Journal of Hydrology 519 (2014) 3054–3068

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Exploring the long-term balance between net precipitation and net groundwater exchange in Florida seepage lakes

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ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form 19 February 2014
Accepted 6 April 2014
Available online 18 April 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Raymond Najjar, Associate Editor

Keywords:
Lake
Evaporation
Water balance
Net precipitation
Groundwater
Sustainable

SUMMARY

The long-term balance between net precipitation and net groundwater exchange that maintains thousands of seepage lakes in Florida's karst terrain is explored at a representative lake basin and then regionally for the State's peninsular lake district. The 15-year water budget of Lake Starr includes El Niño Southern Oscillation (ENSO)-related extremes in rainfall, and provides the longest record of Bowen ratio energy-budget (BREB) lake evaporation and lake-groundwater exchanges in the southeastern United States. Negative net precipitation averaging −25 cm/yr at Lake Starr overturns the previously-held conclusion that lakes in this region receive surplus net precipitation. Net groundwater exchange with the lake was positive on average but too small to balance the net precipitation deficit. Groundwater pumping effects and surface-water withdrawals from the lake widened the imbalance. Satellite-based regional estimates of potential evapotranspiration at five large lakes in peninsular Florida compared well with basin-scale evaporation measurements from seven open-water sites that used BREB methods. The regional average lake evaporation estimated for Lake Starr during 1996–2011 was within 5% of its measured average, and regional net precipitation agreed within 10%. Regional net precipitation to lakes was negative throughout central peninsular Florida and the net precipitation deficit increased by about 20 cm from north to south. Results indicate that seepage lakes farther south on the peninsula receive greater net groundwater inflow than northern lakes and imply that northern lakes are in comparatively leakier hydrogeologic settings. Findings reveal the peninsular lake district to be more vulnerable than was previously realized to drier climate, surface-water withdrawals from lakes, and groundwater pumping effects.

1. Introduction

Net precipitation to lakes, the difference between cumulative precipitation and lake evaporation, governs the relation between lakes and their watersheds. Where precipitation exceeds lake evaporation and net precipitation is positive, lakes export net water to their watersheds to sustain lake levels over the long term. Lakes with negative net precipitation import net water from their watersheds in the form of stream flow, runoff, or groundwater inflow to persist in the landscape (Winter and Woo, 1990). Whereas precipitation is widely and systematically monitored across the United States, few lakes have long-term evaporation rates that have been precisely quantified using energy budgets (Lenters et al., 2005; Winter et al., 2003). Potential evapotranspiration rates are often used as a proxy for open-water evaporation, but the rates differ depending on the methods used to compute them (Douglas et al., 2009; Lu et al., 2005; Rosenberry et al., 2004). Despite increased uncertainty in regionalized estimates compared to basin-scale lake evaporation estimates, the difference between annual average precipitation and potential evapotranspiration is large enough to make the net precipitation to lakes unequivocally positive or negative for many lake districts in the United States (Healy et al., 2007; Winter, 1995b; Winter and Woo, 1990). For thousands of lakes in Florida's peninsular lake district, however, whether net precipitation to lakes is positive or negative remains unclear, and so does the fundamental relation between lakes and their watersheds.

The ambiguity in net precipitation for Florida's extensive lake district derives from differences in the methods used to quantify open-water evaporation and its nearest equivalent, potential evapotranspiration. Net precipitation has long been considered positive for all but Florida's southern tip (Abtew and Melesse, 2012; Farnsworth et al., 1982; Reilly et al., 2008; Visher and

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http://dx.doi.org/10.1016/j.jhydrol.2014.04.009
0022-1694/Published by Elsevier B.V.

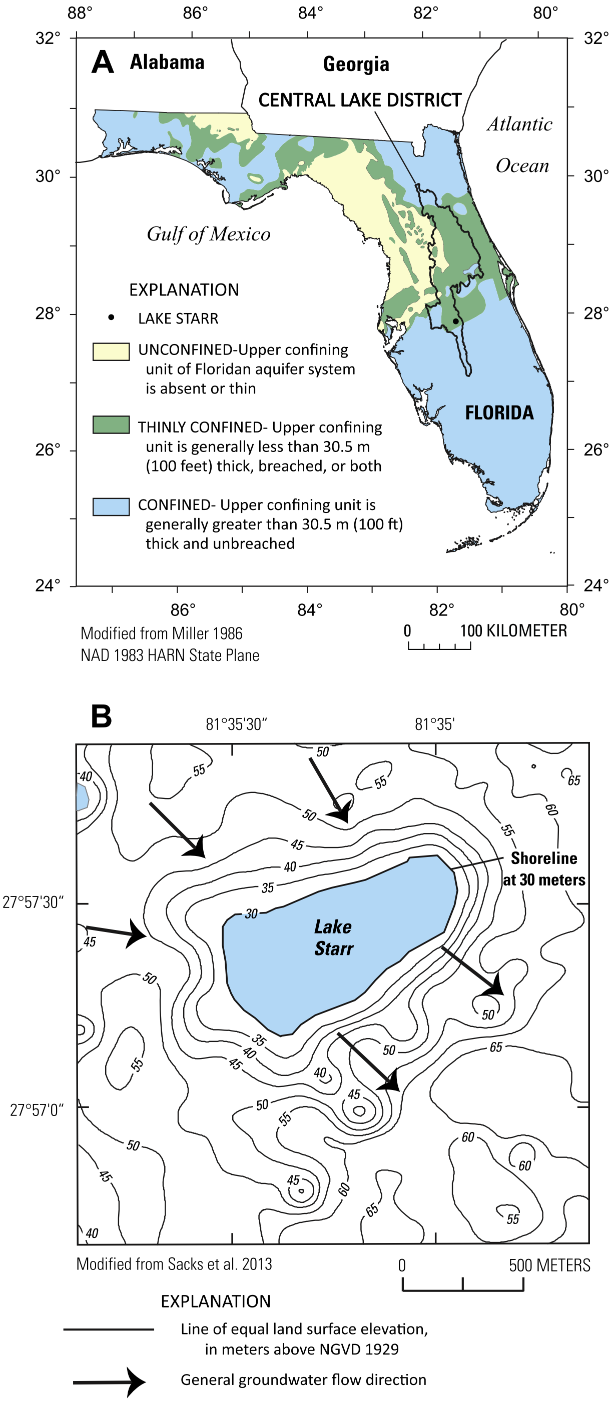
Hughes, 1975; Winter, 1995a), implying that lakes located in both the wetter panhandle of the state and the drier peninsula export surplus water to their watersheds. This regional view stemmed from lake evaporation and potential evapotranspiration rates quantified by pan-evaporation methods, open-water lysimeters, or the temperature-dependent Hamon equation, all of which provide less accurate estimates of evapotranspiration than energy-budget methods (Brutsaert, 1982; Finch and Hall, 2005; Winter, 1995b). Evidence of substantially greater open-water evaporation rates and negative net precipitation in peninsular Florida began accumulating in the early 1990s in basin-scale studies that used rigorous Bowen ratio energy-budget (BREB) micrometeorological methods to estimate open-water evaporation (German, 2000; Lee and Swancar, 1997; Sacks et al., 1994; Sumner and Belaineh, 2005; USGS, 2012). Yet BREB lake evaporation measurements have not been framed into a regional picture of net precipitation for the peninsular lake district because the number of study sites is limited, and measurement periods are typically short and not overlapping. Lake evaporation estimates based on accurate BREB evaporation methods that are long enough to span wet and dry climate cycles are crucial because they can be used to quantify both the year-to-year variation and long-term average net precipitation. Meanwhile, potential evapotranspiration rates derived from Geostationary Operational Environmental Satellite (GOES)-based estimates of daily insolation at a 2-km grid scale became available for Florida starting in 1995 (Jacobs et al., 2008; Mecikalski et al., 2011; Paech et al., 2009; USGS, 2011). However, satellite-based values have not been examined for their ability to reproduce all of the available BREB-based estimates of evaporation for lakes.

The simplified, steady-state water balance of many Florida lakes implies that the magnitude of net precipitation to the lake is roughly equivalent, and opposite in sign, to the magnitude of net groundwater exchange needed to maintain the long-term lake level (Healy et al., 2007; Winter, 1981). Most lakes in the sandhill karst of peninsular Florida are seepage lakes that receive little direct runoff from the basin and interact with the watershed predominantly through unobserved groundwater flows instead of stream flows (Schiffer, 1998). Net groundwater exchanges with lakes in Florida have been quantified using detailed basin-scale water budgets (Grubbs, 1995; Lee, 2000; Lee and Swancar, 1997; Swancar and Lee, 2003). However, net groundwater exchanges with lakes in the region are affected to varying degrees by groundwater pumping from the deeper limestone aquifer (Marella, 2009), which increases downward leakage from lakes and the overlying surficial aquifer (Sepulveda et al., 2012; Southwest Florida Water Management District, 1996). Thus, a long-term lake water budget quantifies the actual net groundwater exchanged with a seepage lake affected by groundwater pumping (Virdi et al., 2013). Alternatively, the atmospheric flux of net precipitation is free from pumping effects and estimates the net groundwater exchange that is required to maintain lake levels over the long term.

This paper examines the balance between net precipitation and net groundwater exchange in detail at a seepage lake where BREB evaporation measurements, net precipitation, and net groundwater exchanges were quantified monthly for 15 years. Lake evaporation is then examined regionally for Florida's peninsular lake district using satellite-based estimates of potential evapotranspiration for open water. Satellite-based estimates of annual average lake evaporation are corroborated with basin-scale estimates of BREB evaporation at seven locations, and then are used to extrapolate lake evaporation and net precipitation rates across peninsular Florida. The north-to-south regional difference in net precipitation across the peninsular lake district is used to infer regional differences in net groundwater exchanges with seepage lakes, and regional differences in lake hydrogeologic setting.

1.1. Background

Florida has about 7800 lakes greater than 0.4 ha in size (Brenner et al., 1990). Lakes are distributed throughout Florida but many are concentrated in the Central Lake District, a physiographic region that extends about 320 km and three degrees of latitude through the interior of the peninsula (Fig. 1). The mantled karst terrain of the Central Lake District is characterized by thousands of small lakes and relatively few large lakes scattered along and between elevated sand ridges (Brooks, 1981; Griffith et al., 1997; White,



Modified from Miller 1986
NAD 1983 HARN State Plane

Modified from Sacks et al. 2013

Fig. 1. (A) Map showing the location of the study lake, the Central Lake District of peninsular Florida, and levels of confinement of the limestone Floridan aquifer system, and (B) topographic map of the Lake Starr basin.

1970). Lakes are typically formed by sinkhole-type subsidence, with unconsolidated mantle sediments subsiding into solution voids in the underlying limestone (Kindinger et al., 1999). Most lakes are small, with more than half estimated to be less than 60 ha in size and 5 m deep, and occur entirely in the sandy surficial sediments well above the limestone (Brenner et al., 1990). Lakes receive shallow groundwater inflow from the surficial aquifer and also leak water through their deeper lakebeds back into the surficial aquifer. The surficial aquifer recharges the underlying limestone aquifer, part of the Floridan aquifer system, which is thinly confined in much of the region (Fig. 1a) (Bush and Johnston, 1988). The permeable recharge setting accelerates infiltration of rainfall, minimizing runoff and eliminating streamflow from most lake basins. Groundwater inflow to the resulting seepage lakes can approach or exceed the precipitation rate (Deevey, 1988; Lee, 2000; Motz et al., 2001; Sacks, 2002). Widespread groundwater pumping from the uppermost zone of the Floridan aquifer system, the Upper Floridan aquifer, increases leakage from lakes in peninsular Florida (Barcelo et al., 1990; Swancar and Lee, 2003; Sepúlveda et al., 2012). Water is also withdrawn directly from lakes to irrigate lawns and crops, which further affects the exchange of water between lakes and their basins.

