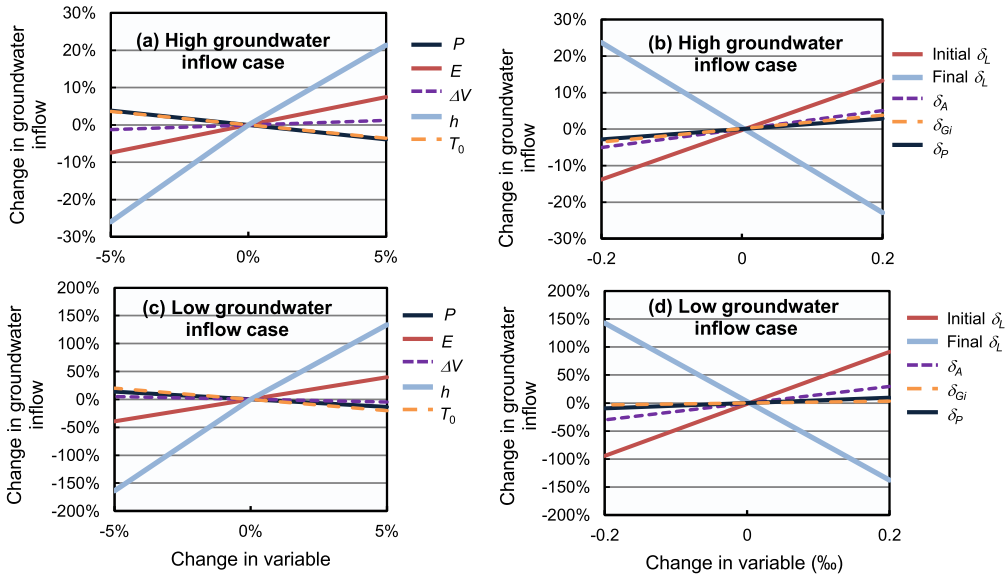

Fig. 9. Sensitivity analysis showing percent change in computed groundwater inflow to change in input variables used to compute groundwater inflow from the isotope balance, for (a–b) high and (c–d) low groundwater inflow cases (original inflow values of 90.6 and 13.7 cm, respectively).

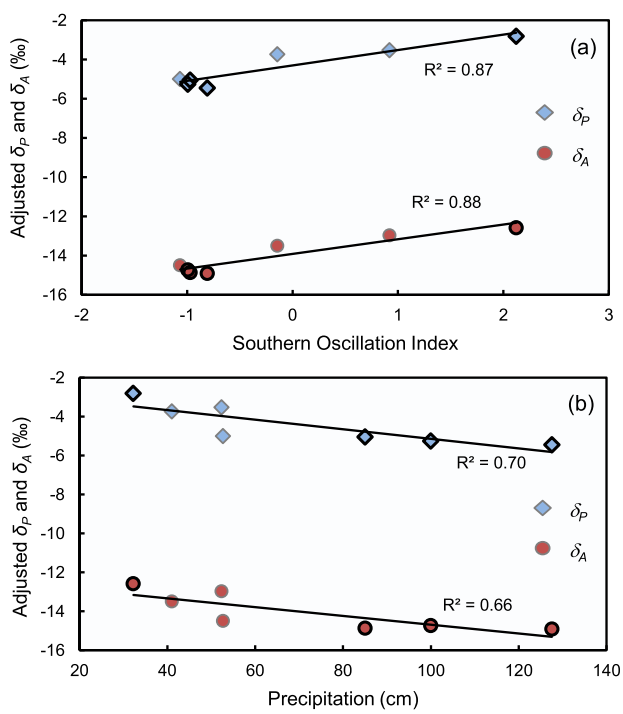

Fig. 10. Values of δ_P and δ_A adjusted to match water-budget groundwater inflow results, plotted against (a) the Southern Oscillation Index and (b) precipitation amount; data with dark outlines are those that have deviations from the water budget that cannot be explained by uncertainty in h (±0.02). Only data for periods originally outside of the water budget error are shown.

