Prepared in cooperation with the Southwest Florida Water Management District

Comparison of Evaporation at Two Central Florida Lakes, April 2005–November 2007

Open-File Report 2015–1075

U.S. Department of the Interior
U.S. Geological Survey

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Appendix (available at http://dx.doi.org/10.3133/ofr20151075)

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	0.2471	acre
	Rainfall rate	
millimeter per hour (mm/hr)	0.003281	foot per hour (ft/hr)
	Pressure	
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
	Mass	
kilogram	2.205	pound avoirdupois (lb)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
	Energy	
joule (J)	2.77×10–7	kilowatthour (kWh)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F–32)/1.8

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

BREB	Bowen ratio energy-budget
RH	relative humidity
SE	standard error

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By Amy Swancar

Abstract

Evaporation from April 2005 through October 2007 at two central Florida lakes, one close to the Gulf of Mexico and one in the center of the peninsula, was 4.043 and 4.111 meters (m), respectively; evaporation for 2006 was 1.534 and 1.538 m, respectively. Although annual evaporation rates at the two lakes were similar, there were monthly differences between the two lakes because of changes in stored heat; the shallower Lake Calm (mean depth 3 m) stored less heat and exchanged heat more rapidly than the deeper Lake Starr (mean depth 5 m).

Both lakes are seepage lakes (no surface-water inflows or outflows) that are dependent on groundwater inflow from their basins to offset an atmospheric deficit, because long-term rainfall in this area is less than evaporation. The Lake Starr basin, where sandy, well-drained ridges surround the lake, has a greater capacity to store infiltrating rain than the Lake Calm basin, which is flat and has poorly drained soils. The storage capacities of the basins affect groundwater exchange with the lakes. Rainfall and net groundwater exchange, which is related to basin characteristics, varied more between these two lakes than did evaporation during this study.

Introduction

Evaporation from open water is a critical component of both global energy and hydrologic cycles. Fresh water is “distilled” from the sea by this energy-intensive process as water moves from the ocean to the atmosphere, with some of that atmospheric water reaching the land when it falls to Earth as rain or snow. Evaporation and transpiration from the land surface continue to extract from the near-surface a substantial percentage of the water that falls as precipitation, reducing recharge to surface-water and groundwater systems that are the main water sources for humans and other species. Therefore, it is important to quantify the range and variability in evaporation so that freshwater supplies can be accurately assessed and prudently managed.

Evaporation is the largest water-loss term in many lake water budgets, and is especially important for seepage lakes that have no surface inflows or outflows. About 70 percent of Florida’s 7,800 lakes are seepage lakes (Schiffer, 1998). Energy-budget evaporation was measured at two lakes in central Florida, Lake Starr and Lake Calm. Lake Starr has a relatively long record of evaporation measurements from 1996 to 2011, and has been integral in a series of lake water budget and lake groundwater interaction studies (Lee, 2002; Sacks and others, 1998; Sacks and others, 2014; Swancar and others, 2000; Swancar and Lee, 2003, Virdi and others, 2012). It would be useful to be able to extrapolate the longer-term evaporation measurements at Lake Starr to other lakes. To answer the question of whether evaporation measurements at Lake Starr can be extrapolated to other lakes, the U.S. Geological Survey conducted a cooperative study with the Southwest Florida Water Management District to collect and analyze evaporation data at Lake Calm from 2005 to 2007.

This report presents (1) a comparison between evaporation rates measured at two central Florida lakes, (2) a discussion of the factors affecting the differences between evaporation rates, and (3) a comparison of water budgets for the two lakes focusing on groundwater exchange. The report presents the water and energy budgets for the two lakes during the period from April 4, 2005, to November 2, 2007.

Site Descriptions

Lake Calm is located in northwest Hillsborough County in the relatively flat-lying terrain of the Gulf Coastal Lowlands (White, 1970) (fig. 1). Lake Starr is located in Polk County in the center of the State. Lakes Calm and Starr are both mid-sized lakes between 40 and 60 hectares (ha) in size that were formed from sinkholes in the mantled-karst terrain of central Florida (table 1). Mantled-karst is a landscape common throughout Florida where carbonate rocks beneath the surface are overlain by clays and sands (Tihansky, 1999). As the carbonates dissolve over time, cavities form that eventually collapse, causing the overlying clay and sand to subside into the cavities. The surface expressions of these collapses can be wetlands, lakes, or sinkholes, depending on the elevation of the water table and the degree of subsidence. Both Lakes Calm and Starr consist of multiple collapse features that are evident in the bathymetry (fig. 2). At Lake Starr, seismic reflection also was used to delineate subsurface collapse features (Swancar and others, 2000).

Lake Calm is shallower than Lake Starr (table 1), with a number of isolated deep holes rather than broad low areas in the bathymetry. Topography in the Lake Calm basin also is flatter and lower in elevation than in the Lake Starr basin. Lake Starr is located along the Lake Wales Ridge, the most prominent north-south trending ridge in the center of the State, which was formed as a relict beach shoreline when sea levels were at least 60 meters (m) higher than modern sea level (White, 1970).

When the water level (stage) of Lake Calm is greater than about 15.25 m above NGVD 29, there is potential for water to flow from Lake Calm to Lake Keystone through a small wetland and canal on the southwest side of the lake (D. Leeper, Southwest Florida Water Management District, written commun., 2005). Historically and through the period of record at Lake Calm (1965 to 2007), outflow probably only occurred during 1970 and 2004 (estimates based on stage record only, no measurements of flow are available). No outflow was observed during this study, even though the stage was between 15.25 and 15.30 m for a few weeks in August 2005. Therefore, for the purpose of this analysis, Lake Calm was considered to be a seepage lake. Lake Starr has a relatively steep, well-defined topographic basin and no surface-water connections (table 1).

Although physiographic differences can be expected to affect the water budgets of the two lakes because they influence groundwater exchange (Lee, 2002; Sacks, 2002), they might not have a large effect on evaporation rates. Evaporation rates are mostly a function of radiant energy entering the lake (sunlight and longwave radiation), which is a function of season and cloud cover (Aslyng, 1974; Finch and Hall, 2005; Tanner and Lemon, 1962). Lake water-budget terms are linked to the energy budget, however, through the change in stored energy and latent and advected energy fluxes (Anderson, 1954). Both water and energy budgets are presented and compared in this report.