The climate of peninsular Florida is humid sub-tropical (Chen and Gerber, 1990) with wet summer months characterized by thunderstorms and occasional tropical storms and hurricanes. All precipitation is in the form of rainfall and annual rainfall within the Central Lake District, and much of the interior of the peninsula, averages about 130 cm. Annual rainfall exceeds 150 cm/yr along the southeast coast of Florida, where tropical storms and hurricanes often make landfall, and exceeds 130 cm/yr along other coastal areas of the peninsula. Freezing air temperatures occur regularly in the northern two-thirds of the Central Lake District, and rarely in its southern third (below about latitude 28°N). Published regional net precipitation estimates are positive and range from 0 to 10 cm (Henry, 1998; Healy et al., 2007; Visher and Hughes, 1975). Lake evaporation rates published from the 1950s to 1980s ranged from 122 to 129 cm/yr (Farnsworth et al., 1982; Kohler et al., 1959; Langbein, 1951) and are based primarily on pan evaporation methods, which are known to have appreciable uncertainty (Brutsaert, 1982). More recent estimates from 2- to 5-year studies that used more accurate BREB methods (Finch and Hall, 2005; Winter, 1981) have yielded lake evaporation rates greater than 140 cm/yr (German, 2000; Lee and Swancar, 1997; Sacks et al., 1994; Sumner and Belaineh, 2005; USGS, 2012). The effects on lake evaporation of seasonal and interannual climate cycles such as the El Niño-Southern Oscillation (ENSO) were not captured in these relatively short-term studies.

1.1.1. Lake Starr description

Lake Starr (54 ha; 9.5 m maximum depth) was selected to be representative of seepage lakes in central Florida and has been the focus of long-term research to understand lake evaporation losses and lake-groundwater exchanges in this karstic terrain (Fig. 1b) (Sacks et al., 1998; Swancar et al., 2000; Swancar and Lee, 2003; Virdi et al., 2013). The lake water budget provides 15 years of continuous BREB lake evaporation data and net groundwater exchanges at monthly timesteps (Sacks et al., 2014). Gross groundwater inflow and lake leakage were quantified for a 10-year period using a three-dimensional variably-saturated flow model of the lake basin (Virdi et al., 2013). The 15-year BREB lake evaporation record at Lake Starr (August 1996 through July 2011) is currently the longest in the southeastern US and includes El Niño and La Niña phases of the ENSO climate cycle and historic wet and dry extremes in rainfall (Sacks et al., 2014; Virdi et al., 2013).

The ENSO ocean–atmosphere phenomenon, which occurs at sub-decadal time scales (2- to 7-year quasi-periodic), affected the weather and water level at Lake Starr (Swancar, 2005; Yeh et al., 2009). Hurricanes, and winter rainfall associated with El Niño-phase ENSO conditions, increased annual rainfall in several of the study years, while in other years the La Niña-phase contributed to severe droughts (Virdi et al., 2013). In response, annual rainfall approached the wettest (2005) and driest (2000) extremes in the 89 years of recorded rainfall at the closest long-term weather station (Mountain Lake 1922–2010) (National Oceanographic and Atmospheric Administration) (NOAA, 2011a). Annual average rainfall at Lake Starr (122.8 cm/yr) for the 15 study years was within 3% of average rainfall at Mountain Lake (126.4 cm/yr) for calendar years 1996–2010.

More than 3,000,000 m^3/yr of groundwater were pumped from the Upper Floridan aquifer within a 3.2-km radius of Lake Starr during the water-budget period, which lowered the potentiometric level of the aquifer beneath the lake and increased lake leakage (Fig. 2) (Southwest Florida Water Management District, 2006; Virdi et al., 2013). Pumping typically peaked in the dry spring months for crop irrigation, especially during drought years (June 1998, April 1999, May 2000) (Fig. 2). Irrigating citrus trees in the basin with groundwater did not affect the simulated groundwater inflow to Lake Starr (Virdi et al., 2013), but the practice enriched calcium and magnesium concentrations in Lake Starr and other lakes in the Central Lake District (Choquette and Kroening, 2009; Sacks et al., 1998; Stauffer and Canfield, 1992). Pumping surface water directly from lakes also is a widespread practice. Surface-water withdrawals exceeding a certain volume require permits, but many smaller withdrawals, like those at Lake Starr, are unregulated (Southwest Florida Water Management District, 2013).

1.1.2. Basin-scale evaporation studies

Comparable BREB methods to those used at Lake Starr have been used to measure evaporation at six other open-water sites in peninsular Florida and one lake (Lake Five-O) in the panhandle (Table 1) (German, 2000; Grubbs, 1995; Lee and Swancar, 1997; Sacks et al., 1994; Sumner and Belaineh, 2005; USGS, 2012). The BREB methods used in Florida were developed by the U.S. Geological Survey (USGS) and have been used at other sites nationwide (Allander et al., 2009; Moreo and Swancar, 2013; Rosenberry et al., 1993; Winter et al., 2003). Six of the open-water sites, including Lake Starr, are lakes ranging in size from 11 to 54 ha. One lake is a drainage lake with a stream outflow; the other five are seepage lakes. Two additional sites are an estuary on the Atlantic coast called the Indian River Lagoon and a wetland in the Everglades (Table 1). Evaporation records vary from 1 to 10 years in length at the study sites, with most sites having less than 3 years (Table 1).

1.1.3. Satellite-based potential evapotranspiration

Satellite-based estimates of potential evapotranspiration and reference evapotranspiration, which begin in 1995 and are ongoing, are available in the Florida Statewide ET Database (USGS, 2012). Potential and reference evapotranspiration estimates are based on incident solar radiation at the Earth's surface (insolation) and spatially-interpolated, field-based meteorological measurements. Ground-based insolation is modeled using the Gautier-Diak-Masse approach and data from the GOES East series of satellites (Mecikalski et al., 2011; Paech et al., 2009). Daily insolation estimates for 1995–2004 were calibrated using 9.5 years of data from 57 ground-based pyranometers (Paech et al., 2009). Insolation estimates are developed into half-hourly and daily integrated solar insolation fields over the state at 2-km resolution (Paech et al., 2009). Net radiation is estimated from insolation data using a four-component approach that relies on measured incoming solar radiation and derived values of surface albedo and Stefan–Boltzmann-based estimates of upwelling and downwelling longwave radiation (Jacobs et al., 2008). Gridded values of net

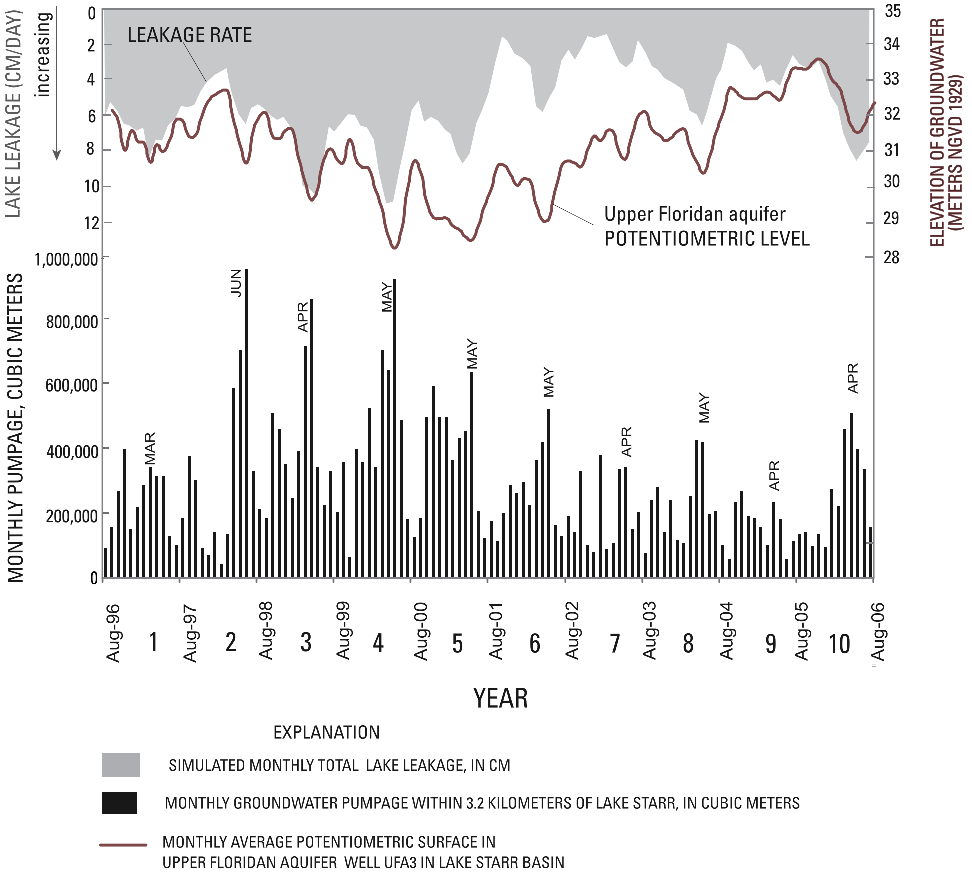


Fig. 2. Monthly groundwater pumpage in the vicinity of Lake Starr, corresponding groundwater levels in the Upper Floridan aquifer, and simulated total lake leakage from August 1996 to July 2006. Modified from Virdi et al. (2013).

Table 1
Description of basin-scale open-water sites that used comparable Bowen ratio energy-budget evaporation methods. [Sites are listed from north to south by descending latitude; ddmmss, degrees minutes seconds; (ha) hectares; NA, not applicable; mos, months; yrs, years].

Surface water	Latitude (ddmmss)	Longitude (ddmmss)	Surface water type	Lake surface area (ha)	Period of record	Length of record	BREB evaporation rate (cm/yr)	Source
Lake Five-O	302518	852518	Seepage lake	11	6/1989–12/1990	19 mos	127.6	Sacks et al. (1994)
Lake Barco	294034	820030	Seepage lake	11	6/1989–12/1990	19 mos	151.2	Sacks et al. (1994)
Reedy Lake	282457	813648	Drainage lake	45	12/2001-Current	10 yrs	150.9	Douglas et al. (2009), and http://fl.water.usgs.gov/et/etdata
Lake Calm	280820	823500	Seepage lake	48	4/2005–11/2007	30 mos	153.4	Unpublished USGS data
Lake Lucerne	280444	814100	Seepage lake	18	10/1985–9/1986	12 mos	147.1	Lee and Swancar (1997)
Indian River Lagoon	280340	803440	Estuary	NA	1/2002–1/2004	25 mos	158	Sumner and Belaineh (2005)
Lake Starr	275715	813531	Seepage lake	54	8/1996–7/2011	15 yrs	147.5	Sacks et al. (2013)
Everglades Open Water #3	263740	802612	Wetland	NA	1/1996–12/1997	24 mos	145.7	German (2000)

radiation and meteorological estimates are used in a Priestley–Taylor model to compute potential evapotranspiration and reference evapotranspiration rates at a 2-km grid scale across Florida (Mecikalski et al., 2011; USGS, 2011).

2. Methods

2.1. Basin-scale

2.1.1. Evaporation and rainfall

The Bowen ratio energy-budget (BREB) approach was used to make all basin-scale measurements of actual evaporation (Table 1). Meteorological and water temperature data from land and/or raft weather stations were used to compute lake evaporation. The BREB method estimates the energy used for evaporation by quantifying energy gains and losses and change in stored energy (Anderson, 1954; Moreo and Swancar, 2013; Parkhurst et al., 1998). The energy-budget equation is

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_e - Q_h - Q_w + Q_v = Q_x \qquad (1)$$

where Q_s is incoming solar radiation, Q_r is reflected solar radiation, Q_a is incoming longwave radiation, Q_{ar} is reflected longwave radiation, Q_{bs} is emitted longwave radiation (the sum of Q_{ar} and Q_{bs} is sometimes called upwelling longwave radiation), Q_e is energy used for evaporation, or the latent-heat flux, Q_h is energy advected from the lake to the atmosphere as sensible heat, Q_w is energy advected from the lake to the atmosphere by the evaporating water, Q_v is net energy advected into the lake (e.g., by rain, streams, groundwater), and Q_x is change in stored heat.

Heat exchange with bottom sediments is assumed to be negligible. The first five terms can be measured or estimated separately, or combined as net radiation, Q_n. All Q terms are expressed in W/m^2.

The evaporation rate, E, in m/s, is

$$E = \frac{Q_e}{\lambda \rho_w} \tag{2}$$

where λ is latent heat of vaporization, 2.45×10^6 J/kg at 20 °C, ρ_w is the density of water, 1000 kg/m^{3}at 4 °C.