wide range and still have resultant groundwater inflow within the water-budget error. For instance, keeping the assumed values of δ_A and δ_{Gi} fixed, the values of δ_P could have an average range of 4.0‰ and still predict groundwater inflow values within the water-budget error. Similarly, keeping both δ_A and δ_P constant, values of δ_{Gi} could vary over an even larger range (average of 8.1‰). When both δ_P and δ_{Gi} were held constant, values of δ_A could vary over an average range of 1.4‰. The fairly wide range in possible values for δ_P, δ_{Gi}, and δ_A suggests that precise definition of these terms was not necessary for the approach used here, although the sensitivity varied for individual balance periods. In contrast, δ_L (which was measured) could vary within a much smaller range (average of 0.36‰) and still have resultant groundwater inflow within the water-budget error bounds.

Lastly, a steady-state analysis of the isotope balance equation was also solved for groundwater inflow using mean δ_L and input variables averaged over the 9.5-year isotope-balance period. The steady-state isotope-balance G_i was within the water-budget error (112.1 cm yr^{-1} compared to a water-budget value of 90.6 ± 35.4 cm yr^{-1}). This analysis was a useful check to compare the decade-long study period to steady-state conditions.

4. Discussion

The transient isotope balance analysis presented here discerned large differences in semiannual groundwater inflow to the lake, providing detailed information about that flux not available through a steady-state analysis. Isotope-balance results confirm water-budget results indicating that groundwater inflow varied by an order of magnitude over the course of a decade that included both wet and dry climatic extremes. This transient isotope balance relied on semiannual measurements of lake-water isotopic composition and used the simplifying assumptions of constant isotopic compositions of rainfall, groundwater inflow, and atmospheric moisture. Despite these simplifying assumptions, more than 60% of the estimates agreed with the results of the analytical water budget, and patterns of low and high groundwater inflow were consistent with the water budget. The consistency between isotope-balance and water-budget results indicates that it makes a suitable survey approach for other lakes in similar settings, and can be a viable approach for tracking the magnitude of groundwater inflow to seepage lakes over less-than-annual time periods.

While the isotope-balance approach yielded similar patterns of groundwater inflow as the independent water budget, magnitudes were over or under predicted during periods of climatic extremes. The assumption of constant δ_P was unsuitable when semiannual budget periods had large amounts of net precipitation from hurricanes or El Niño conditions. During these periods δ_P was significantly more depleted in ^{18}O than the mean δ_P initially assumed.

In addition, the value of δ_A may have been more enriched in ^{18}O than the assumed value during a period of extreme drought (high negative net precipitation), possibly due to the influence of local lake evaporate.

Although rainfall isotopic data were not collected for the study, the influence of rainfall more depleted in ^{18}O than the regional mean was discernible in the lake's isotopic composition, and, consequently, in its isotope balance. Isotope-balance results indicate that rainfall from a period with several hurricanes was significantly depleted in ^{2}H and ^{18}O. Rainfall from hurricanes that are highly depleted in ^{18}O has been noted in other studies (Lawrence and Gedzelman, 1996; Lawrence et al., 1998; Price et al., 2008) and is attributed to a hurricane's high condensation efficiency, as well as its size, height, intensity of updrafts, and longevity. Results also indicate that rainfall associated with El Niño conditions was depleted in ^{18}O compared to mean rainfall. These results are consistent with those from other studies linking rainfall depleted in ^{18}O to El Niño events (Frederickson and Criss, 1999; Vuille et al., 2004). The El Niño conditions observed here were mild (average SOI of −0.80 to −0.99) compared to other recent events (e.g., 1997–1998; average SOI for comparable period was −2.0), and the impact would be expected to be even more pronounced during stronger El Niño events. The influence of high rainfall that was significantly depleted in ^{2}H and ^{18}O was also apparent from the slope of the lake evaporation trend line, resulting in the intercept between the MWL and evaporation trend line being more depleted in ^{2}H and ^{18}O than VWM δ_P (Fig. 6).