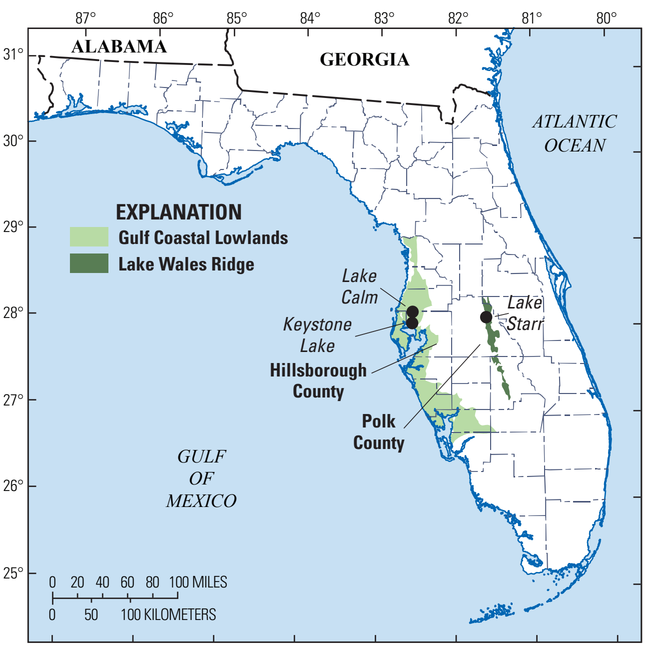

Figure 1. Location of Lakes Starr and Calm in central Florida.

Table 1. Characteristics of Lakes Calm and Starr.

[USGS, U.S. Geological Survey; m, meter; NGVD 29, National Geodetic Vertical Datum of 1929; ha, hectare]

Descriptor	Lake Calm	Lake Starr
USGS station identifier	02307227	02293763
Latitude (degrees, minutes, seconds)	28°08'20"	27°57'15"
Longitude (degrees, minutes, seconds)	82°35'00"	81°35'33"
Sections	10, 11, 14, 15	14, 23
Township-Range	T 27S, R17E	T 29S, R 27E
Reference lake surface elevation (m above NGVD 29)	14.63*	31.7
Surface area (ha) at reference elevation	48.16*	54.23
Maximum depth at reference elevation (m)	8.23*	9.75
Mean depth at reference elevation (m)	3.05	4.88
1:24,000 USGS quadrangle name	Odessa, FL	Lake Wales, FL
Drainage basin area (ha)	104*	298
Maximum elevation of drainage divide (m above NGVD 29)	19.8	68.6

*Data from D. Leeper (Southwest Florida Water Management District, written commun., 2005).

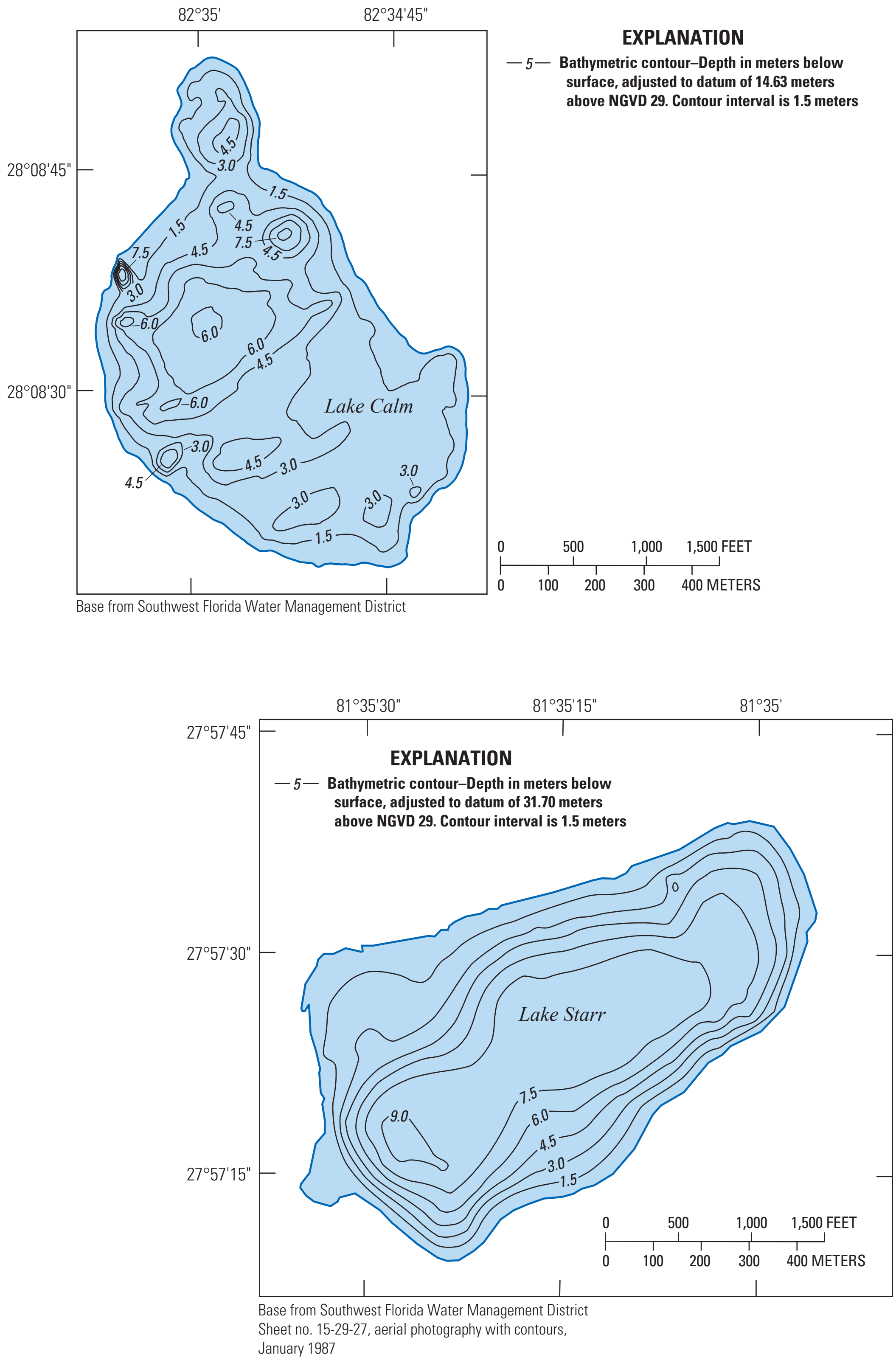

Figure 2. Bathymetry of Lakes Calm and Starr.

Methods

The energy-budget method was used to calculate evaporation at Lakes Calm and Starr. Water-budget analyses incorporated data on rainfall, evaporation, and estimates of runoff and pumpage, which were used to calculate groundwater exchanges at these two seepage lakes.

Evaporation Methods

The energy-budget method used to calculate evaporation at the two lakes was originally described by Anderson (1954) for Lake Hefner in Oklahoma, and has been applied throughout the world since then (dos Reis and Dias, 1998; Harbeck and others, 1958; Rosenberry and others, 2004; Roulet and Woo, 1986; Rouse and others, 2005; Sacks and others, 1994; Sturrock and others, 1992; Wiche, 1992; Winter and others, 2003). This method, commonly called the Bowen ratio energy-budget variant or BREB, estimates the energy used for evaporation by quantifying energy gains and losses and the change in stored energy. 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 (backscattered) longwave radiation;
- Q_e is energy used for evaporation, or the latent-heat flux;
- Q_h is energy conducted 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; and
- Q_x is change in stored energy (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 watts per square meter.

