Groundwater/Surface Water Interaction in a Florida Augmentation Lake

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ABSTRACT

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Mountain Lake, Florida, is augmented with water pumped from the underlying Floridan aquifer to maintain the water level, and a detailed 1990 water budget was developed for this lake to determine how the lake interacts with the surrounding groundwater system. Groundwater interaction with the lake was calculated from flow-net analysis of surficial well data, seepage meter data, and the residual of the water budget equation. Strong leakage through the lake bottom was observed, primarily controlled by the head difference between the lake and the Floridan aquifer and the sediment hydraulic leakance (sediment hydraulic conductivity/thickness). Areas of seepage into the lake (15% of the lake area) were observed at possible sinkhole features in the central portion of the lake. Areas of strong leakage occurred in shore areas where steep outflow gradients and sandy sediments existed. Results from this study indicate that the lake recycles groundwater, as the equivalent of over 90% of augmentation water returns to the groundwater system. Water budget data from this lake dispute the public perception in Florida that lake augmentation is a wasteful practice.

Key Words: water budget, augmentation, seepage, flow-net, leakage.

Errors associated with indirect measurement techniques currently used to estimate groundwater/surface water interaction have not always been understood or appreciated. For example, the gross water budget or subtraction method (mass balance) accumulates measurement errors from each of the other water-balance components (Winter 1981*b*). Modeling and flow-net analyses require assumptions about watershed geological characteristics, and each suffers from various drawbacks (Winter 1976, 1978, 1981*b*). Winter (1983) showed that wells need to be carefully located to accurately define geological boundaries, vertical and horizontal hydraulic conductivities and hydraulic gradients for accurate modeling results (Winter 1976, 1981*a*, *b*, 1983).

Use of the direct measurement seepage meter technique avoids errors, assumptions, and input data associated with indirect techniques and allows distribution of seepage along the bottom profile to be portrayed. The seepage meter technique has been recommended by the Environmental Protection Agency (EPA) and has been established as an accurate and reliable technique through field and tank test studies (Lee 1977, Ericksor 1981, Cherkauer and McBride 1988, Belanger and Montgomery 1992). With adequate numbers and proper placement, seepage meters are a very effective way to estimate ground-surface water interaction.

Groundwater interactions with lakes can be quite complex and are governed primarily by groundwater configuration, hydraulic properties of the aquifer system surrounding the lake, and leakance of lake sediments (McBride and Pfannkuch 1975, Winter 1976, 1983, Winter et al. 1988). Porous soils, high water table, Karst topography, and lack of surface water inlets or outlets in many Florida lakes (seepage lakes) suggest groundwater seepage may be a significant water input to these lakes. Several previous studies in East Lake Tohopekaliga (Belanger and Mikutel 1985), Lake Conway (Fellows and Brezonik 1980), and the Indian River Lagoon (Belanger and Walker 1990) support this conclusion.

This paper presents the results of a water budget study on Mountain Lake, Florida (Fig. 1)—a small 43 ha lake that receives water pumped from the Floridan aquifer to maintain the lake level. Our objective was to calculate the percentage of pumped groundwater that was recycled to or lost from the groundwater system. In order to estimate groundwater-surface water interaction we used indirect flownet computations based on a surficial well network, and direct seepage meter measurements.

Methods

Study Area

The Mountain Lake watershed is approximately 483 ha (1194 acres) in area and is primarily agricultural (citrus) and residential in land use. Topographic relief ranges from a low of approximately 30.5 m (100 ft) above National Geodetic Vertical Datum (NGVD) to a high of about 88.4 m (290 ft) NGVD. The dominant physiographic feature in the area is the Lake Wales ridge. The ridge is a fairly thick sequence of sand and clay which is thought to be the remains of a more extensive deltaic formation that has been modified by wave action and solution of underlying limestone and dolostone formations.

The local surficial aquifer occurs in sand and clayey sand units that are generally restricted to the upper 21.3 m (70 ft) of sediments. Underlying surficial sediments are lower permeability units, also consisting of clay and sand in various percentages. The immediate lake area is likely of sinkhole origin, and breaches these units. Internal drainage through sinkholes, where the land surface is connected with the Floridan aquifer, is common in central Polk County, as documented by Fernald and Patton (1984) and Barcelo et al. (1988), and is shown in Fig. 2. Here, the overlying sediments have moved into voids within the underlying limestone deposits. The result is that relatively high permeability units underlie the lake within the area of sinkhole activity.