Q_h is derived from the Bowen ratio, R, the ratio of Q_h to Q_e (Bowen, 1926)

$$Q_h = RQ_e \tag{3}$$

Q_w is calculated from

$$Q_w = c_w \rho_w E(T_e - T_b) \tag{4}$$

where c_w is the specific heat of water, 4186 J/kg °C at 15 °C, T_e is the temperature of evaporating water (assumed equal to the water-surface temperature, T_o), in °C, and T_b is the base temperature, set to 0 °C. Inserting Eqs. (2)–(4) into Eq. (1), and solving for E (in cm/d) gives

$$E = 8.64 \times 10^6 \times \frac{(Q_n - Q_x + Q_v)}{\rho_w \lambda[(1 + R) + c_w(T_o - T_b)]} \tag{5}$$

The 8.64×10^6 multiplier is used to convert units from m/s to cm/d. For this form of the energy budget (called the BREB variant), R is calculated from the vapor pressure and temperature differences using the following equation:

$$R = 0.061P\frac{(T_o - T_a)}{(e_o - e_a)} \tag{6}$$

where P is average atmospheric pressure, set to 101.4 kPa for Lake Starr, T_a is air temperature, in °C, e_o is saturation vapor pressure at the water-surface temperature, in kPa, and e_a is vapor pressure of the air, in kPa, and 0.061 is the psychrometric constant used at Lake Starr, in kPa/°C. Vapor pressures were calculated every 30 min or hourly from temperature and relative humidity data, then averaged daily and monthly.

Rainfall was measured in individual basins. Annual evaporation for each site was the average of all available annual values. Monthly and annual rainfall and evaporation measured at Lake Starr were correlated to the multivariate ENSO index (MEI) (NOAA, 2011b; Wolter and Timlin, 2011). The extended multivariate ENSO index (MEI.ext) was selected from a comparison of available indices as a robust indicator of ENSO signals.

2.1.2. Long-term water balance and net groundwater exchange at Lake Starr

A long-term water budget of Lake Starr was used to compute net groundwater and net precipitation (Eqs. (7) and (8)). For a seepage lake with no stream flows and negligible runoff, the water-budget equation is:

$$\Delta V = P - E + G_i - G_o - Q \tag{7}$$

and the net groundwater exchange is

$$GW_{\text{net}} = (G_i - G_o) = \Delta V - P + E + Q \tag{8}$$

where ΔV is the change in lake volume, P is precipitation (rainfall), E is evaporation, G_i is groundwater inflow, G_o is groundwater outflow (herein called lake leakage), and Q is direct withdrawal from the lake for lawn and citrus irrigation. Precipitation, evaporation, and lake stage were directly measured at the lake, and surface-water withdrawals from the lake were estimated as in Swancar et al. (2000). Net precipitation (P–E) was derived directly from measured values, and net groundwater exchange indirectly using Eq. (8). G_i is assumed to include any runoff occurring near the lakeshore following high rainfall events. Runoff was zero from all but the nearshore region of the Lake Starr basin because the basin soils are excessively drained silica sands (Swancar et al., 2000). Rejected infiltration (e.g., runoff) near the shoreline was quantified by Virdi et al. (2013) for a 10-year period using a variably-saturated groundwater flow simulation of the basin, and it contributed on average 27% as much as the annual groundwater inflow. Lake leakage was simulated daily for the 10-year period August 1996 to July 2006 (Virdi et al., 2013). For the 60 months that extend beyond the simulation period (August 2006–July 2011), lake leakage was estimated based on a regression using a polynomial equation relating monthly net groundwater exchange to lake leakage during the simulation period ($R^2 = 0.68$; standard error = 1.28 cm $G_o = 0.00846\ GW_{\text{net}}^2 - 0.35932\ GW_{\text{net}} + 5.7457$) (Sacks et al., 2014). Non-linear (volumetric) water-budget terms are converted to daily values in linear units (cm) over the daily average lake surface area, and then are summed to derive monthly and annual rates directly comparable to rainfall and evaporation. Estimated errors in water-budget terms follow those presented in Swancar et al. (2000) and Sacks et al. (2014). Errors in the BREB annual evaporation estimates are assumed to be 10% (Swancar and Lee, 2003; Winter et al., 2003). Errors in the long-term average estimates of annual rainfall and lake evaporation are assumed to be 5% (Winter, 1981).

The complete monthly and annual water budgets for Lake Starr from August 1996 to July 2011 are available in Sacks et al. (2014). Groundwater levels were monitored in about 49 basin wells and used to calibrate groundwater simulations of the surrounding basin (Swancar and Lee, 2003; Virdi et al., 2013). Stage, rainfall, select meteorological parameters, and groundwater levels are available online (http://waterdata.usgs.gov).

2.2. Regional scale

2.2.1. Lake evaporation

Basin-scale BREB measurements of actual lake evaporation were compared to satellite-based potential evapotranspiration rates for open water. Regional estimates of potential evapotranspiration (PET) were taken from the Statewide Florida ET database, a database of daily PET and reference evapotranspiration rates from 1995 to present (2013) derived using GOES satellite data (Jacobs et al., 2008; Mecikalski et al., 2011; Paech et al., 2009; USGS, 2011). Gridded surfaces of potential evapotranspiration for the 16 calendar years 1996 through 2011 were averaged to create a map of the annual average PET for the state. The Priestley–Taylor equation, a simpler alternative to the energy-budget equation, was used to derive potential evapotranspiration (Douglas et al., 2009). The Priestley–Taylor method calculates potential evapotranspiration from the equation

$$\lambda \rho_w ET_o = \alpha\left(\frac{\Delta}{\Delta + \gamma}\right)(Q_n - G) \tag{9}$$

where ET_o is the potential evapotranspiration [m/d], λ is the latent heat of vaporization [MJ/kg], ρ_w is the density of water [kg/m^3], Δ is the slope of the saturation vapor pressure temperature curve [kPa °C], γ is the psychrometric constant [kPa °C], Q_n is the net radiation [W/m^2], and G is the soil/canopy heat flux [W/m^2]. G is assumed to equal zero over the course of a day, and α is assumed to be a constant value of 1.26 (Priestley and Taylor, 1972). The Priestley–Taylor equation is simpler than the BREB method used in basin studies because it assumes stored heat changes are negligible (zero) and because the relationships between Q_h, Q_w, and Q_e (described in Eqs. (2)–(4)) are combined empirically in the term $\alpha\ (\Delta/(\Delta + \gamma))$.

PET values for the five largest lakes in Florida were used to evaluate the regional distribution of evaporation and net precipitation along the peninsula. Different albedo values are used for land cover and open water when computing the gridded values of net radiation (Q_n) used in the Florida Statewide ET database (Jacobs et al., 2008). Daily albedo measurements were reviewed for a variety of Florida land covers over differing time periods. Surface albedo was ultimately estimated using separate, time-constant values for the land albedo (0.149) and the water albedo (0.062), which were then applied based on the predominance of either land or water in each 2-km pixel (Jacobs et al., 2008; Mecikalski et al., 2011). Albedo for open water was used to estimate gridded value of Q_n only when open water covered 75% or more of the 2-km (400 ha) grid cell.

The majority of Florida's lakes are smaller than 60 ha, whereas a minimum lake size of 300 ha would be needed to meet the requirements of an open-water pixel in the Florida Statewide ET database, and that is assuming lake area falls within a single pixel, which it typically does not. In this study the five largest lakes on the peninsula were used to estimate lake evaporation and net precipitation to lakes at different latitudes. Open-water evaporation rates were assumed to be the comparable gridded values of potential evapotranspiration at the center of each lake. Regional lake evaporation estimates and net precipitation estimates are presented to the nearest cm.

The five natural lakes that were used to represent regional spatial variation in lake evaporation each has a surface area greater than 10,000 ha, allowing multiple pixels to fall entirely within open-water areas. The lakes are distributed from north to south through the interior of the peninsular, but only two fall inside the Central Lake District. The southernmost lake, Lake Okeechobee, lies beyond the southern limit of the lake district whereas the northernmost lake, Lake George, lies about 64 km inside its northern limit. The lakes from north to south are Lake George (190 km^2), Lake Apopka (125 km^2), Lake Kissimmee (140 km^2), Lake Istokpoga (112 km^2), and Lake Okeechobee (1770 km^2).

2.2.2. Rainfall and net precipitation

Regional net precipitation at the five largest lakes, and for the peninsula, was computed as the difference between annual average rainfall and annual average potential evapotranspiration. Gridded rainfall data were obtained from the PRISM Climate Group and were based on NOAA National Climate Data Center data for calendar years 1996 through 2011 (Daly et al., 2004; Di Luzio et al., 2008; PRISM Climate Group, 2012). The spatially-interpolated estimates have recognized uncertainties (Daly, 2006), but were preferable to shorter-term NEXRAD rainfall (Hoblit et al., 2003; NOAA, 2011a). NOAA relies on PRISM gridded surfaces of average rainfall during 1971–2000 to compute the annual departures in their radar-based (NEXRAD) rainfall data (NOAA, 2012; PRISM Climate Group, 2011).

3. Results

3.1. Basin-scale

3.1.1. Lake Evaporation

Annual average evaporation for the seven BREB sites in peninsular Florida ranged from 145.7 cm to 158.0 cm (Table 1). Evaporation averaged 20–30 cm/yr less at Lake Five-O in the northern panhandle. Evaporation was largest at Indian River Lagoon. The geographic range in average evaporation rates at the seven peninsula sites was less than the annual variation at Lake Starr over 15 years (137.6–155.0 cm/yr) (Table 2).

Evaporation was the largest water-budget component at Lake Starr on average (147.5 cm/yr), and had the least annual variation (Fig. 3). Rainfall was the second largest term (122.8 cm/yr) followed by groundwater inflow, which had the largest interannual range of the four principal water-budget terms, 30–159 cm/yr (Table 2; Fig. 3). Groundwater inflow contributed less than rainfall on the lake surface, despite the watershed's greater size, a characteristic of certain Florida lakes in mantled karst (Sacks, 2002). On average, groundwater inflow, which is assumed to include all transient runoff and groundwater flow responses to rainfall occurring along the shoreline, contributed 71% as much water to Lake Starr as rainfall. Annually, groundwater inflow contributed 31–110% as much as rainfall. Lake leakage averaged 65.6 cm/yr and ranged from 26.8 to 97.2 cm/yr, exceeding groundwater inflow in 5 years (Table 2).

Annual lake evaporation from Lake Starr showed no significant trend over time, however, seasonal evaporation during the dry-season months of October through May showed a small but statistically significant upward trend over 15 years ($R^2 = 0.31$; $p = 0.03$) (Fig. 4). Further, dry-season evaporation and rainfall totals were significantly correlated with the multivariate ENSO index (MEI) (Fig. 5). The monthly MEI values themselves showed no significant trend in time that could affect the correlation, and rainfall and evaporation monthly values were not correlated to monthly MEI climate indices.

3.1.2. Short-term and long-term balance in net precipitation and net groundwater

Net precipitation and net groundwater exchanges from Lake Starr tended to be negative in the same months and positive in the same months, on average, and so had a reinforcing instead of compensating effect on lake stage. Both terms reached their most negative values in April and May, causing the largest monthly-average decreases in lake stage (Fig. 6). Groundwater pumping from the Upper Floridan aquifer also typically peaked around April and May (Fig. 2). Both terms were most positive in August and September, and the largest increases in lake stage occurred in August. Some lag was apparent, as the month with the most positive net precipitation (August), was followed by the month with the most positive net groundwater exchange (September). The estimated surface-water withdrawals from the lake were smallest in July and August (Table 2).

Annually, net precipitation to Lake Starr averaged −24.8 cm/yr over the study period and varied from −62.8 to 49.9 cm/yr, predominantly due to the large range in annual rainfall (Fig. 3). Net precipitation was positive in 2 years of the study and negative in the other 13 years. Net precipitation during this study should be close to the average for the past 3 to 4 decades, as the average rainfall during the study (122.8 cm/yr) was within 3% of the 30-year normals for 1981–2010 and 1971–2000 at Mountain Lake NOAA site (125.9 cm/yr and 122.1 cm/yr, respectively).