The evaporation rate, E, in meters per second is

$$E = Q_e \rho_w^{-1} \lambda^{-1}, \qquad (2)$$

where

- λ is latent heat of vaporization, 2.45×10^6 joules per kilogram (J kg^{-1}) at 20 °C,
- ρ_w is the density of water, 1,000 kilograms per cubic meter (kg m^{-3}) at 4 °C, and 1 joule (J) = 1 watt second (W s).

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

$$Q_h = R Q_e. \qquad (3)$$

Q_w is calculated from

$$Q_w = c_w \rho_w E (T_e – T_b), \qquad (4)$$

where

- c_w is the specific heat of water, 4,186 J kg^{-1} °C^{-1} at 15 °C;
- T_e is the temperature of evaporating water (assumed equal to the water-surface temperature), in degrees Celsius; and
- T_b is the base temperature, set to 0 °C.

Substituting equations 2–4 into equation 1, and solving for E gives

$$E \text{ (millimeters per day)} = 8.64\times10^7 \times \frac{(Q_n - Q_x + Q_v)}{\rho_w\left[\lambda(1+R) + c_w(T_o - T_b)\right]} \qquad (5)$$

The 8.64×10^7 multiplier is used to convert units from meters per second to millimeters per day.

For this form of the energy-budget equation (the BREB variant), R is calculated from vapor pressure and temperature differences using the following equation:

$$R = 0.062\ (T_o – T_a) / (e_o – e_a)\ , \qquad (6)$$

where

- T_o is water-surface temperature, in degrees Celsius;
- T_a is air temperature, in degrees Celsius;
- e_o is saturation vapor pressure at the water-surface temperature, in kilopascals, and
- e_a is vapor pressure of the air, in kilopascals; and
- 0.062 is the psychrometric constant, in kilopascals per degree Celsius.

The energy budget is calculated over a selected time period called a thermal survey period. Assuming that temperature profiles at a single site are representative of the whole lake and continuous water temperature profiles are measured at that site, daily thermal survey periods can be defined starting at midnight each day. However, the change in stored heat over a single day tends to be small, and the error in estimating this change is large relative to the daily difference, often as much as 100 percent. For this reason, thermal survey periods are usually defined as a week or longer, over which stored heat changes in the lake can be more accurately measured. Weekly thermal surveys were used in this analysis except for periods of missing data; 67 percent of thermal survey periods were a week in length and 87 percent were between 7 and 10 days in length. Because thermal survey periods can be irregular in length and consequently have irregularly spaced start and end dates, monthly evaporation also was calculated at both sites for ease of presentation. For Lake Calm, daily average evaporation rates calculated by thermal survey period were aggregated to estimate monthly rates.

Details on data collection at Lake Starr and how the energy budget was applied can be found in Swancar and others (2000). Additional analysis of up to 15 years of evaporation data from Lake Starr can be found in Lee and others (2014) and Sacks and others (2014). Advected energy is assumed to come only from rain, and this term is small in magnitude. Advected energy from groundwater at these sites also is negligible compared to other energy fluxes. Table 2 summarizes the instruments used at the two lakes. The main difference in data collection between the two sites was that a raft was deployed in the deepest part of Lake Starr to continuously measure lake water temperature at 0.3-m intervals, as well as air temperature and relative humidity (RH) at 2 m above the lake surface. At Lake Calm, air temperature and RH were measured over the lake from a dock on the south side of the lake. Lake temperature profiles at Lake Calm were measured in two ways: (1) manually from a boat at weekly to biweekly intervals at the beginning and end of the study at 0.3-m depth intervals, and (2) using a string of temperature sensors at 1-m depth intervals that was deployed in the deepest part of the lake from November 16, 2005, to April 9, 2007.

Table 2. Instrumentation at Lakes Calm and Starr.

[RH, relative humidity; CSI, Campbell Scientific, Inc.]

Parameter	Lake Calm	Lake Starr
Net radiation	REBS Q*7.1 (2)	Eppley PSP and PIR
Air temperature and RH	Vaisala HMP45	CSI HMP35
Water temperature	HOBO Water temp Pro or CSI type-T thermocouple	CSI type-T thermocouple
Rainfall	Texas electronics TE525-M	Texas electronics TE525
Change in stage	DAA H-310 or KPSI pressure transducer	Handar 436B shaft encoder with float tape
Datalogger	CR10X	CR10X

Water-Budget Methods

The water budget for a lake is useful for estimating the net groundwater seepage to or from the lake. For the seepage lakes discussed in this report, which have no surface-water flows, the water-budget equation is

$$\text{delta } S \pm e_{\text{delta S}} = P - E + G_i - G_o - Q + R \pm e_P \pm e_E \pm e_{Gi} \pm e_{Go} \pm e_Q \pm e_R, \quad (7)$$

where

- delta S is change in volume,
- P is precipitation,
- E is evaporation,
- G_i is groundwater inflow,
- G_o is groundwater outflow,
- Q is direct pumping from the lake, and
- R is runoff from the basin,

and the remaining terms are errors associated with each component. P and E are typically the largest water gain and loss terms, respectively, for seepage lakes in Florida; however, groundwater fluxes may exceed P and E in the water budget of some lakes (Grubbs, 1995; Sacks and others, 1998). Water-budget terms can be expressed either as linear units over the average lake surface area during the water-budget period, as they were in this study, or as volumes.

The seepage-lake water budget can be used to estimate net groundwater flow. Net groundwater flow (groundwater inflow minus outflow) can be calculated by rearranging equation 7 to get

$$\text{Net GW} = G_i - G_o = \text{delta } S - P + E + Q - R \pm e_{\text{delta } S} \pm e_P \pm e_E \pm e_Q \pm e_R \quad (8)$$

The magnitude of net groundwater flow gives an indication of the magnitudes of groundwater inflow and outflow, but for a lake that has both, the magnitude will always be less than the actual inflow or outflow. For example, during a period when net groundwater flow is positive, there is usually still outflow occurring, so the actual (gross) groundwater inflow is probably greater than the computed (net) inflow.

Results

This section will first present evaporation differences, then water budget differences, and finally differences in net groundwater exchange calculated as a residual to the two lake water budgets. Comparison of evaporation rates at these two lakes is most relevant in the context of their water budgets, because uncertainty in the large evaporative flux adds uncertainty to the entire budget. Supporting data (energy-budget terms and evaporation by thermal survey period) for the two lakes are included in appendix 1.

Evaporation

Overall, evaporation at Lake Calm was only 0.2 percent less than that of Lake Starr, totaling 4.043 m during the 31-month study, compared to 4.111 m at Lake Starr (table 3, fig. 3). This small difference in evaporation is well within the overall error in the method, and also within the 17-percent standard error (SE) of the regression between evaporation measured at the two sites by thermal survey period (fig. 4). Error in energy-budget evaporation is assumed to range from 10 to 15 percent for monthly and weekly calculations, respectively, and 10 percent annually (Sacks and others, 1998; Winter, 1981). This error range is based on accumulating errors in individual terms, and assumes errors may all be in the same direction (for example, all positive bias) (Ramette, 1981).