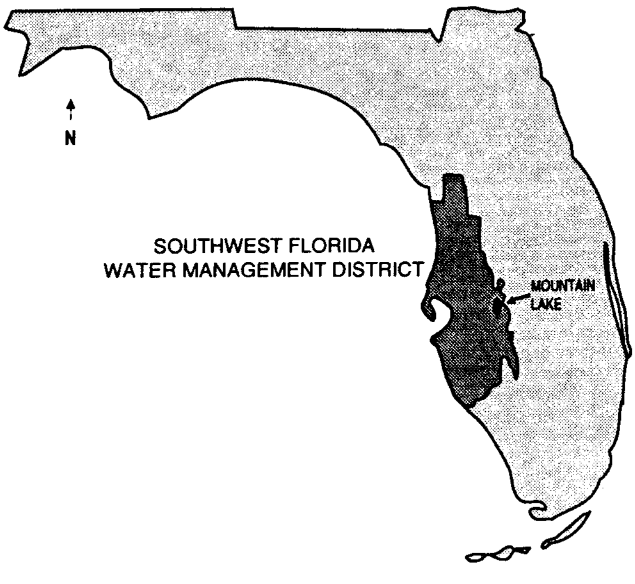

Figure 1.—Location of study site.

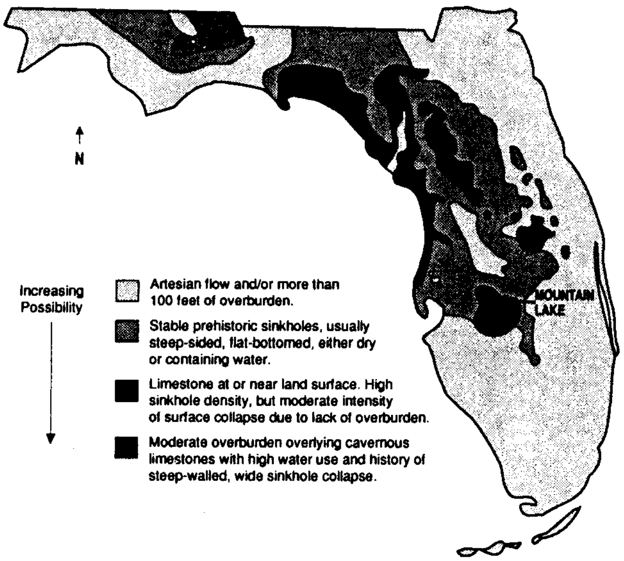

Figure 2.—Possibility of sinkhole development in Florida based on hydrogeology and number of past occurrences (from Fernald and Patton 1984).

Mountain Lake is a small (43 ha) private residential lake located in Polk County near Lake Wales, Florida (Fig. 1), less than 1 mile from the highest point in peninsular Florida (91.4 m NGVD). Its maximum depth (5.5 m) is at the north end, and several isolated areas reach a depth just over 4.3 m. Configuration of the deepest areas are consistent with the suspected sinkhole origin of the lake, which is typical of lakes in this region (Fernald and Patton 1984).

Mountain Lake has been augmented since 1975 to maintain the lake level. Augmentation water is pumped initially into Gate Lake from Floridan aquifer deep wells which are regulated by the Southwest Florida Water Management District (SWFWMD). Gate and Mountain lakes function hydraulically as a single unit because they are connected through a narrow channel without control structures, and there are no outflow points from either lake. During our study, the Mountain Lake surface was maintained near 32.84 m above NGVD, while Gate Lake was maintained at a level approximately 0.9 m higher to allow for gravity flow from Gate to Mountain Lake.

The 1990 yearly total rainfall (101.1 cm) for this area was considerably less than the annual mean (130.7 cm) from 1935 to 1989 (Table 1).

Seepage Meters

Water fluxes through the lakebed were measured directly using seepage meters, a technique cited by EPA as one of the best methods for this purpose (USEPA 1988). Seepage meters followed the design

Table 1. Comparison of 1935-89 mean monthly rainfall with 1990 accumulations (cm).