Net groundwater exchange averaged 22.2 cm/yr and varied more year-to-year than net precipitation, from −67.8 to 121.7 cm/yr, due to the large variability in both groundwater inflow and lake leakage (Table 2). Although positive on average, net groundwater exchange with the lake was smaller than the net precipitation deficit, and the cumulative imbalance over 15 years was −38.5 cm (−2.6 cm/yr). Surface-water withdrawals widened the imbalance by another −103 cm (−6.9 cm/yr). Together, the imbalance between net precipitation and net groundwater exchange, including surface-water withdrawals, reduced lake stage by −141.7 cm over the study period. Annually, the imbalance between net precipitation and net groundwater

Table 2
Annual and cumulative Lake Starr water budget for 15 years, and the cumulative water budget for a sustainable decade. [All values are in centimeters per year (cm/yr) unless noted; m^3/yr, cubic meters per year; UFA, Upper Floridan aquifer; GW, groundwater].

Study year	12-Month period	UFA withdrawals (million m^3/yr)	Lake withdrawals	Rain	Evaporation	Net precipitation	GW inflow	Lake leakage	Net GW exchange	Imbalance (net precip + net GW)	Total change in lake volume
1	August 1996–July 1997	2.72	5.9	128.7	145.0	−16.3	89.8	79.7	10.1	−6.2	−12.0
2	August 1997–July 1998	3.87	7.4	137.3	141.9	−4.7	101.9	58.7	43.3	38.6	31.1
3	August 1998–July 1999	4.76	7.0	103.7	143.7	−40.0	57.8	90.7	−32.9	−72.9	−79.9
4	August 1999–July 2000	5.13	8.8	92.0	151.8	−59.8	46.5	93.7	−47.2	−107.0	−115.8
5	August 2000–July 2001	4.55	8.4	88.4	148.5	−60.1	79.3	80.8	−1.4	−61.5	−69.9
6	August 2001–July 2002	3.11	6.3	138.9	141.9	−3.0	116.8	43.2	73.6	70.6	64.3
7	August 2002–July 2003	2.40	4.7	169.0	137.6	31.4	131.1	26.8	105.4	136.7	132.1
8	August 2003–July 2004	2.67	6.8	124.4	144.7	−20.3	57.8	53.7	5.0	−15.3	−22.1
9	August 2004–July 2005	1.83	5.5	191.1	141.2	49.9	158.8	38.0	121.7	171.6	166.1
10	August 2005–July 2006	2.91	7.5	106.1	151.8	−45.7	95.1	66.2	30.5	−15.2	−22.7
11	August 2006–July 2007	3.11	7.1	96.0	155.0	−59.0	29.5	97.2	−67.8	−126.8	−133.8
12	August 2007–July 2008	3.91	6.8	119.1	154.7	−35.6	51.5	83.1	−31.6	−67.2	−74.0
13	August 2008–July 2009	3.47	7.9	91.6	154.3	−62.8	103.2	54.7	48.5	−14.2	−22.1
14	August 2009–July 2010	3.43	5.4	123.8	147.5	−23.6	84.9	64.8	20.1	−3.6	−9.0
15	August 2010–July 2011	4.21	7.7	131.2	153.2	−22.1	108.0	52.1	55.9	33.8	26.2
15-Year cumulative (cm)		52.1 (million m^3)	103.2	1841.3	2212.9	−371.5	1312.0	983.4	333.1	−38.5	−141.7
15-Year annual average		3.5	6.9	122.8	147.5	−24.8	87.5	65.6	22.2	−2.6	−9.4
Sustainable decade annual average (April 1997–March 2007)		3.4	6.9	127.2	145.3	−18.1	88.9	64.4	24.9	6.9	0.0

exchange varied more than either term individually, from −126.8 cm/yr to +171.6 cm/yr, as the two terms could either offset one another or be additive (Table 2).

Of the 13 years with a net precipitation deficit, net groundwater exchange balanced the deficits in 3 years (years 2, 6, and 15; Table 2). Net groundwater exchange was too small to balance the deficit in the other 10 years. The net groundwater exchange itself was negative in 5 of the 15 study years. The rate of recurrence of negative net groundwater exchange suggests risks to the sustainability of the long-term average lake stage of Lake Starr. Years with negative net groundwater exchange and negative net precipitation caused the greatest annual declines in lake stage.

3.1.3. Sustainable balance

Sustainable conditions were evident at Lake Starr for a 10-year period from April 1997 to March 2007, as this was a period that began and ended with the same lake stage (31.88 m or 104.59 ft National Geodetic Vertical Datum of 1929 (NGVD 29) (Sacks et al., 2014, supplemental tables). The sustainable period included wet climate extremes associated with El Niño (years 2, 7, and 9 in Table 2) (Virdi et al., 2013). Annual rainfall was 4.4 cm/yr greater on average in this period than during the 15-year period, and lake evaporation averaged about 2.2 cm/yr less. Annual net precipitation averaged −18.1 cm/yr in the sustainable period compared with −24.8 cm/yr over all 15 years. Groundwater pumping from

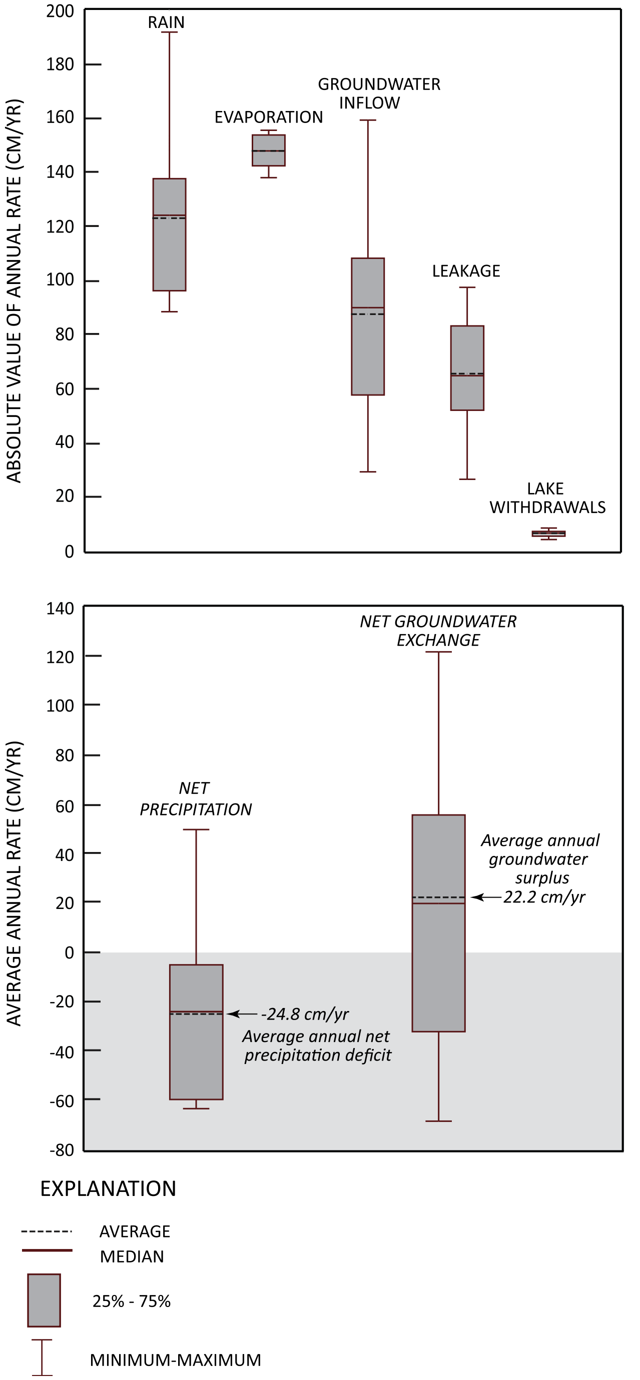


Fig. 3. Box and whisker plots showing the statistical distribution of annual water-budget components for Lake Starr over the 15 study years.

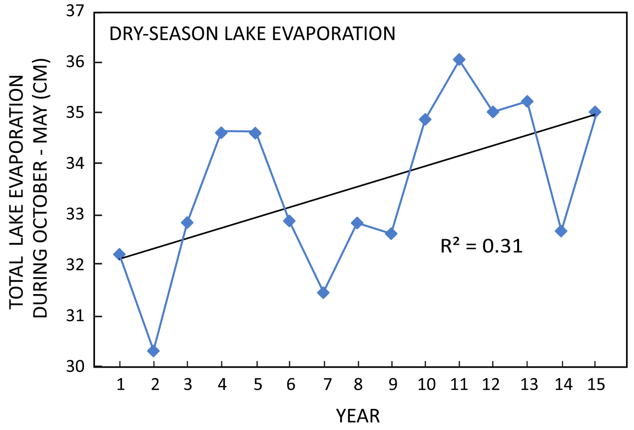


Fig. 4. Upward trend in the dry-season evaporation at Lake Starr.

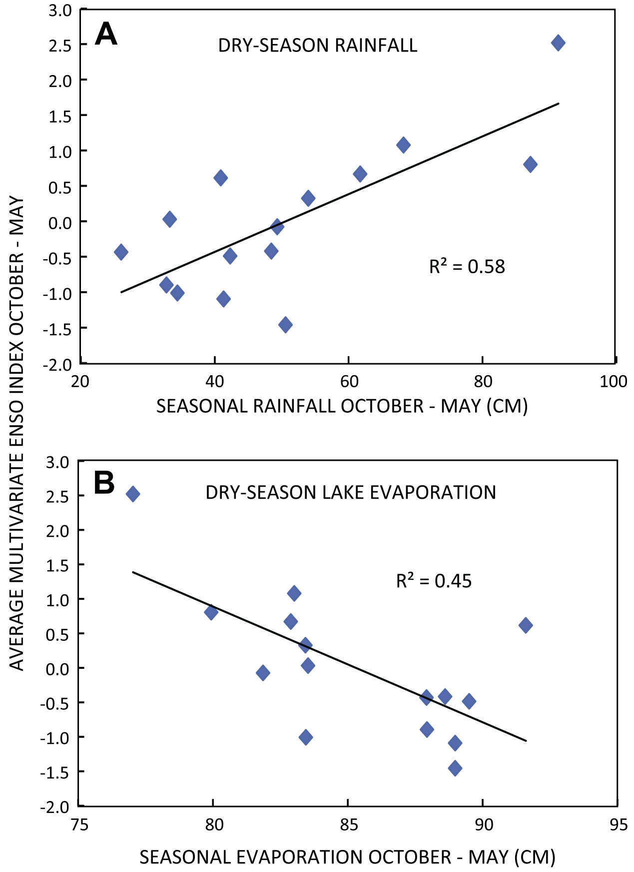


Fig. 5. Correlation between the dry season multivariate ENSO index (MEI) and (A) rainfall and (B) lake-evaporation totals.

the Upper Floridan aquifer was similar for both the 10-year and 15-year periods based on annual averages (3.40 million m^3/yr and 3.47 million m^3/yr, respectively), although individual years vary widely. Monthly average groundwater levels in the Upper Floridan aquifer for both periods were also similar (31.7 m and 31.8 m NGVD 29, respectively) at ROMP 57, a continuously monitored well located 6.8 km from the lake (Virdi et al., 2013). Average net groundwater exchange was greater during the sustainable decade (24.9 cm/yr) than for the 15 years (22.2 cm/yr), due mainly to years 7 and 9, when groundwater inflows were largest and leakage losses were smallest. Net groundwater exchange during this period balanced the net precipitation deficit and surface-water withdrawals from the lake despite ambient groundwater-pumping effects.