The energy budget incorporates a number of different measurements, and the evaporation calculated from equation 1 is more sensitive to some measurements than others (Lee and Swancar, 1997). Evaporation on an annual timescale is most sensitive to incoming and emitted longwave radiation, incoming shortwave radiation, and water-surface temperature (Lee and Swancar, 1997; Sacks and others, 1994). Errors in stored heat add the greatest uncertainty to the estimate, especially over periods less than a week (Anderson, 1954; Winter and others, 2003). Advected heat (Q_v) is generally small for seepage lakes, and the energy budget method is insensitive to this term in these settings.

Values of measured parameters by thermal survey period were used to compare measurements that are inputs to the energy budget at the two sites (fig. 5). Air (T_a) and water-surface (T_o) temperatures both show strong relations between the two lakes, with coefficient of determination (r^2) = 0.99 and SE = 2 percent for both. This difference also is close to the combined errors of the instruments used to measure temperature (0.2 to 0.3 °C, or 1 percent on average). Both relations show a small deviation from a 1:1 line, however. Air and water-surface temperatures were higher at Lake Calm than Lake Starr in the summer and lower than Lake Starr in the winter (fig. 5).

Average net radiation showed a good relation between the two sites (r^2= 0.92, SE = 9 percent), but the average net radiation was 2 percent lower at Lake Calm than at Lake Starr (fig. 5). This difference is within the range of the combined errors of the instruments used to measure net radiation (6 percent and 3 percent for the REBS Q*7.1 and Eppley PSP and PIR radiometers, respectively), and less than the standard error of the regression. Net radiation (Q_n) is the sum of incoming and reflected short-wave radiation and incoming, reflected, and emitted longwave radiation. The comparison of radiation terms was confined to net radiation rather than the individual radiation components because only net radiation was measured at Lake Calm. The difference in net radiation may be due to local weather at the two lakes, but also may be due to the radiometers used at these sites. In controlled field experiments, Brotzge and Duchon (2000) and Cobos and Baker (2003) found that the REBS radiometers used at Lake Calm underestimate daytime net radiation by 11 and 7 percent, respectively, compared to

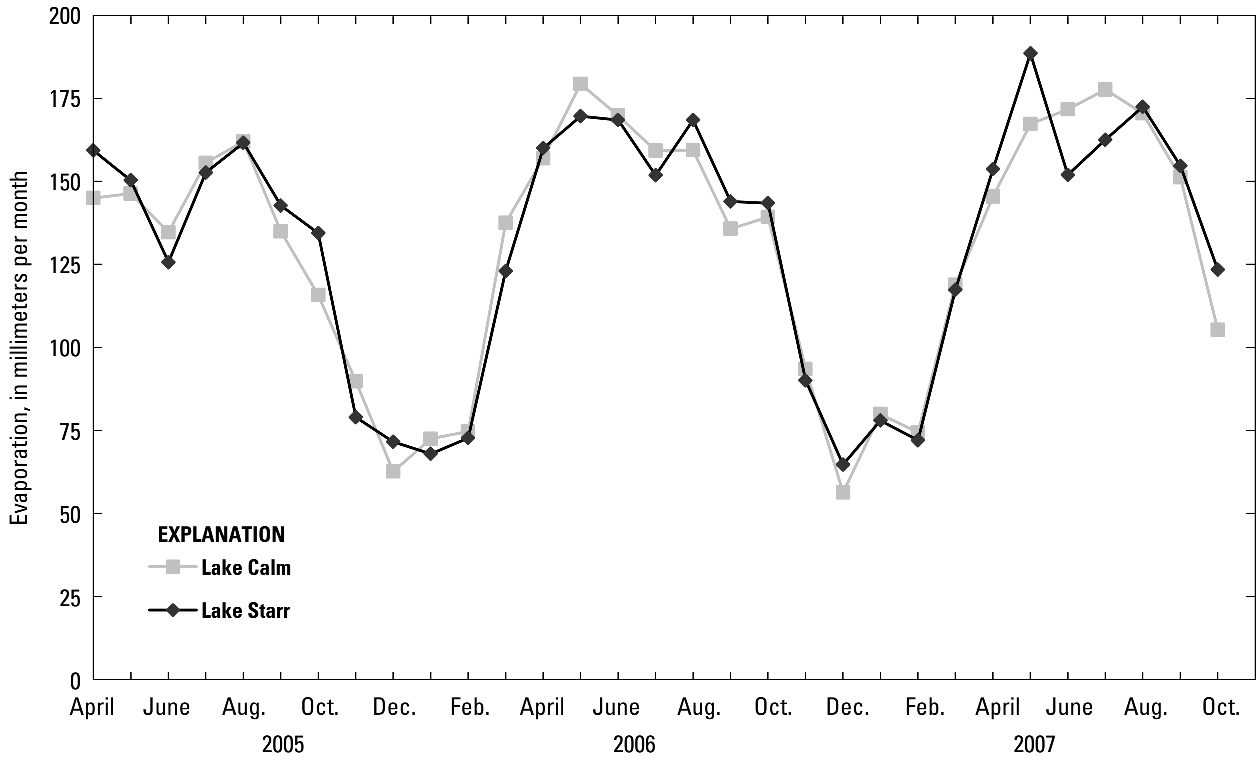

Figure 3. Monthly evaporation at study lakes.

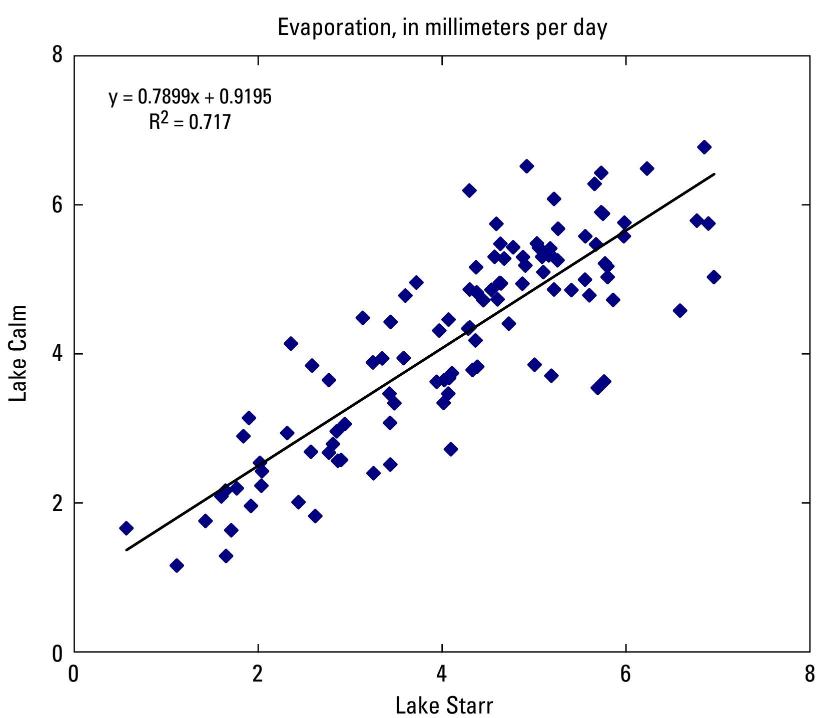

Figure 4. Relation between energy budget evaporation at the study lakes by thermal survey period.