	1935-89	1990
January	5.84	0.41
February	7.24	9.02
March	8.97	3.35
April	5.94	5.46
May	10.52	11.89
June	19.35	16.18
July	20.37	17.27
August	18.95	12.75
September	16.00	5.79
October	7.37	11.56
November	4.93	4.19
December	5.18	3.18
TOTAL	130.66	101.05

of Lee (1977), with slight modifications (Fig. 3). Each meter consisted of a 55 gallon steel drum cut to produce a hollow cylinder open at one end with a surface area of 0.29 m^2. A hole in the top of the meter was connected to a plastic collection (reservoir) bag by a polyethylene tube fitted through a rubber stopper.

Meters were installed without a reservoir bag and left undisturbed for a minimum of 1 day prior to measurement, allowing time for the initial flow disturbance to subside and the meter to settle into a fixed position. When the meter was ready, a reservoir bag with 1 L of water was attached and the change in volume in the bag was determined over a defined time period. SCUBA techniques were used at deep water stations. The seepage inflow or outflow [(change in volume) (collection time)$^{-1}$ (area enclosed)$^{-1}$] was converted to units of liters per square meter per hour ($L\ m^2\ hr^{-1}$). These units are dimensionally equivalent to units of millimeters per hour ($mm\ hr^{-1}$). Correction factors were applied to the data to correct for flow field disturbance and friction losses within the meter (Erickson 1981, Cherkauer and McBride 1988, Belanger and Montgomery 1992).

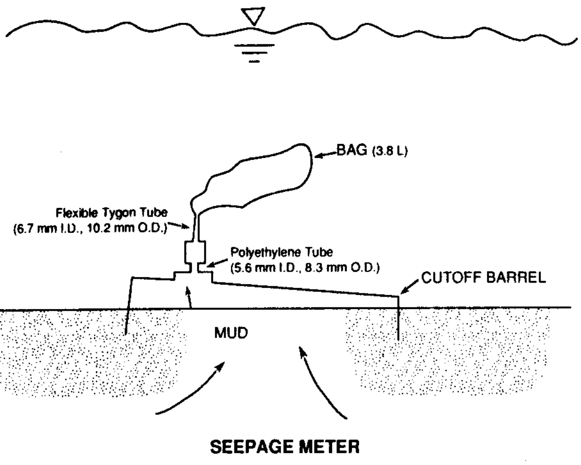

Figure 3.—Diagram of seepage meter.

Seepage measurements were made on 7 dates in 1990 (6/25, 7/15, 8/11, 8/12, 10/6, 12/20, and 12/21). Seepage data (141 measurements) were collected from 47 seepage meters (Fig. 4), although all meters were not sampled on every sampling date. Seepage meter data were not collected for the complete 1990 year, but data are considered representative, because the surficial aquifer and lake water levels remained very stable. For example, the lake stage varied from 32.73 to 32.85 m above NGVD and was similar to the 1990 mean (32.84 m) and range (32.73-32.89 m). Also, the 1990 rainfall range was similar to the 1935-89 range (Table 1). An areal weighting technique, outlined in Belanger and Walker (1990), in which average meter data were applied to various seepage zones in the lake, was used to calculate leakage from the lake.

Flow-Net

A network of 20 wells was installed and groundwater levels were monitored to: 1) determine the direction of groundwater flow, 2) compare water level data with seepage meter data, and 3) perform flow-net analysis. Wells were distributed around Mountain Lake, primarily in pairs, and generally were perpendicular to the shoreline (Fig. 4). The basic well design used 0-61 m of slotted polyvinyl chloride screen (0.025 cm) penetrating the upper 1.5 m of the water table. At locations MW-6 and MW-14, three wells were installed at different depths. At each location, an upper water table monitoring well was installed adjacent to two deeper monitoring wells. The screened section (0.61 m) of the deeper piezometers penetrated the surficial aquifer 3.0 and 6.0 m below the water table within the surficial aquifer. Wells were assigned A, B, and C suffixes in order of increasing depth. The aquifer thickness was determined physically and hydraulically from the MW-6 and MW-14 well nests.