Lake Starr stage is sustained by importing net water from the watershed. For that reason, water exported from the lake or watershed can have a measurable effect on lake stage over time. This sensitivity was explored hypothetically at Lake Starr by recomputing lake volume (lake stage in the linear values used here) after making small changes to groundwater flows and surface-water withdrawals. The conceptual analysis ignores the effect of lake stage changes on subsequent groundwater fluxes. In the measured water budget, lake stage declined −141.7 cm after

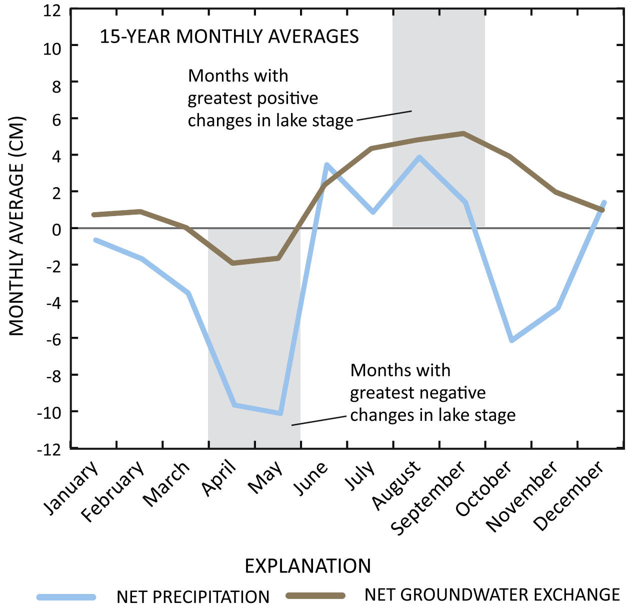


Fig. 6. Monthly average values of net groundwater exchange and net precipitation at Lake Starr over 15 years.

15 years. Eliminating surface-water withdrawals in the conceptual analysis makes little difference in the lake stage for the first several years, but ultimately reduces the cumulative stage decline to −38 cm (Fig. 7A). If, at the same time, the monthly groundwater inflow is increased by 2% and monthly lake leakage is decreased by 2%, the stage change would be a 4-cm rise after 15 years (Fig. 7B). Conversely, keeping the surface-water withdrawals and decreasing groundwater inflow by 2% while increasing lake leakage by 2%, increases the observed stage decline by another 50 cm, to −192 cm (Fig. 7B). The conceptual analysis likely overestimates the actual stage changes in both directions by not including the feedback between lake stage and groundwater exchanges. However, the feedback effect may not be large as rainfall controls groundwater inflow and lake leakage magnitudes more than lake stage change, and the two groundwater terms tend to reinforce, not offset, one another in lowering and raising annual lake stage.

3.2. Regional scale

Potential evapotranspiration over the five largest lakes, from north to south, varied from 147 cm/yr at Lake George to 168 cm/yr at Lake Okeechobee, a range of about 21 cm (Fig. 8). Potential evapotranspiration at Lake Kissimmee (155 cm/yr), located at roughly the same latitude as Lake Starr, was about 5% greater than Lake Starr (about 148 cm/yr) and within the range of its annual values (Tables 2 and 3). Regional potential evapotranspiration rates for land grid cells were less than for water at the same latitude due to higher albedo for land (Fig. 8). Potential evapotranspiration over land surface ranged from about 120 cm/yr at the northern end of the Central Lake District to over 135 cm/yr at the southern end.

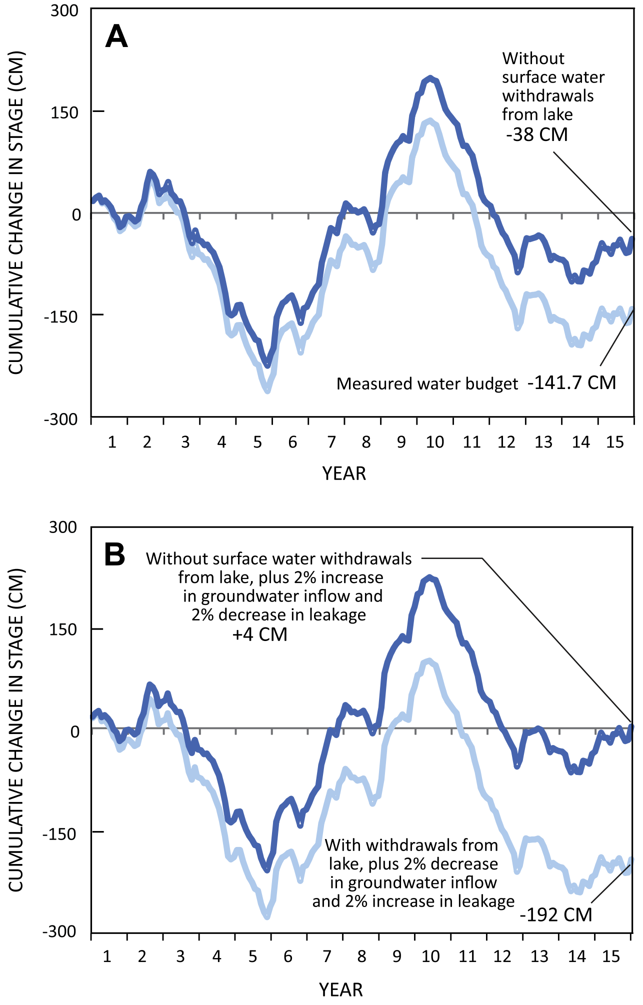


Fig. 7. The hypothetical effect of small changes in monthly groundwater exchanges and surface-water withdrawals on Lake Starr stage when accumulated over 15 years.

Lake evaporation at the seven basin-scale sites was comparable to the gridded values of potential evapotranspiration for the five largest lakes, but lacked the clear north-to-south increase (Table 3). Among the basin-scale sites, Indian River Lagoon had the highest measured evaporation (158.0 cm/yr) rate and the lowest rainfall, whereas, among regional sites, Lake Okeechobee had the highest evaporation rate (168 cm/yr) and lowest rainfall. Both of these expansive open-water areas likely had less cloud cover than adjacent land areas (Henry and Dicks, 1985). Abtew (2001) made basin-scale estimates of evaporation for Lake Okeechobee from 1993 to 1998 based on the Priestley–Taylor and Penman models that averaged 153.4 cm/yr and 156.7, respectively, in a study where net radiation and climate parameters were measured over the lake surface. Evaporation from Florida Bay, an estuary off of Florida's southern coast, was 163 cm/yr based on a Priestley–Taylor model and *in situ* net radiation and climate measurements (Price et al., 2007).

Regional estimates of net precipitation to lakes and other open-water areas large enough to be represented in 2-km gridded values are negative throughout the central peninsula (Fig. 9 and Table 3). Average annual net precipitation varied from −16 cm/yr at Lake George to −48 cm/yr at Lake Okeechobee (Table 3). The measured net precipitation for Lake Starr, −24.8 cm/yr, is within 10% of the regional net precipitation of −23 cm/yr at nearby Lake Kissimmee (Fig. 9). Negative net precipitation estimates also occur in the northeast corner of Florida. Most of the variation in net precipitation to lakes in the central peninsula was dictated by spatial variation in potential evapotranspiration instead of rainfall. The 30-year rainfall average (1971–2000) is similar between Lake George and Lake Istokpoka, at around 130 cm/yr (Table 3). Farther south, Lake Okeechobee received about 10 cm/yr less rainfall on average than the other four lakes, and lost about 10 cm/yr more to evaporation (Table 3). Site 13, the basin-scale BREB site in the Everglades, received the largest annual rainfall of all sites on the peninsular and had slightly positive net precipitation. This site

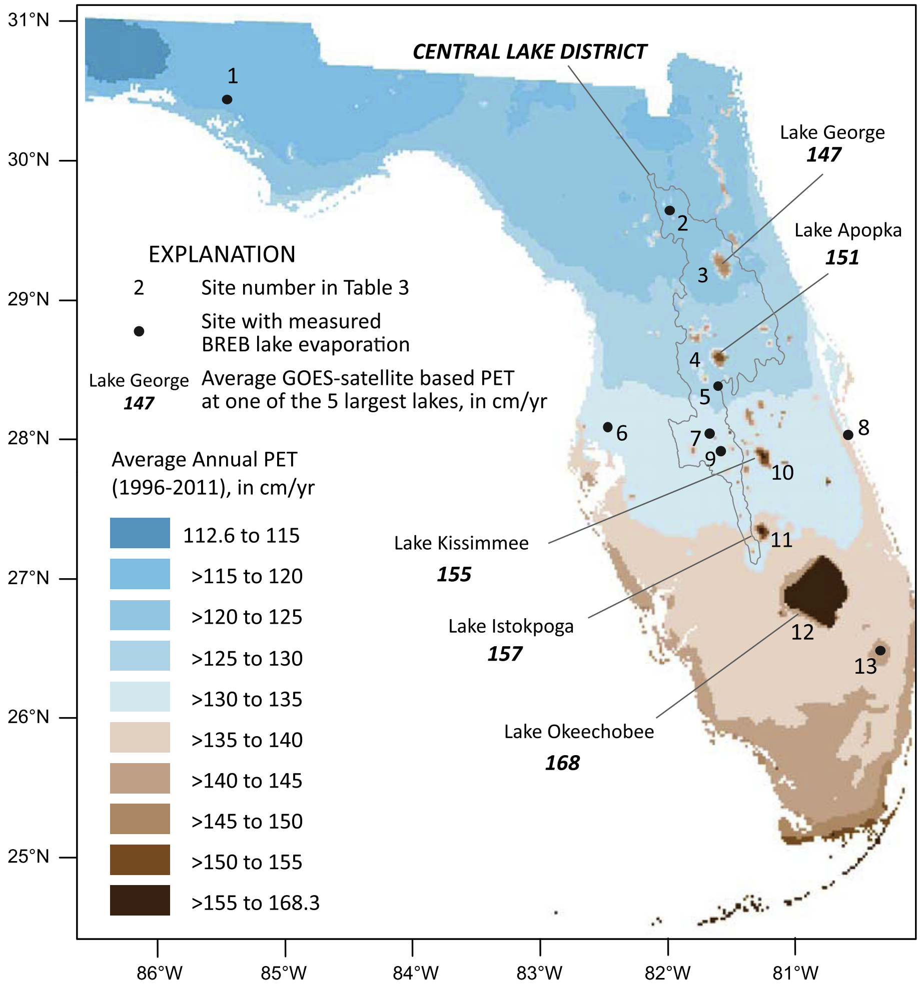


Fig. 8. Annual average potential evapotranspiration during 1996–2011 for peninsular Florida and part of the panhandle.

was the farthest southeast of all of the BREB sites and is in an area where the net precipitation over land is positive on the regional map (Fig. 9).

The annual average net precipitation to lakes and other open-water areas was consistently negative throughout the interior of the peninsula and the Central Lake District. However, net precipitation over the land surface shifted from being positive over roughly the northeastern third of the lake district, to being negative over the southwestern two-thirds, including Lake Starr (Fig. 9). Unlike open water, net precipitation rates computed over land define a conceptual minimum in available water, not an estimate of actual net precipitation, as the actual evapotranspiration is typically substantially less than potential evapotranspiration (Douglas et al., 2009; Sumner and Jacobs, 2005). Regional differences in the minimum net precipitation over land, however, reveal relatively greater amounts of atmospheric water available for groundwater recharge in northern lakes basins compared to southern basins (Reilly et al., 2008).

4. Discussion

The results of the study indicate lakes throughout the interior of peninsular Florida receive negative net precipitation. This finding overturns the long-held perception that net precipitation is positive for lakes in the Central Lake District of Florida, and can be negative only farther south in the Everglades, Lake Okeechobee, and the Florida Keys (e.g., Deevey, 1988; Henry, 1998). The long-term evaporation results at Lake Starr corroborated results from shorter-term basin-scale studies in Florida that used similar BREB methods. The small standard deviation in the annual average evaporation at Lake Starr, despite the historic extremes in annual rainfall, suggest that several years of basin-scale BREB lake evaporation can provide a rough approximation of the longer-term average. Study findings resolve that lakes in the peninsular lake district of Florida are net importers of water from their watersheds. Seepage lakes, the most prevalent lake type, are sustained by a positive net groundwater exchange: a net inflow of groundwater. Their reliance on net groundwater inflow emphasizes the susceptibility of lakes in this region of the US to stage declines due to groundwater pumping and surface-water withdrawals that export water from their watersheds, and their susceptibility to drier climate trends that increase the net precipitation deficit.