Table 3. Monthly water budgets for Lakes Calm and Starr.

[NGVD 29, National Geodetic Vertical Datum of 1929; m, meter; mm, millimeter; m^2, square meter; SA, surface area: n/a, not applicable]

Month/year	Lake Calm						
	Stage on first day of month (0000 hour), in m above NGVD 29	Average SA, in m^2	Change in stage as average volume to average SA, in mm	Rain, in mm	Evaporation, in mm	Runoff, in mm	Net groundwater, in mm
Apr-2005	15.06	508,807	–74	86	145	10	–25
May-2005	14.98	500,475	–24	108	146	29	–15
Jun-2005	14.96	497,019	141	185	135	0	91
Jul-2005	15.10	512,818	124	189	156	30	61
Aug-2005	15.22	524,529	43	177	162	0	28
Sep-2005	15.27	528,519	–144	26	135	0	–35
Oct-2005	15.12	515,088	–107	41	116	0	–32
Nov-2005	15.02	505,072	–98	42	90	0	–50
Dec-2005	14.92	494,518	–40	57	63	0	–34
Jan-2006	14.88*	492,009	–88	22	72	0	–37
Feb-2006	14.79	486,448	48	110	75	21	–8
Mar-2006	14.84	489,524	–180	0	138	0	–42
Apr-2006	14.66	478,270	–192	13	157	0	–48
May-2006	14.47	466,424	–186	33	179	0	–39
Jun-2006	14.28	455,130	146	236	170	39	41
Jul-2006	14.43	464,004	183	243	159	21	78
Aug-2006	14.61	475,255	**	160	159	**	**
Sep-2006	**	**	**	154	136	**	**
Oct-2006	14.83*	488,941	–110	26	139	12	–9
Nov-2006	14.72	482,074	–9	81	94	0	3
Dec-2006	14.71	481,503	–6	61	56	0	–10
Jan-2007	14.71	481,123	–36	53	80	0	–9
Feb-2007	14.67	478,840	–49	28	74	0	–3
Mar-2007	14.62	475,813	–128	19	119	0	–28
Apr-2007	14.49	467,914	–137	25	145	0	–16
May-2007	14.36	459,577	–253	4	167	0	–89
Jun-2007	14.10	444,401	–54	82	172	13	23
Jul-2007	14.05	441,196	–52	117	178	0	9
Aug-2007	14.00	438,169	–6	141	170	10	14
Sep-2007	13.99	437,813	–67	96	151	0	–12
Oct-2007	13.92	433,896	3	124	105	0	-16
Nov-2007	13.93	n/a	n/a	n/a	n/a	n/a	n/a
Annual Totals							
First year (Apr 2005-Mar 2006)	n/a	n/a	–398	1,041	1,432	91	–99
Second year (Apr 2006-Mar 2007)	n/a	n/a	–168	1,106	1,523	n/a	n/a
Calendar year 2006	n/a	n/a	–174	1,137	1,534	n/a	n/a
31-month Total	n/a	n/a	n/a	2,735	4,043	n/a	n/a

*Estimated.

**Missing stage data, unable to estimate accurately because of heavy rain, water-budget terms that rely on this data are also excluded.

the Eppley radiometers used at Lake Starr. At night, however, these studies found that the REBS radiometer overestimated net radiation compared to the Eppleys. Nighttime radiation fluxes over lakes are particularly important because of the emitted longwave radiation given off by the water.

Vapor pressure of water in air above the lake surface (e_a), which is calculated from the measured air temperature and relative humidity, also shows a strong relation between the two sites (r^2=0.99, SE = 3 percent). While e_a is lower at Lake Calm by 5 percent on average, this difference also is close to the combined errors of the sensors (1 percent for temperature, 2–3 percent for RH).

Change in stored heat (Q_x) differed between the two sites more than any other energy-budget term; Lake Calm had only about half the change in stored heat observed at Lake Starr, on average (fig. 5).

Table 3. Monthly water budgets for Lakes Calm and Starr.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; m, meter; mm, millimeter; m^2, square meter; SA, surface area: n/a, not applicable]

Month/year	Lake Starr						
	Stage on first day of month (0000 hour), in m above NGVD 29	Average SA, in m^2	Change in stage as average volume to average SA, in mm	Rain, in mm	Evaporation, in mm	Pumping from lake, in mm	Net groundwater, in mm
Apr-2005	32.50	568,959	–55	101	160	3	8
May-2005	32.45	566,330	–20	129	151	3	5
Jun-2005	32.42	565,347	371	427	126	0	70
Jul-2005	32.83	582,543	122	149	153	0	126
Aug-2005	32.96	587,751	185	247	164	2	103
Sep-2005	33.18	595,213	23	83	144	3	87
Oct-2005	33.20	596,118	160	241	136	0	55
Nov-2005	33.40	602,133	25	38	80	6	73
Dec-2005	33.43	603,039	19	38	73	8	63
Jan-2006	33.45	603,755	–42	13	69	10	24
Feb-2006	33.40	602,224	–22	62	74	9	–1
Mar-2006	33.37	601,399	–134	4	124	13	–1
Apr-2006	33.21	596,317	–162	24	161	7	–18
May-2006	33.02	589,852	–146	65	170	5	–36
Jun-2006	32.86	583,728	–74	122	170	8	–19
Jul-2006	32.78	580,489	–58	124	154	3	–26
Aug-2006	32.71	577,886	–59	152	170	1	–39
Sep-2006	32.65	575,210	–51	149	146	2	–52
Oct-2006	32.59	572,859	–198	22	145	12	–64
Nov-2006	32.38	563,357	–134	16	91	10	–48
Dec-2006	32.24	556,601	0	127	66	4	–57
Jan-2007	32.24	556,601	–94	51	79	10	–56
Feb-2007	32.14	551,711	–68	63	73	5	–53
Mar-2007	32.07	548,103	–196	16	118	10	–83
Apr-2007	31.87	537,342	–158	70	154	6	–68
May-2007	31.71	528,296	–239	43	190	6	–87
Jun-2007	31.47	514,051	–93	114	154	3	–51
Jul-2007	31.37	508,367	–48	136	165	1	–19
Aug-2007	31.32	505,402	–30	192	175	2	–45
Sep-2007	31.29	503,538	–133	59	155	1	–36
Oct-2007	31.16	495,257	–39	104	123	4	–15
Nov-2007	31.12	n/a	n/a	n/a	n/a	n/a	n/a
Annual Totals							
First year (Apr 2005-Mar 2006)	n/a	n/a	632	1,533	1,453	58	611
Second year (Apr 2006-Mar 2007)	n/a	n/a	–1,240	932	1,543	78	–551
Calendar year 2006	n/a	n/a	–1,081	880	1,538	85	–337
31-month Total	n/a	n/a	–1,349	3,182	4,111	159	-262