Water level (staff gage) measurements were determined weekly throughout 1990 for Gate and Mountain lakes. Mountain Lake stage was read from a staff gage located on the northwest corner of the lake. Gate Lake was measured from a surveyed datum located in the bridge overlying the lake surface. Water level measurements in the wells were made weekly for 6 months. Measurements were made with a chalked black tape and an electrical probe, with a measurement accuracy of +0.01 ft. "Slug" tests also were performed on selected wells around the lake to determine horizontal hydraulic conductivity in the surficial aquifer (Hvorslev 1951, Cooper et al. 1967). Tests were analyzed and cross-checked using Stepmatch analytical software developed by In-Situ, Inc., with an analytical procedure developed by Cooper et al. (1967). A flow-net analysis was performed to determine the net move-

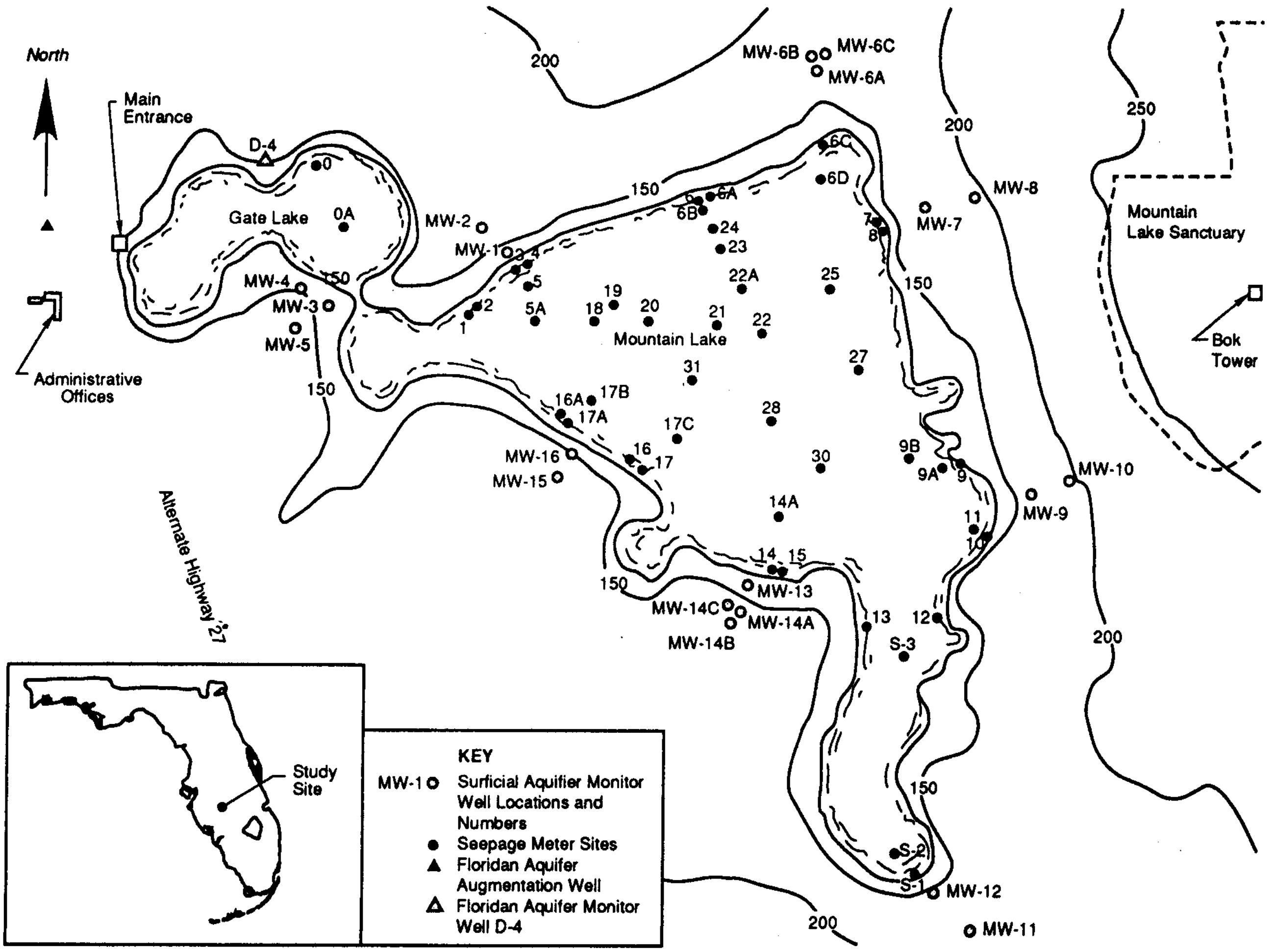

Figure 4.—Seepage meter sampling site and well locations.

ment of water between the surface water system and the surficial aquifer (Kirkner 1991). Flow corridors were defined by adjacent streamlines which were drawn perpendicular to water table contours.