4.1. Comparing basin-scale and regional lake evaporation

The satellite-based regional estimates of potential evapotranspiration at the five largest lakes in peninsular Florida were comparable to lake evaporation from seven basin-scale studies when both were viewed as annual averages. The agreement between results from the energy-budget method and Priestley–Taylor method indicates that the net radiation term primarily controls the evaporation rates for both methods when other terms are averaged long

Table 3
Basin-scale and regional estimates of evapotranspiration and net precipitation from north to south for selected lakes and open-water sites in Florida. [Sites listed from north to south; all values are in centimeters per year (cm/yr) unless noted; normal text values are from BREB-measured sites; ***italicized bold*** values are satellite-based regional estimates; NOAA, National Oceanographic and Atmospheric Administration; PET, potential evapotranspiration from the Florida ET Database; ddmmss, degrees minutes seconds].

Site number Shown on Fig. 8	Lake name	Latitude (ddmmss)	Longitude (ddmmss)	PET (1996–2011) or measured lake evaporation	Rainfall PRISM 16-yr average (1996–2011)	Net precipitation 16-yr average (1996–2011)	Rainfall PRISM 30-yr average (1971–2000)	Representative long-term net precipitation (1971–2000)
1[a]	Lake Five-O	302518	852518	127.6			164	36
2	Lake Barco	294034	820030	151.2			132	−19
3	***Lake George***	***291658***	***813537***	***147***	***127***	***−20***	***131***	***−16***
4	***Lake Apopka***	***283733***	***813729***	***151***	***128***	***−23***	***130***	***−21***
5	Reedy Lake	282457	813648	150.9			129	−22
6	Lake Calm	280820	823200	153.4			132	−22
7	Lake Lucerne	280444	814100	147.1			129	−18
8	Indian River Lagoon	280340	803440	158.0			118[b,c]	−40
9	Lake Starr	275724	813516	147.5		−24.8	127	−21
10	***Lake Kissimmee***	***275522***	***811610***	***155***	***132***	***−23***	***133***	***−22***
11	***Lake Istokpoga***	***272210***	***811649***	***157***	***123***	***−34***	***129***	***−28***
12	***Lake Okeechobee***	***265533***	***804958***	***168***	***117***	***−51***	***120***	***−48***
13	Everglades Open Water #3	263740	802612	145.7			149	4

[a] Located in the panhandle of Florida.
[b] PRISM rainfall not available for offshore locations.
[c] Rainfall is average at NOAA station, Melbourne, FL, used in Sumner and Belaineh (2005).

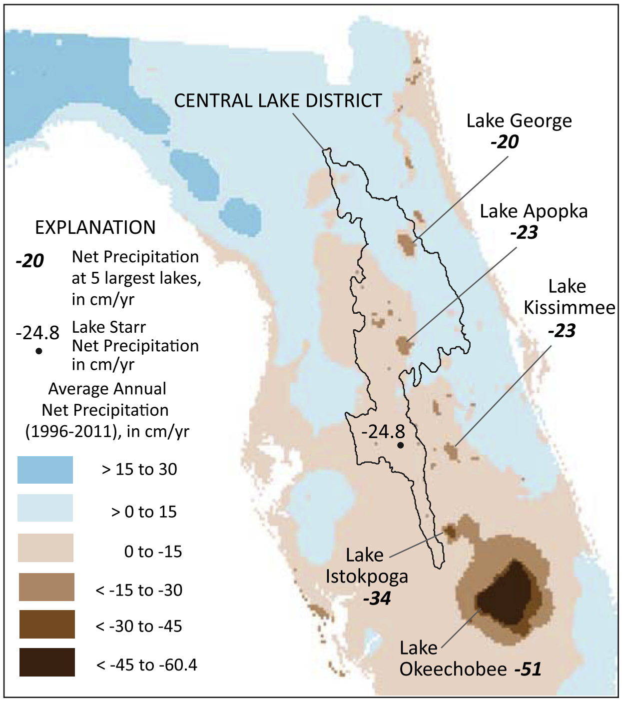


Fig. 9. Annual average net precipitation for the five largest lakes in peninsular Florida.

term. Stored heat effects that are ignored in the Priestley–Taylor method should also be negligible over the long-term average in estimates made using the BREB method. The assumption of a constant daily albedo used to determine the net radiation values used in the Priestley–Taylor method generated results that were similar to BREB estimates on an annual average basis, but discrepancies would be likely on a monthly or seasonal basis (Jacobs et al., 2008; Sumner et al., 2011).

The constant albedo may not be representative of atypical lakes. For example, at an expansive, shallow spring-fed lake located outside the Central Lake District, higher albedo attributed to whitish carbonate sediments that resuspended in the water column resulted in annual BREB evaporation rates of around 115 cm/yr (McBride et al., 2011). Evaporation from Lake Okeechobee is probably greater than evaporation from smaller water bodies at the same latitude because the lake's large size inhibits cloud formation (Henry and Dicks, 1985). As a result, Lake Okeechobee receives less rainfall and more insolation than adjacent areas and has the highest net precipitation deficit of any lake on the peninsula. The overall agreement in evaporation values from both methods reflects their ability to account for cloud cover by using either directly measured or satellite-based estimates of ground-level net radiation. Diminished cloud cover also may affect evaporation and net precipitation rates from closely-spaced smaller lakes in the Central Lake District, as less cumulus cloud cover was observed in satellite images over the "southeast-northwest oriented string of lakes near the center of the state" (Henry and Dicks, 1985).

4.2. Implications for sustainable lake-groundwater interactions

The inherent long-term balance between net precipitation, net groundwater exchange, and lake stage in seepage lakes can be used to draw inferences about sustainable lake-groundwater exchanges across the geographically large Central Lake District (Fig. 10). The increase in the net precipitation deficit with distance southward across the district suggests that net groundwater exchanges with lakes become more positive moving southward to maintain long-term stage equilibrium. That is, the quantity by which groundwater inflow exceeds lake leakage is greater, on average, for lakes in the southern part of the Central Lake District than for lakes farther north. Southern lakes do not have to receive more groundwater inflow than northern lakes to make their net groundwater exchanges more positive; they could simply leak substantially less relative to the groundwater inflow they receive. Or they could do both; gain comparatively more groundwater inflow and leak comparatively less.

Lakes farther north in the Central Lake District have a smaller net precipitation deficit that can be balanced by a smaller positive net groundwater exchange. To experience less net groundwater inflow, northern lakes could receive comparatively less groundwater inflow than southern lakes, or could leak comparatively faster relative to the inflow they receive, or both. Basins that surround lakes in the northern Central Lake District receive positive annual net precipitation, whereas the basins surrounding southern lakes receive negative net precipitation. The difference suggests that northern lake basins could have more recharge to the surficial aquifer and more groundwater inflow to lakes than southern lake basins in equivalent settings. If northern lakes receive comparatively more groundwater inflow, they would need to leak faster than southern lakes to maintain lake stage over the long term. If basin recharge is greater but northern lakes receive comparatively less groundwater inflow than southern lakes, then groundwater inflow is being lost, potentially by downward leakage in the surrounding basin. This reasoning, however, again would imply that northern lakes occupy a leakier hydrogeologic setting than southern lakes. By similar logic, if the surficial aquifer in the southern end of the Central Lake District receives less recharge and generates less groundwater inflow to lakes, southern lakes, as a group, would have to leak comparatively less than northern lakes to be sustained in the landscape. If southern lakes occupy basins that leak less, it could increase the groundwater inflow they receive despite less recharge to the basin.

Finally, in the panhandle of Florida, the regional net precipitation to lakes and lake basins is markedly positive, implying that seepage lakes in this region export net water to groundwater to maintain lake stage. That is, losses due to lake leakage are greater than groundwater inflow on average. In a detailed 2-year water budget for Lake Five-O, the only seepage lake in the panhandle with BREB evaporation measurements, lake leakage did exceed groundwater inflow (Grubbs, 1995; Pollman et al., 1991).

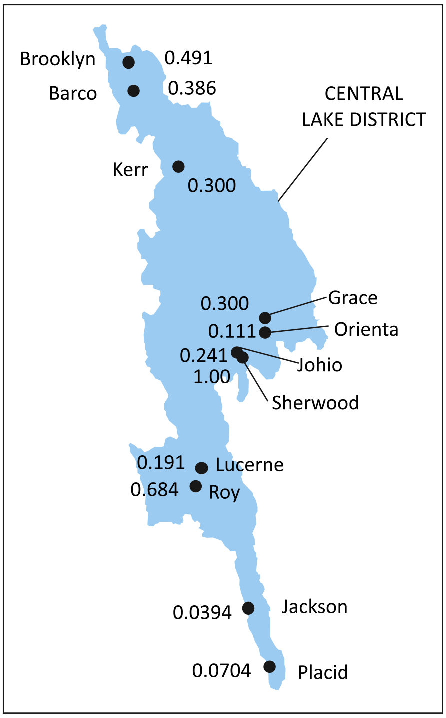


Fig. 10. Vertically-averaged vertical hydraulic conductance for lakes in units of [yr^{-1}] from Motz (1998) shown mapped onto the Central Lake District.

4.3. Inferences about regional and local hydrogeologic characteristics

The large regional variation in net precipitation to lakes and lake basins along the Florida peninsula suggests regional differences in the hydrogeologic setting that controls groundwater exchanges with seepage lakes. The requirement for greater net groundwater inflow to lakes in the southern Central Lake District could be met, irrespective of differences in groundwater recharge, if the hydrogeologic characteristics of the basin tended to increase the groundwater inflow to these lakes and decrease lake leakage compared to basins farther north (Lee, 2002). Sacks (2002) quantified the steady-state groundwater inflow rates to 47 seepage lakes scattered in the southern third of the Central Lake District and found that lakes with the greatest groundwater inflow rates, defined as receiving more than 50% of the total (rainfall plus groundwater) inflow from groundwater, were concentrated farthest south. This shared water-budget characteristic, and the preponderance of comparatively deep lakes in this subgroup, could reflect the physical prerequisites for lakes to persist in this region, where net precipitation deficits are greatest.

In a statistical analysis of factors explaining the variability of stage fluctuations in lakes in west-central Florida, many of the variables in final regression models were related to hydrogeologic characteristics (Sacks et al., 2008). Some factors were site specific, such as groundwater pumping near the lake and the magnitude of negative net groundwater exchange, whereas others were regional in nature, such as the thickness of the intermediate confining unit and the head gradient between the lake and the Upper Floridan aquifer. The statistical significance of regional hydrogeologic characteristics alludes to the importance of regional factors in controlling lake-groundwater interactions within the peninsular lake district, in addition to the importance of local basin-scale characteristics such as lake depth.

Field studies currently provide limited evidence to argue regional difference in the net groundwater exchanges and hydrogeologic settings of northern lakes compared to southern lakes. The hydraulic conductance of the geologic units directly underlying sinkhole lakes may decrease with distance south. Motz (1998) used published leakage rates for 11 lakes to compute the “vertically-averaged vertical hydraulic conductance” of the column of material between the lake bottom and the top of the Upper Floridan aquifer. When these values are mapped, two exceptionally leaky lakes (Sherwood and Roy) appear in the center of the Central Lake District; possibly because lakes with large stage declines tended to be the focus of studies. Other values generally decrease from north to south; lakes with the smallest vertical hydraulic conductance values are farthest south, whereas lakes farthest north have relatively large vertical hydraulic conductance values (Fig. 10).

Groundwater pumping effects can override the basin hydrogeologic characteristics that cause positive net groundwater exchanges with a lake, and lead to negative net groundwater exchanges instead. This effect appears to be happening at Lake Starr, which lost more water to leakage than it gained by groundwater inflow in 5 of the 15 years studied. Is annual lake leakage naturally greater than groundwater inflow at this frequency? Or is the frequency of negative net groundwater exchange a consequence of groundwater pumping in and around the basin? Net groundwater exchanges were positive in the remaining 10 years, but were only able to offset negative net precipitation in 3 of those 10 years. Small changes in the monthly rates of leakage and groundwater inflow – changes that increasing or decreasing pumping can plausibly cause – could substantially alter the long-term stage of Lake Starr. As of 2005, more groundwater was withdrawn from the Upper Floridan aquifer in the southern counties of the Central Lake District than in its northern counties (Marella, 2009; Southwest Florida Water Management District, 2013). However, if lakes of the northern Central Lake District occupy comparatively leakier hydrogeologic settings than lakes farther south, as this analysis suggests, northern lakes could be more, not less, vulnerable to groundwater pumping effects than southern lakes like Lake Starr. Surface-water withdrawals from Lake Starr were a small part of the annual water budget, but contributed to stage declines. The practice intensifies the problem of maintaining the long-term average stage for Lake Starr and other lakes that import net water to balance deficit net precipitation.