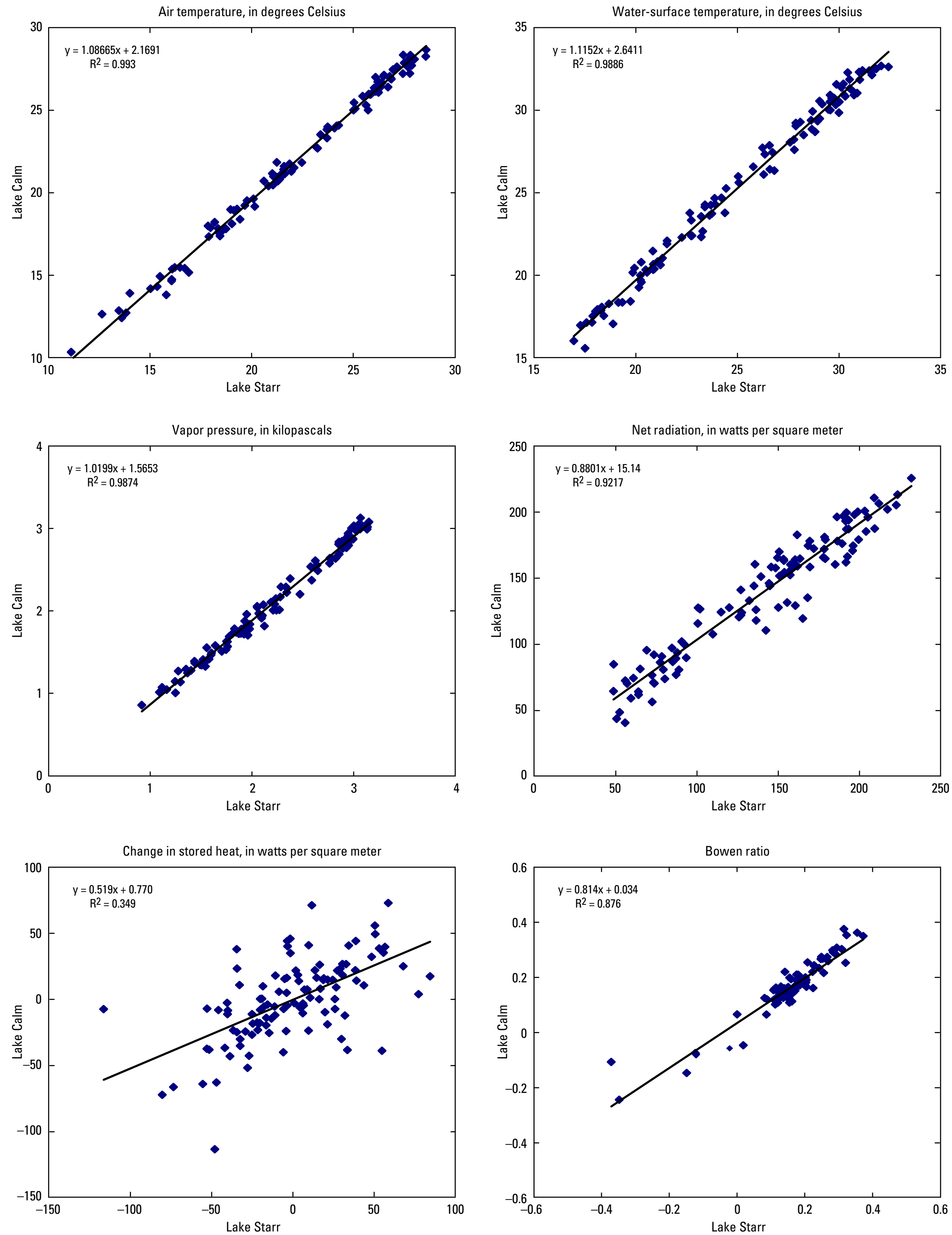

Figure 5. Relations between energy budget parameters at the study lakes by thermal survey period.

In addition, the relation between the two sites for this parameter was poor ($r^2 = 0.35$, SE = 90 percent). Although the error in calculating the change in stored heat is typically high, a poor relation is reasonable because Lake Calm is not as large or deep as Lake Starr. The greater volume of water in Lake Starr accounts for the larger total stored heat, and, consequently, the larger change in stored heat (Gorham, 1964; Rouse and others, 2005).

The Bowen ratio, which is calculated as the ratio of the temperature difference to the vapor pressure difference above the lake surface using equation 6, is an important parameter that indicates how much of the net energy is partitioned to evaporation. Bowen ratios were similar at the two lakes during this study, indicating that near-surface evaporative processes are similar ($r^2=0.88$, SE = 20 percent). Negative Bowen ratios that occur during winter periods when the lake surface is cooler than the overlying air are responsible for most of the scatter in this relation (fig. 5). Evaporation rates calculated during winter periods can be problematic because of the effects of small temperature and vapor pressure differences on the Bowen ratio, which may be subject to relatively larger errors compared to other seasons. These higher errors are not detrimental to evaporation rate calculations, however, because evaporation rates are typically low during this time of the year.

Water Budgets

Rainfall is the most variable water-budget term both spatially and temporally in Florida because of the effect of localized summer convective thunderstorms (Chen and Gerber, 1990; Sumner and Belaineh, 2005). Although evaporation is the largest loss from Florida seepage lakes, groundwater outflows are typically the next greatest in magnitude (Lee, 2002). Reduced lake levels caused by groundwater withdrawals are a problem in some areas of west-central Florida (Southwest Florida Water Management District, 2006). Determining how losses are partitioned between evaporation and groundwater exchanges requires accurate evaporation values. Although evaporation is somewhat difficult to quantify, groundwater fluxes are even more so, primarily because of potentially large errors in estimating the hydraulic properties of aquifers underlying lake basins.

Rainfall, Runoff, and Pumpage

Total rainfall at Lake Starr during the study was 3,182 millimeters (mm), with almost half of that rain falling in the first 12 months (table 3). Total rainfall at Lake Calm was lower (2,735 mm), but was more evenly distributed in time (fig. 6). Most of the difference in total rainfall (450 mm) during the 31-month study period was due to greater than normal rainfall at Lake Starr in 2005, when about 1,140 mm of rain fell from June through October, compared to 617 mm at Lake Calm. Lake Calm received more rainfall in the summer of 2006, however, totaling 810 mm from June through October, compared to 570 mm at Lake Starr. Although large spatial variations in rainfall are characteristic of Florida's climate, there is no evidence of long-term differences between rainfall in these two areas (Southwest Florida Water Management District, 2009).

Lake Starr stage increased by more than 1 m in response to rainfall in the summer of 2005 and the associated net groundwater inflow (fig. 6). Lake Starr stage then declined after 2005 in response to below-normal rainfall. Lake Calm had less stage variation and less rise and fall, but stage in both lakes decreased by at least 1 m during the study period.