The observed water table elevation gradient and average horizontal hydraulic conductivity for the surficial aquifer were used in the equation:

$$Q = K \times I \times L \times b \qquad (1)$$

Where:

Q = Horizontal Component of Groundwater Inflow/Outflow ($m^3\ d^{-1}$)

K = Surficial Aquifer Horizontal Conductivity ($m\ d^{-1}$)

I = Water Table Elevation Gradient along the flow corridor ($m\ m^{-1}$)

L = Width of the flow corridor (m)

b = Thickness of the Surficial Aquifer Contributing Horizontal Inflows, or Receiving Horizontal Leakage (m)

Flow from all corridors was summed to determine net groundwater exchange with the lake for the study period. Surficial aquifer contour maps were produced on a monthly basis, and net outflow from the lake to the surficial aquifer was always observed.

Hydrologic Budget

A water budget for 1990 was constructed to derive net groundwater flow to and from the lake. Sources of data for the water budget were as follows: precipitation—Mountain Lake National Oceanographic Atmospheric Association (NOAA) weather station; evaporation—corrected pan evaporation data from Lake Alfred experimental station 24 km to the northwest; pumpage—recorded by totalizing flow meter; storm water inflow—estimated by TR-55 method (USDA 1975); groundwater inflow/outflow — flow-net analysis from surficial aquifer well network data; leakage to Floridan aquifer—directly measured by seepage meters and calculated as residual to water budget equation; storage change—calculated from lake gage data and stage/storage relationship.

There was no indication of pumped withdrawals or surface water discharges from the lake in 1990, and these components were eliminated from water budget analysis. Because Gate Lake and Mountain Lake function hydraulically as a single unit, and segregation of surface water inflow and groundwater seepage was not possible, they were treated as such for water budget analysis. Annual 1990 values were used for water budget variables with the exception of groundwater fluxes (GWO, GWI). These values are 6-month averages of flow through discrete corridors within the surficial aquifer surrounding the lake, but were used for the entire 1990 water budget.

Water budget terms were used as input to the following water budget equation for Gate and Mountain lakes (1990 data):

$$\Delta S = (P + SWI + Q) - (E + GWO + L) \quad (2)$$

Where:

ΔS = Change in lake storage over the study period (m^3)

P = Annual precipitation (m^3)

SWI = Surface water inflow (m^3)

Q = Groundwater inflow determined from flow-net analysis (m^3)

E = Evaporation from lake surface (m^3)

GWO = Net groundwater outflow through the surficial aquifer determined by flow-net analysis (m^3)

L = Leakage through the lake bottom, calculated as a residual (m^3). Note: combined GWO + L value was also determined from seepage meter data.

Rearranging terms, annual leakage was determined by the following equation:

$$L = (P + SWI + Q) - (E + GWO + \Delta S) \quad (3)$$

Study duration was great enough to minimize effects of short-term variations in measured variables. However, seepage meter and water level (flow-net) measurements were only made over a 6-month period and extrapolated to the entire year. The estimated water budget (Table 2) includes an estimate of the percent error associated with each budget component. Errors assigned to precipitation and evaporation are typical values from the literature. Remaining values are based on our understanding of the accuracy of methods applied. Although these error values are somewhat arbitrary, they provide some context for values presented.

In a worst-case scenario, water budget errors are amplified by values that are either over or underestimated, having maximum effect on the component calculated as a residual (groundwater leakage in this study).