4.4. Context to climate variability and change

Exploring the long-term balance between net precipitation, net groundwater exchange, and sustainable lake levels also requires understanding the variability of climate over longer time period than the 15 years of this study. The Atlantic Multidecadal Oscillation (AMO) occurs over 30- to 70-year warm and cool phases that create wetter and drier climate conditions in Florida. This study period occurred within a warm phase of the AMO that began in 1996. Warm phases are associated with increased tropical storm activity in peninsular Florida and above-average rainfall (Enfield et al., 2001; Kelly and Gore, 2008). In addition, the climate is expected to change throughout the 21st century because of anthropogenic climate change (IPCC, 2012). Much uncertainty remains as to exactly how these changes will manifest in Florida because of the complexity of ocean-atmospheric circulation processes that influence local conditions. Current projections of deceased rainfall coupled with higher evaporation, however, would result in greater deficit net precipitation over this century and lower lake stages than under current conditions (Misra et al., 2011; Selman et al., 2013; USGCRP, 2009).

5. Conclusions

The balance between net precipitation and net groundwater exchange was explored in the Central Lake District of peninsular Florida using a 15-year water budget for a representative lake, and using regionalized, satellite-based estimates of lake evaporation and net precipitation for the same period for the Florida peninsula. The main findings from the analysis are:

1. Lakes in the Central Lake District, and more generally in the interior of peninsular Florida, receive deficit net precipitation over the long-term average, not positive net precipitation as previously thought. At Lake Starr, in the southern half of the lake district, the average measured net precipitation deficit over 15 years was about −25 cm/yr. From north to south within the latitudinal range of the Central Lake District, the regional net precipitation deficits to lakes for 1996–2011 ranged from −20 cm/yr at Lake George to −34 cm/yr at Lake Istokpoga. The net precipitation deficit farther south at Lake Okeechobee was −51 cm/yr.
2. The revised view of net precipitation to lakes is derived from improved estimates of open-water evaporation at the basin and regional scales that used daily net radiation at the land or water surface. For lakes in peninsular Florida, basin-scale evaporation estimated using BREB methods, and regional evaporation estimates computed using a form of the Priestley–Taylor method, were all consistently greater than 140 cm/yr and values ranged from about 146 to 158 cm/yr. Regional evaporation at Lake Okeechobee, south of the Central Lake District, was markedly higher at about 168 cm/yr.
3. Potential evapotranspiration estimates in the Florida Statewide Evapotranspiration database, at 2-km grid cells that represent open water, provide a reasonable proxy for lake evaporation measured by the BREB method in basin-scale studies when both estimates are averaged over multiple years. During 1996–2011, regional lake evaporation for Lake Kissimmee, at the same approximate latitude as Lake Starr, was within 5% of the BREB-measured average at Lake Starr, and the regional net precipitation agreed within 10% of the basin-scale estimate.
4. Lakes in peninsular Florida are net importers of water from their watersheds. This means that for seepage lakes, the dominant lake type in Florida, to be sustainable over the long term, they must gain more groundwater inflow (including nearshore runoff) from their basins than they lose to lake leakage. The amount of net groundwater inflow must equal the net precipitation deficit on average to sustain lake levels over the long-term. This revised view of the peninsular lake district reveals lakes in the region to be more vulnerable than previously realized to drier climate, surface-water withdrawals, and groundwater pumping.
5. Net groundwater exchanges with Lake Starr are being reduced by groundwater pumping effects. Currently the lake is not importing sufficient net groundwater inflow from its basin to balance the net precipitation deficit. Surface-water withdrawals from the lake increase the imbalance.
6. Latitudinal differences in the regional net precipitation to lakes in peninsular Florida suggest that latitudinal differences exist in both the magnitude of net groundwater exchanges to lakes and the hydrogeologic settings of lakes. Results indicate net groundwater exchanges are comparatively more positive at seepage lakes in the southern end of the Central Lake District. Findings further suggest that lakes in the northern end of the Central Lake District are in comparatively leakier hydrogeologic settings.

Acknowledgements

This study and the long-term study of Lake Starr were the result of funding by the Southwest Florida Water Management District through the U.S. Geological Survey Cooperative Water Program. The authors gratefully acknowledge the land owners in the Lake Starr basin who allowed us to use their property, and the members of Lake of the Hills Community Club. We also thank Jennifer Jacobs (Univ. New Hampshire), David Sumner, Barclay Shoemaker, Rick Spechler (USGS), and three anonymous reviewers for their reviews of the manuscript.

References

Abtew, W., 2001. Evaporation estimation for Lake Okeechobee in Southern Florida. J. Irrig. Drain. Eng., 140–147.

Abtew, W., Melesse, A., 2012. Lake evaporation. In: Abtew, W., Melesse, A. (Eds.), Evaporation and Evapotranspiration: Measurements and Estimations. Springer Science + Business Media, Dordrecht Netherlands, p. 206.

Allander, K.K., Smith, J.L., Johnson, M.J., 2009. Evapotranspiration From the Lower Walker River Basin, West-Central Nevada, Water Years 2005–2007: U.S. Geol. Surv. Scientific Investigations Report 2009–5079; pp. 62.

Anderson, E.R., 1954. Energy-budget studies, in Water-loss investigations: Lake Hefner studies, technical report: U.S. Geol. Surv. Professional Paper 269, 71–119, <http://pubs.er.usgs.gov/publication/pp269>.

Barcelo, M.D., Slonena, D.L., Camp, S.C., Watson, J.D., 1990. Ridge II, A Hydrogeologic Investigation of the Lake Wales Ridge. Southwest Florida Water Management District, Brooksville, Florida; pp. 121.

Brenner, M., Binford, M.W., Deevey, E.S., 1990. Lakes. In: Myers, R.L., Ewel, J.J. (Eds.), Ecosystems of Florida. University of Central Florida Press, Orlando, pp. 364–391.

Brutsaert, W., 1982. Evaporation into the Atmosphere. Kluwer Academic, Dordrecht The Netherlands, pp. 299.

Bush, P.W., Johnston, R.H., 1988. Ground-Water Hydraulics, Regional Flow, and Ground-Water Development of the Floridan Aquifer System in Florida and in

Parts of Georgia, South Carolina, and Alabama: U.S. Geol. Surv. Professional Paper 1403-C; pp. 80.

Chen, E., Gerber, J.F., 1990. Climate. In: Meyers, R.L., Ewel, J.J. (Eds.), Ecosystems of Florida. University of Central Florida Press, Orlando, pp. 11–34.

Choquette, A.F., Kroening, S.E., 2009. Water Quality and Evaluation of Pesticides in Lakes in the Ridge Citrus Region of Central Florida. U.S. Geol. Surv. Scientific Investigations, Report 2008–5178; pp. 55.

Daly, C., 2006. Guidelines for assessing the suitability of spatial climate data sets. Int. J. Climatol. 26, 707–721.

Daly, C., Gibson, W.P., Doggett, M., Smith, J., Taylor, G., 2004. Up-to-date monthly climate maps for the conterminous United States. In: Proc., 14th AMS Conf. on Applied Climatology, 84th AMS Annual Meeting Combined Preprints, Amer. Meteorological Soc., Seattle. <http://prism.oregonstate.edu/pub/prism/docs/appclim04- uptodate_monthly_climate_maps-daly.pdf>.

Deevey Jr., E.S., 1988. Estimation of downward leakage from Florida lakes. Limnol. Oceanogr. 33, 1308–1320.

Di Luzio, M., Johnson, G.L., Daly, C., Eisheid, J.K., Arnold, J.G., 2008. Constructing retrospective gridded daily precipitation and temperature datasets for the conterminous United States. J. Appl. Meteorol. Climatol. 47, 475–497.

Douglas, E.M., Jacobs, J.M., Sumner, D.M., Ray, R.L., 2009. A comparison of models for estimating potential evapotranspiration for Florida land cover types. J. Hydrol. 373, 366–376.

Enfield, D.B., Mestas-Nunez, A.M., Trimble, P.J., 2001. The Atlantic multi-decadal oscillation and its relation to rainfall and river flow in the continental U.S. Geophys. Res. Lett. 28, 277–280.

Farnsworth, R.K., Thompson, E.S., Peck, E.L., 1982. Evaporation atlas for the contiguous 48 United States. National Oceanic and Atmospheric Administration Technical Report NWS 33; pp. 26.

Finch, J.W., Hall, R.L., 2005. Evaporation from lakes. In: Anderson, M.G. (Ed.), Encyclopedia of Hydrological Sciences. John Wiley and Sons.

German, E.R., 2000. Regional Evaluation of Evapotranspiration in the Everglades. U.S. Geol. Surv. Water-Resources Investigations, Report 00-4217; pp. 48.

Griffith, G.E., Canfield, D.E., Horsburgh, C.A., Omernik, J.M., 1997. Lake regions of Florida. U.S. Environmental Protection Agency Report EPA/R-97/127. National Health and Environmental Effects Research Laboratory, Corvallis, Oregon; pp. 89.

Grubbs, J.W., 1995, Evaluation of Ground-Water Flow and Hydrologic Budget for Lake Five-O, a Seepage Lake in Northwestern Florida, U.S. Geol. Surv. Water-Resources Investigations, Report 94-4145; pp. 41.

Healy, R.W., Winter, T.C., LaBaugh, J.W., Franke, O.L., 2007, Water budgets: Foundations for Effective Water-Resources and Environmental Management, U.S. Geol. Surv. Circular 1308; pp. 90.

Henry, J.A., 1998. Weather and climate. In: Fernald, E.A., Purdum, E.D. (Eds.), Water Resources Atlas of Florida. Institute of Science and Public Affairs, Florida State University, Tallahassee, Florida, p. 312.

Henry, J.A., Dicks, S.E., 1985. Land-water cloud cover contrasts over Florida. Natl. Weather Dig. 10, 15–16.

Hoblit, B.C., Castello, C., Liu, L., Curtis, D., 2003. Creating a seamless map of gage-adjusted radar rainfall estimates for the state of Florida. In: Proceedings of the EWRI World Water and Environmental Congress, Philadelphia, Pennsylvania, June 23–26, 2003. http://dx.doi.org/10.1061/40685(2003)215.

IPCC, 2012. Summary for policymakers. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, New York, NY, pp. 1–19.

Jacobs, J.M., Mecikalski, J., and Paech, S., 2008. Satellite-based Solar Radiation, Net Radiation, and Potential and Reference Evapotranspiration Estimates over Florida. Technical Report (accessed 28.03.13) <http://fl.water.usgs.gov/et/publications/GOES_FinalReport.pdf>.

Kelly, M.H., Gore, J.A., 2008. Florida river flows and the Atlantic multidecadal oscillation. River Res. Appl. 24, 598–616.

Kindinger, J.L., Davis, J.B., Flocks, J.G., 1999. Geology and evolution of lakes in north-central Florida. Environ. Geol. 38, 301–321.

Kohler, M.A., Nordenson, F.J., Baker, D.R., 1959. Evaporation maps for the United States. U.S. Weather Bureau Technical Paper 37.

Langbein, W.B., 1951. Research on Evaporation from Lakes and Reservoirs. International Association of Scientific Hydrology Assemblee Generale de Bruxelles, vol. 4, pp. 409–425.

Lee, T.M., 2000. Effects of nearshore recharge on groundwater interactions with a lake in mantled karst terrain. Water Resour. Res. 36, 2167–2182, http://dx.doi.org/10.1029/2000WR900107.

Lee, T.M., 2002. Factors Affecting Ground-Water Exchange and Catchment Size for Florida Lakes in Mantled Karst Terrain. U.S. Geol. Surv. Water-Resources Investigations, Report 02-4033; pp. 54.

Lee, T.M., Swancar, A., 1997. Influence of Evaporation, Ground Water, and Uncertainty in the Hydrologic Budget of Lake Lucerne, a Seepage Lake in Polk County, Florida. U.S. Geol. Surv. Water-Supply Paper 2439; pp. 61.