Several minor water-budget components, including surface runoff (Lake Calm) and pumpage (Lake Starr), were not measured directly for the purposes of this study. For Lake Calm, stage increases in excess of the rainfall amount indicate that surface runoff from the basin can contribute water to the lake, but only during heavy rains (typically greater than 25 millimeters per hour [mm h^{-1}]). This process is not evident at Lake Starr, mainly because soils in that basin are excessively drained (Natural Resources Conservation Service, 2008). In the Lake Calm basin, soils are poorly drained (Natural Resources Conservation Service, 2008). The amount of runoff at Lake Calm was estimated as the daily stage increase greater than 9 mm that was not accounted for by that day's rainfall. Using this method, inflow from runoff varied from zero during most months to 39 mm in June 2006 (table 3). Some of this increase could have been due to short-term groundwater inflow caused by transient water-table mounds (Metz and Sacks, 2002; Swancar and others, 2000). Lake Calm is in a hydrologic setting similar to two of the lakes studied by Metz and Sacks (2002) where transient mounds were observed that lasted up to a week. Transient mounds that lasted more than a day would be expected to continue to generate stage increases in excess of rainfall. Stage increases in excess of associated rainfall, and thus possibly caused by transient groundwater inflow, were not observed at Lake Calm except on days with heavy rain, however. Therefore, these stage increases are attributed mostly to runoff, although it is still likely that some transient groundwater inflow also occurs.

Swancar and others (2007) found that a few local property owners pump directly from Lake Starr to irrigate citrus and other landscape plants. Using the method developed during that study, direct withdrawals were estimated for the purposes of this study by assuming that residents would irrigate when rainfall did not occur during the previous 7 days. Estimates of direct pumping ranged from near zero to about 13 mm per month at Lake Starr during this study (table 3).

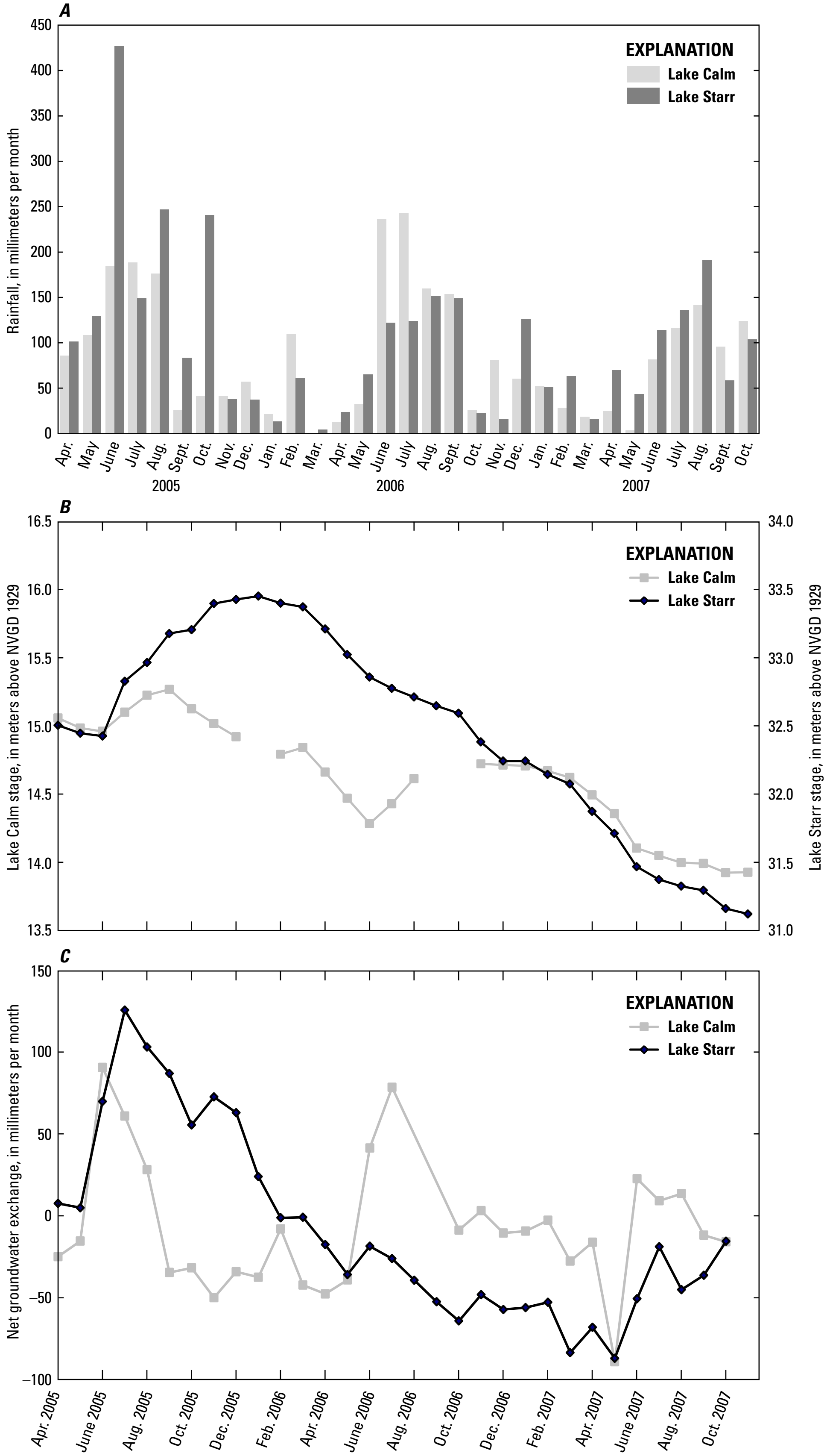

Figure 6. Monthly rainfall, lake stage, and net-groundwater exchange at study lakes.

Groundwater Exchange

Rainfall, change in lake stage, evaporation, and other terms were used to calculate net groundwater exchange at the two lakes using equation 8 (fig. 6). Month-to-month variations in net groundwater exchange with Lake Starr are lower than those with Lake Calm, probably because Lake Starr has a larger contributing basin, and the unconfined aquifer beneath the water table under the upper parts of the basin has a larger capacity to store infiltrating rainwater, which can recharge groundwater and subsequently flow to the lake. Thus, net groundwater remains positive at Lake Starr from May 2005 through the end of that year in response to rain during summer 2005, while at Lake Calm net groundwater flow was positive only in June, July, and August in 2005. This pattern is partly due to the very large rain events at Lake Starr in 2005, but the same short-lived effect of rainfall on groundwater exchange also occurred in 2006, when rainfall was almost 250 mm more at Lake Calm than at Lake Starr.

The thicker unconfined aquifer and longer flow paths for groundwater flowing to Lake Starr also are evident in the relation between monthly rainfall and net groundwater flow at the two lakes. Comparing the relations between monthly net groundwater exchange and cumulative rainfall over the previous 1- to 6-month periods (data not shown), the relation at Lake Calm is strongest between net groundwater flow and rainfall within a given month ($r^2 = 0.73$) and weakens as longer periods of cumulative rainfall are considered as predictors of monthly net groundwater exchange. This pattern indicates that net groundwater flow to Lake Calm occurs primarily during the month that rain occurs, and through relatively short groundwater flow paths. In contrast, there is no relation between net groundwater exchange and rainfall at Lake Starr for a given month ($r^2 = 0.00$), and the relation is strongest for cumulative rainfall for the previous 6 months ($r^2 = 0.54$). The relation at Lake Starr can vary, however, depending on the period of study. Sacks and others (1998) reported that the strongest relation at Lake Starr was found between cumulative net-groundwater exchange and rainfall over the previous 4 months for the period from October 1995 through December 1996.

