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

Terrie M. Lee [a,*], Laura A. Sacks [b], Amy Swancar [a]

[a] U.S. Geological Survey, Florida Water Science Center (Tampa), 4446 Pet Lane, Lutz, FL 33559, USA
[b] Contractor to U.S. Geological Survey, 2305 Highway 3A, Castlegar, BC, Canada

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

* Corresponding author. Tel.: +1 813 498 5030; fax: +1 813 498 5002.
E-mail address: tmlee@usgs.gov (T.M. Lee).

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,

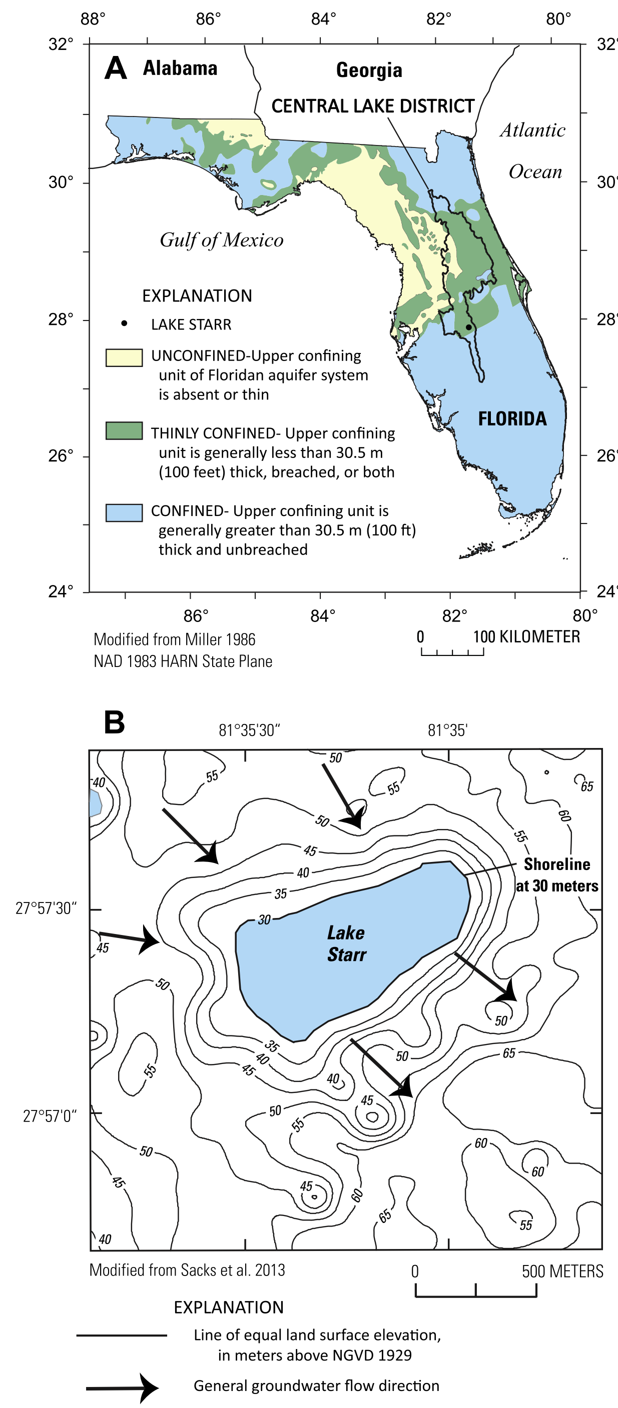

Fig. 1. (A) Map showing the location of the study lake, the Central Lake District of peninsular Florida, and levels of confinement of the limestone Floridan aquifer system, and (B) topographic map of the Lake Starr basin.