Lenters, J.D., Kratz, T.K., Bowser, C.J., 2005. Effects of climate variability on lake evaporation: Results from a long-term energy budget study of Sparkling lake, northern Wisconsin (USA). J. Hydrol. 308, 168–195.

Lu, J., Sun, G., McNulty, S.G., Amatya, D.M., 2005. A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. J. Am. Water Resour. Assoc. 41, 621–633.

Marella, R.L., 2009. Water Withdrawals, Use, and Trends in Florida, 2005. U.S. Geol. Surv. Scientific Investigations, Report 2009-5125; pp. 49.

McBride, W.S., Bellino, J.C., Swancar, A., 2011. Hydrology, Water Budget, and Water Chemistry of Lake Panasoffkee, West-Central Florida. U.S. Geol. Surv. Scientific Investigations, Report 2010-5237; pp. 96.

Mecikalski, J.R., Sumner, D.M., Jacobs, J.M., Pathak, C.S., Paech, S.J., Douglas, E.M., 2011. Use of visible geostationary operational meteorological satellite imagery in mapping reference and potential evapotranspiration over Florida, In: Labedzki, L. (Ed.), Evapotranspiration. InTech: online open-source publishing, http://dx.doi.org/10.5772/585 accessed at <http://www.intechweb.org/books/show/title/evapotranspiration on 5/4/201>.

Misra, V., Carlson, E., Craig, R.K., Enfield, D., Kirtman, B., Landing, W., Lee, S.K., Letson, D., Marks, F., Obeysekera, J., Powell, M., Shin, S.L., 2011. Climate Scenarios: A Florida-Centric View. Florida Climate Change Task Force. (accessed 04.05.11) <http://floridaclimate.org/whitepapers/>.

Moreo, M.T., Swancar, A., 2013. Evaporation from Lake Mead, Nevada and Arizona, March 2010 through February 2012: U.S. Geological Survey Scientific Investigations Report 2013-5229, pp. 40, <http://dx.doi.org/10.3133/sir20135229>.

Motz, L.H., 1998. Vertical leakage and vertically averaged vertical conductance for karst lakes in Florida. Water Resour. Res. 34, 159–167.

Motz, L.H., Sousa, G.D., Annabel, M.D., 2001. Water budget and vertical conductance for Lowry (Sand Hill) Lake in north-central Florida, U.S.A. J. Hydrol. 250, 134–148.

Natl. Oceanic Atmos. Adm., 2011a. National Weather Service Advanced Hydrologic Prediction Service (AHPS). (accessed May 2011) <http://water.weather.gov/precip/download.php>.

Natl. Oceanic Atmos. Adm., 2011b. Global Change Master Directory. (accessed 13.06.11) <http://gcmd.nasa.gov/records/GCMD_NOAA_NWS_CPC_MEI.html>, (accessed 13.06.11) <http://www.esrl.noaa.gov/psd/data/correlation/mei.data>.

Natl. Oceanic Atmos. Adm., 2012. Normal Precipitation. (accessed 26.03.12) <http://water.weather.gov/precip/about.php>.

Paech, S.J., Mecikalski, J.R., Sumner, D.M., Pathak, C.S., Wu, Q., Islam, S., Sangoyomi, T., 2009. A calibrated, high-resolution GOES satellite solar insolation product for a climatology of Florida evapotranspiration. J. Am. Water Resour. Assoc. 45, 1328–1342.

Pollman, C.D., Lee, T.M., Andrews, W.J., Sacks, L.A., Gherini, S.A., Munson, R.K., 1991. Preliminary analysis of the hydrologic and geochemical controls on acid-neutralizing capacity in two acidic seepage lakes in Florida. Water Resour. Res. 27, 2321–2335.

Price, R.M., Nuttle, W.K., Cosby, B.J., Swart, P.K., 2007. Variation and uncertainty in evaporation from a subtropical estuary: Florida Bay. Estuaries Coasts 30, 1–10.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100, 81–92.

PRISM Climate Group, 2011. Digital map of U.S. Precipitation 30-Arcsec Normals, 1971–2000. Oregon State University, (accessed 14.04.11) <http://prism.oregonstate.edu/products/matrix.phtml?vartype=ppt>.

PRISM Climate Group, 2012. Oregon State University, (accessed 04.09.12) <http://prism.oregonstate.edu/products/matrix.phtml?vartype=ppt&view=data>.

Reilly, T.E., Dennehy, K.F., Alley, W.M., Cunningham, W.L., 2008. Ground-Water Availability in the United States. U.S. Geol. Surv. Circular 1323; pp. 70. <http://pubs.usgs.gov/circ/1323/>.

Rosenberry, D.O., Sturrock, A.M., Winter, T.C., 1993. Evaluation of the energy budget method of determining evaporation at Williams Lake, Minnesota, using alternative instrumentation and study approaches. Water Resour. Res. 29, 2473–2483.

Rosenberry, D.O., Stannard, D.I., Winter, T.C., Martinez, M.L., 2004. Comparison of 13 equations for determining evapotranspiration from a prairie wetland, Cottonwood Lake area, North Dakota, USA. Wetlands 24, 483–497.

Sacks, L.A., 2002. Estimating Ground-Water Inflow to Lakes in Central Florida Using the Isotope Mass-Balance Approach. U.S. Geol. Surv. Water-Resources Investigations, Report 02-4192; pp. 47.

Sacks, L.A., Lee, T.M., Radell, M.J., 1994. Comparison of energy-budget evaporation losses from two morphometrically different Florida seepage lakes. J. Hydrol. 156, 311–334.

Sacks, L.A., Swancar, A., Lee, T.M., 1998. Estimating Ground-Water Exchange with Lakes Using Water-Budget and Chemical Mass-Balance Approaches for Ten Lakes in Ridge Areas of Polk and Highlands Counties, Florida. U.S. Geol. Surv. Water-Resources Investigations, Report 98-4133; pp. 52.

Sacks, L.A., Ellison, D.L., Swancar, A., 2008. Regression Analysis of Stage Variability for West-Central Florida Lakes. U.S. Geol. Surv. Scientific Investigations, Report 2008-5147; pp. 25.

Sacks, L.A., Lee, T.M., Swancar, A., 2014. The suitability of a simplified isotope-balance approach to quantify transient groundwater-lake interactions over a decade with climatic extremes. J. Hydrol. 519, 3042–3053.

Schiffer, D.M., 1998. Hydrology of Central Florida Lakes – A primer, U.S. Geol. Surv. Circular 1137; pp. 38.

Selman, C., Misra, V., Stefanova, L., Dinapoli, S., Smith III, T.J., 2013. On the twenty-first-century wet season projections over the Southeastern United States. Reg. Environ. Change 13, 153–164. http://dx.doi.org/10.1007/s10113-013-0477-8.

Sepulveda, N., Tiedeman, C.R., O'Reilly, A.M., Davis, J.B., Burger, P., 2012. Groundwater Flow and Water Budget in the Surficial and Floridan Aquifer Systems in East-Central Florida: U.S. Geol. Surv. Scientific Investigations, Report 2012-5161; pp. 214.

Southwest Florida Water Management District, 1996. Northern Tampa Bay Water Resources Assessment Project, vol. 1, Surface-Water/Ground-Water Interrelationships. Brooksville, Florida; pp. 468. <http://www15.swfwmd.state.fl.us/LibraryImages/NORTHERN%20TPABAY%20WTR%20RES%20INTERRELATI.PDF>.

Southwest Florida Water Management District, 2006. Southern Water Use Caution Area Recovery Strategy, Final Report. Brooksville, Florida; pp. 305. Accessed online at <http://www.swfwmd.state.fl.us/documents/plans/swuca_recovery_strategy.pdf>.

Southwest Florida Water Management District, 2013. 2011 Estimated Water Use Report, Water Resources Section, Brooksville, FL, April 9, 2013; pp. 431 <http://www.swfwmd.state.fl.us/documents/reports/2011_estimated_water_use.pdf>.

Stauffer, R.E., Canfield Jr., D.E., 1992. Hydrology and alkalinity regulation of soft Florida waters: an integrated assessment. Water Resour. Res. 28, 1631–1648.

Sumner, D.M., Belaineh, G., 2005. Evaporation, precipitation, and associated salinity changes at a humid, subtropical estuary. Estuaries 28, 844–855.

Sumner, D.M., Jacobs, J.M., 2005. Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. J. Hydrol. 308, 81–104.

Sumner, D.M., Wu, Q., Pathak, C.S., 2011. Variability of albedo and utility of MODIS albedo product in forested wetlands. Wetlands 31, 229–237.

Swancar, A., 2005. Effect of El Niño Southern Oscillation Weather Patterns on Central Florida Lake Water Budgets – Lessons from Lake Starr. U.S. Geol. Surv. Open-File, Report 2005-1213; pp. 35.

Swancar, A., Lee, T.M., 2003. Effects of Recharge, Upper Floridan Aquifer Heads, and Time Scale on Simulated Ground-Water Exchange with Lake Starr, a Seepage Lake in Central Florida. U.S. Geol. Surv. Water-Resources Investigations, Report 02-4295; pp. 53.

Swancar, A., Lee, T.M., O'Hare, T.M., 2000. Hydrogeologic Setting, Water Budget, and Preliminary Analysis of Ground-Water Exchange with Lake Starr, a Seepage Lake in Polk County Florida, U.S. Geol. Surv. Water-Resources Investigations, Report 00-4030; pp. 66.

USGCRP, 2009. Global Climate Change Impacts in the United States. In: Karl, T.R., Melillo, J.M., Peterson, T.C. (Eds.), United States Global Change Research Program. Cambridge University Press, New York, NY.

U.S. Geol. Surv., 2011. Hydrologic Data Web Portal—Florida Potential and Reference Evapotranspiration 1995–2008. (accessed 03.02.11) <http://hdwp.er.usgs.gov/>.

U.S. Geol. Surv., 2012. USGS Florida Evapotranspiration Stations. Reedy Lake at Center Near Vineland, FL, (accessed 02.10.12), <http://fl.water.usgs.gov/et/etdata.html>.

Virdi, M.L., Lee, T.M., Swancar, A., Niswonger, R.G., 2013. Simulating the effect of climate extremes on groundwater flow through a lakebed. Ground Water 51, 203–218, http://dx.doi.org/10.1111/j.1745-6584.2012.00969.x.

Visher, F.N., Hughes, G.H., 1975. The Difference Between Rainfall and Potential Evaporation in Florida. second ed., Florida Bureau of Geology Map Series 32.

White, W.A., 1970. The Geomorphology of the Florida Peninsula. Florida Geological Survey Bulletin 51. Tallahassee, Florida, pp. 164.

Winter, T.C., 1981. Uncertainties in estimating the water balance of lakes. J. Am. Water Resour. Assoc. 17, 82–115.

Winter, T.C., 1995a. Hydrological process and the water budget of lakes. In: Lerman, A., Imboden, D., Gat, J. (Eds.), Physics and Chemistry of Lakes. Springer-Verlag, Berlin, pp. 37–62.

Winter, T.C., 1995b. A landscape approach to identifying environments where ground water and surface water are closely interrelated, In: Proceedings of the International Symposium Water Resources Engineering Division, ASCE, San Antonio, TX, p. 139–144.

Winter, T.C., Woo, M., 1990. Chapter 8, Hydrology of lakes and wetlands, In: Wolman, M., Riggs, H., (Eds.), The Geology of North America, vol. O-1, Surface Water Hydrology, The Geological Society of America, Boulder CO, p. 159–187.

Winter, T.C., Buso, D.C., Rosenberry, D.O., Likens, G.E., Mau, D.P., 2003. Evaporation determined by the energy-budget method for Mirror Lake, New Hampshire. Limnol. Oceanogr. 48, 995–1009.

Wolter, K., Timlin, M.S., 2011. El Niño/Southern Oscillation behavior since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). Int. J. Climatol. 31, 1074–1087.

Yeh, S.-W., Kug, J.-S., Dewitte, B., Kwon, M.-H., Kirtman, B.P., Jin, F.-F., 2009. El Niño in a changing climate. Nature 461, 511–514.