Discussion

On an annual timescale, the 0.8-percent difference in evaporation rates between the two lakes is within the error of the energy-budget method and is not considered significant. The difference is due partly to lower net radiation measured at Lake Calm compared to Lake Starr. Based on a sensitivity analysis of the energy-budget equation, a 2-percent reduction in net radiation is equivalent to 1 percent less evaporation overall, assuming this is the only difference in the energy budgets of the two sites. Differences in changes in heat storage between the two lakes do not affect annual evaporation because the annual change in stored heat is near zero.

On a monthly timescale, differences in net radiation, air and water temperature, and the Bowen ratio between the two lakes are relatively small and do not translate to significantly different evaporation rates. When these terms are combined in the energy budget, positive and negative differences appear to partly cancel, so that differences between evaporation rates show no relation to any of these individual differences.

Variability in the change in stored heat (Q_x) appears to control most of the month-to-month difference in evaporation rates for the two lakes. Almost 70 percent of the difference between short-term lake evaporation at the two lakes can be explained by the difference in Q_x (fig. 7). Sacks and others (1994) reported a similar result, whereby the difference in capacity to store and release heat was the most significant factor influencing the difference in evaporation rates between two lakes. The magnitude of the difference was greater at the two lakes studied by Sacks and others (1994), Lakes Barco and Five-O, than between Lakes Calm and Starr, because Lake Five-O is three times deeper than Lake Barco (average depths 9.45 and 3.05 m, respectively). A noticeable lag in evaporation in the spring at Lake Five-O compared to Lake Barco was due to energy going into storage. The opposite was true in the fall, when evaporation was higher at the deeper lake as energy was released from storage. This seasonality is not evident at Lakes Calm and Starr (fig. 3), perhaps because the difference in mean depth between these lakes is not as great (3.05 and 4.88 m, respectively) as it was for the lakes in Sacks and others (1994).

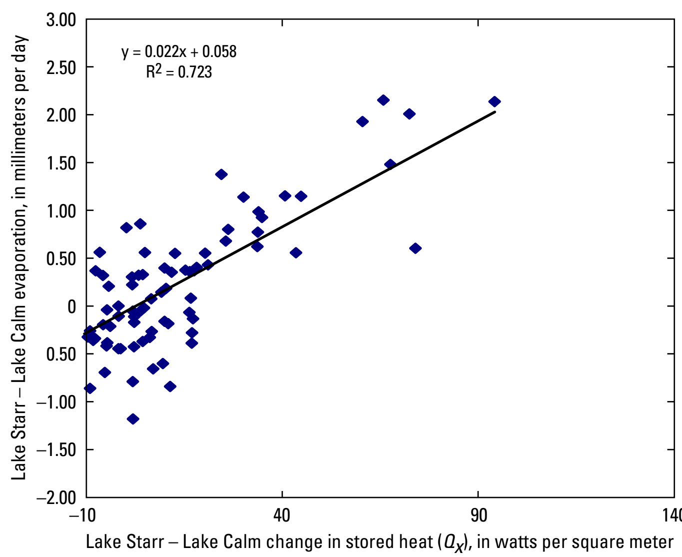

Figure 7. Difference in evaporation between the two sites in relation to the difference between change in stored heat by thermal survey period.

The changes in stored heat also may be responsible for the differences in surface-water temperature at Lakes Calm and Starr. As the lakes store and release heat, the energy exchange affects the surface temperature. The pattern of differences at Lake Calm and Starr is consistent with this process; water-surface temperatures rise more slowly in the first part of the year at Lake Starr, when the lake is warming, compared to Lake Calm. This slower temperature rise reflects energy going into storage. In the second half of the year when the lakes are cooling, water-surface temperatures drop more slowly at Lake Starr, reflecting energy lost from storage.

Differences in meteorological conditions that might be due to the difference in location of the two lakes are not evident from this study. Because Lake Calm is the closest to the Gulf of Mexico, it was hypothesized that air and water temperatures might be moderated by the Gulf, and that this might lead to reduced evaporation, or at least reduced month-to-month variability in evaporation. Neither of these effects was observed in the data from these two sites beyond potential measurement errors. Another difference that might be related to location is rainfall, which is generally lower closer to the Gulf because convective summer thunderstorms build as the air masses move inland. Lower rainfall at Lake Calm may have been partially attributable to this effect, at least in the short term. Solar radiation and net radiation should be higher closer to the coast because of reduced cloud cover, but solar radiation at Lake Calm was, on average, within a few percent of Lake Starr and net radiation was 7 percent lower. Even though Lake Calm is closer to the Gulf than Lake Starr, it is about 20 kilometers (km) inland, so coastal effects may not have been as large as hypothesized.

There may be limitations to this analysis because of differences in instrumentation between lakes. Even though standard instruments were used and calibrated before and after data collection, substantial differences are sometimes observed between sensors, particularly those measuring radiation (Blonquist and others, 2009; Brotzge and Duchon, 2000; Cobos and Baker, 2003). The lack of measurements over the center of Lake Calm may have obscured differences in air temperature and relative humidity between that site and Lake Starr. Most differences in meteorological parameters between the two sites were within, or comparable to, the magnitude of the measurement errors or the scatter in the relations between the variables.

Conclusions

Differences in short-term evaporation rates between the two lakes were mostly due to differences in the change in stored heat; the deeper lake (Lake Starr) had about twice the change in stored heat as the shallower lake (Lake Calm). Annual evaporation from the two lakes was essentially the same, however, and the 0.8-percent difference was well within the error of the energy-budget method.

Seasonal evaporation rates measured at Lake Starr should be directly comparable to those of other lakes in central Florida having similar depths, within an assumed 10-percent error in monthly evaporation for the energy-budget method. Comparison to shallower lakes in the same region that do not store and release heat energy through the seasons may generate a small bias during spring and fall, but annual rates will likely be of similar magnitude. Differences in air temperature, lake temperature, relative humidity, net radiation, and evaporation between the two lakes were all within 10 percent, about the same scale as measurement errors and less than the standard errors of relations between variables.

Although the temporal rainfall distribution differed between the two lakes and there was about 540 millimeters less rain at Lake Calm compared to Lake Starr, stage at both lakes decreased by at least 1 meter during the course of the study (April 2005 through October 2007). The Lake Starr basin, which contains well-drained sand ridges that can store water during the rainy season, contributes water to the lake through groundwater exchange for up to 6 months after the rainfall occurs. Rainfall in the Lake Calm basin generates groundwater inflow to the lake that contributes to the lake volume primarily during the same month that it occurred. The Lake Calm basin does not have the same capacity to store shallow groundwater as the Lake Starr basin, and during heavy rainfall, runoff is observed at Lake Calm but not at Lake Starr. Net groundwater exchange at these two lakes is primarily controlled by basin characteristics.

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