Findings of this study support the assumed value of δ_A from earlier work by Sacks (2002), which was derived from a steady-state isotope balance of Lake Starr. That value (−14.01‰) appears to be valid for most of the study period, and is slightly more depleted in ^{18}O than the value assuming isotopic equilibrium with VWM δ_P (average −13.4‰). The reason for this discrepancy remains unresolved, but other studies have noted that δ_A conditions can differ from isotopic equilibrium, particularly when close to the vapor source (e.g., coastal settings) (Gat et al., 2001). There are few data available for δ_A in Florida, and none of those data are continuous or over long time periods (Sacks, 2002; Schoch-Fischer et al., 1984). The value of δ_A used here is on the high end of monthly mid-day point samples of δ_A from Lake Starr and another Florida lake for 1999–2000 (−16.78‰ to −10.91‰ for 23 point samples; Sacks, 2002). Weak, but statistically significant, relations were found in that data set between δ_A and temperature, relative humidity, and vapor pressure. New technologies for sampling δ_A continuously (Iannone et al., 2009; Landsberg et al., 2011; Sturm and Knohl, 2010) would lead to a better understanding of diurnal, seasonal, and interannual changes in δ_A, lending more accuracy to the isotope-balance approach. Sensitivity analyses from this study, however, show that precise definition of δ_A was not necessary to define groundwater inflow using the isotope-balance approach as δ_A values could have an average range of about 1.4‰ and still be within the water-budget error.

Similarly, study results indicate that the assumed value for δ_{Gi}, which was set equal to VWM δ_P, was adequate for seepage lakes like Lake Starr. The value for δ_{Gi} measured near Lake Starr was fairly well constrained, with a range in $\delta^{18}O$ of 2.16‰ (Sacks, 2002). Isotope-balance results were not particularly sensitive to δ_{Gi}, and values could range by 8‰ and still be within the water-budget error. For most balance periods, direct precipitation on the lake was greater than groundwater inflow, which explains the lower sensitivity, particularly for periods when groundwater inflow was low. In addition, temporal variability in δ_{Gi} is considerably less than δ_P because it represents a composite of rainfall over time. Thus, although water depleted in ^{2}H and ^{18}O enters the shallow groundwater system following high recharge events, driven by tropical cyclones or El Niño conditions, its influence on semiannual ground-water inflow appears to be minimal. Results indicate that assumptions from the earlier synoptic sampling appear to adequately describe δ_{Gi}, allowing greater focus to be placed on quantifying other parameters.

Because the isotope balance is quite sensitive to uncertainties in several of the input parameters (δ_L, h, and E; Fig. 9), emphasis should be placed on accurately quantifying these parameters in future studies. For example, a greater benefit might be gained from improving accuracy in these terms, rather than increasing the sampling for δ_{Gi} and δ_A. Relative humidity (h), normalized to lake surface temperature, was among the most sensitive variables in the isotope balance; precise measurements are needed for accurate determination of the kinetic fractionation factor needed to define δ_E (Eq. (4)). However, relative humidity sensors typically have accuracy ranges of 2–4%, which can cause relatively large uncertainties in results (Fig. 9); given currently available technology, a better estimate of h may be difficult. Sensitivity analyses also underscore the importance of precise quantification of δ_L, as the method can be limited by the analytical uncertainty of $\delta^{18}O$.

This study corresponded to a decadal period that included extreme climatic events, and, hence, results likely span the range of potential isotopic composition of this subtropical seepage lake over the past 90 years. Periods of drought contrasted with periods of very high excess precipitation, which caused the range of δ_L to vary considerably ($\delta^{18}O$ by 2.68‰), reflecting the wide range in lake volume (±45%) and stage (about 4 m, Fig. 4). Nonetheless, δ_L oscillated around a typical value of about +2.3‰ over 15 years, validating the premise of a long-term steady-state isotopic composition of the lake. This typical δ_L value was similar to that used in the earlier steady-state analysis (+2.32‰; Sacks, 2002), even though those data were averaged over a much shorter period (1.5 years). Had that data collection occurred in a very wet or dry period, however, it would not have been representative of steady-state conditions. Thus, caution is needed when assuming a period is representative of steady-state conditions when few data are available, and knowledge of meteorological conditions preceding data collection is necessary. Lake Starr has an average water residence time of about 2.2 years, and success of the method for other lakes would be expected to vary depending on the residence time. Specifically, semiannual differences in groundwater inflow may be more difficult to discern for a lake with a much longer residence time.

The isotopic composition of water from Lake Starr is a significant indicator of regional climatic conditions influencing the lake, as it was highly correlated with rainfall amount, net precipitation, lake stage, and groundwater inflow. In addition, lake-water $\delta^{18}O$ was weakly correlated with the SOI, even though the water-budget terms for the semiannual balance periods were not. These relations could be useful for tracking future changes in climate, as well as for potentially ground-truthing paleoclimate reconstructions using $\delta^{18}O$ from lake cores. Extreme climatic events such as tropical cyclones, El Niño episodes, and droughts should be recorded as proxies in the $\delta^{18}O$ record of organic material and diatoms in the sediments of low carbon lakes such as Lake Starr (Anderson et al., 2001; Chapligin et al., 2012; Huang et al., 2002; Lamb et al., 2004). Researchers have used isotopic, trace element, and pollen data from lake sediment cores and speleothems to reconstruct relatively long-term climatic variability in Florida (100's to 10,000's of years) (Cross et al., 2004; Grimm et al., 2006; van Beynen et al., 2008). If suitable techniques were available, results from this study suggest that shorter-term climatic variability on seasonal to decadal time scales could be inferred from isotopic data in lake cores over more recent time periods to quantify natural cycles of rainfall, stage variability, and extreme climatic events.

5. Conclusions

Groundwater inflow to a Florida seepage lake was estimated semiannually using a simplified transient isotope-balance approach over a decade characterized by climatic extremes. The main findings from this analysis are:

1. Isotope-balance groundwater inflow was within the error bounds of groundwater inflow from an independent water budget for the majority of the calculation periods, and patterns of low and high groundwater inflow were consistent with the water budget.
2. The transient δ^{18}O analysis discerned large differences in semi-annual groundwater inflow, providing detailed information not available using a more typical steady-state isotope balance; this approach is viable for tracking the magnitude of groundwater inflow to lakes in similar settings over less-than-annual time periods.
3. Results were most sensitive to uncertainty in relative humidity, evaporation, and the isotopic composition of lake water; accuracy of these variables based on available technology may limit more precise quantification of groundwater inflow in similar settings.
4. The simplifying assumptions of constant isotopic composition of precipitation (δ_P), atmospheric moisture (δ_A), and groundwater inflow were valid for most calculation periods, with the notable exception of several periods characterized by climatic extremes.
   a. For periods with large amounts of net precipitation from tropical cyclones or El Niño conditions, values of δ_P were considerably more depleted in ^{18}O than the regional average.
   b. During a period of extreme drought, the value of δ_A may have been more enriched in ^{18}O due to the influence of local lake evaporate.
   c. Isotope-balance estimates of groundwater inflow during these periods were outside the error bounds of the independent water budget, and additional data about δ_P and δ_A during very wet and dry periods would help refine results.
5. The 15-year δ^{18}O and δ^{2}H record for Lake Starr was highly correlated with rainfall amount and lake volume, quantifying the isotopic variability of a subtropical lake over a range of climatic conditions; such relations may be useful if isotopic data from lake cores were used to interpret seasonal or interannual climatic variability.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2013.12.012.

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