Results

Seepage Meters

The mean outseepage rate calculated for Mountain Lake between June and December 1990 was -792 mL m^{-2} hr^{-1}. Agreement was generally good between replicate measurements (Table 3), but rates varied considerably with time (Table 4). A discrepancy between seepage at stations 3 and 4 on 7/15/90, when both positive and negative seepage was obtained, is anomalous and may have resulted from an undetected leak in the positive seepage bag. Rates were generally less variable on the south side of the lake than in the northeast or center. Variability among sites (areal) was much more significant than temporal variability (Tables 3 and 4). Individual seepage meter rates varied from -15,371 mL m^{-2} hr^{-1} at site S-1 on 12/20/90 to + 4533 mL m^{-2} hr^{-1} at site 22 on 8/12/90 (Table 4). Mean seepage rates over the study ranged from -15,925 mL m^{-2} hr^{-1} at site S-1 to + 1054 at site 22 (Table 4).

Table 2. Estimated water budget components (m^3 yr^{-1}).

value (m^3)	Estimated measured error (%)	Estimation (m^3)	Error volume
Precipitation	5.3 x10^5	10	5.3x10^4
Evaporation	7.6 x10^5	10	7.6x10^4
Pumpage	3.11x10^6	5	7.6x10^5
Storm/surface water inflow	2.9 x10^5	50	1.5x10^5
Groundwater outflow[1]	1.8 x10^5	50	0.9x10^5
Storage change	1.9 x10^5	10	1.9x10^4
Leakage as residual[1]	3.2 x10^6	--	----

[1] Combined value calculated from seepage meter data was 3.7 x 10^6 m^3 yr^{-1}.

Table 3. Mountain Lake seepage meter precision (mL m^{-2} hr^{-1}).

Date(1990)	6/25	7/15	7/16	8/11	8/12	10/06	12/20
Lake level (NGVD, m)	32.72	32.79	32.79	32.75	32.75	32.73	32.73
Station 1	0	-1400	-1300	-1500	-6300	----	-9600
2	0	-1500	-1200	-1500	-6300	----	-7600
Station 3	0	-500	0	40	-53	120	----
4	0	56	-95	-21	-53	-100	----
Station 14	-180	-120	-280	----	-770	-690	----
15	-160	-120	-230	----	-800	-710	----
Station 16	-1100	-790	----	----	----	----	----
17	-1100	-700	----	----	----	----	----
Station 16A	----	----	----	----	----	-620	-500
17A	----	----	----	----	----	-580	-660
Station 7	-800	-1800	----	-2300	-4200	-200	-5700
8	-1600	-1700	----	-2100	-4100	-300	-5400

Table 4. Mountain Lake seepage rates (mL m^{-2} hr^{-1}).

Station #	Depth below lake surface (m)	Range		# times sampled (N)	Mean seepage rate
		Max	Min		
1, 2 (duplicates)	0.18	0	-8600	6	-3400
3, 4 (duplicates)	0.18	0	-270	6	-74
5	1.52	0	-1500	6	-420
5A	1.82	-120	-200	3	-160
6	0.30	-3300	-8100	6	-5100
6A	0.30	-1100	-9000	6	-4400
6B	1.52	-310	-480	2	-400
6C	0.30		-6900	1	-6900
6D	1.52		-360	1	-360
7, 8 (duplicates)	0.18	-260	-5600	6	-2500
9	0.24	-1800	-6100	4	-3100
9A	0.61	-530	-950	3	-780
9B	1.22	-88	-500	2	-300
10	0.30	-88	-780	3	-370
11	1.83	0	-260	3	-90
12	0.61	-1600	-7900	3	-1800
13	0.30	-1600	-2100	2	-1800
14, 15 (duplicates)	0.18	-120	-800	5	-370
14A	1.68		-1900	1	-1900
16, 17 (duplicates)	0.24	-750	-1100	2	-910
16A, 17A	0.30	-580	-600	3	-590
17B	1.46	-8300	-8900	3	-8400
17C	1.46		-4000	1	-4000
18	3.93	0	-88	3	-46
19	3.75	0	-100	4	-58
20	4.33	0	-320	4	-120
21	4.27	1000	160	3	560
22	4.27	4500	310	4	1100
22A	427		97	1	97
23	3.96	29	-170	3	-65
24	3.05	0	-53	3	-28
25	3.66	0	-140	4	-64
27	4.75	1000	130	4	550
28	4.57	430	51	2	240
30	4.57	-33	-140	2	-88
31	3.35	-290	-320	2	-310
S-1	0.30	-15,000	-16,000	2	-116,000
S-2	1.83		120	1	120
S-3	1.83		-690	1	-690
O	0.76		29	1	29
A0	244		14	1	14

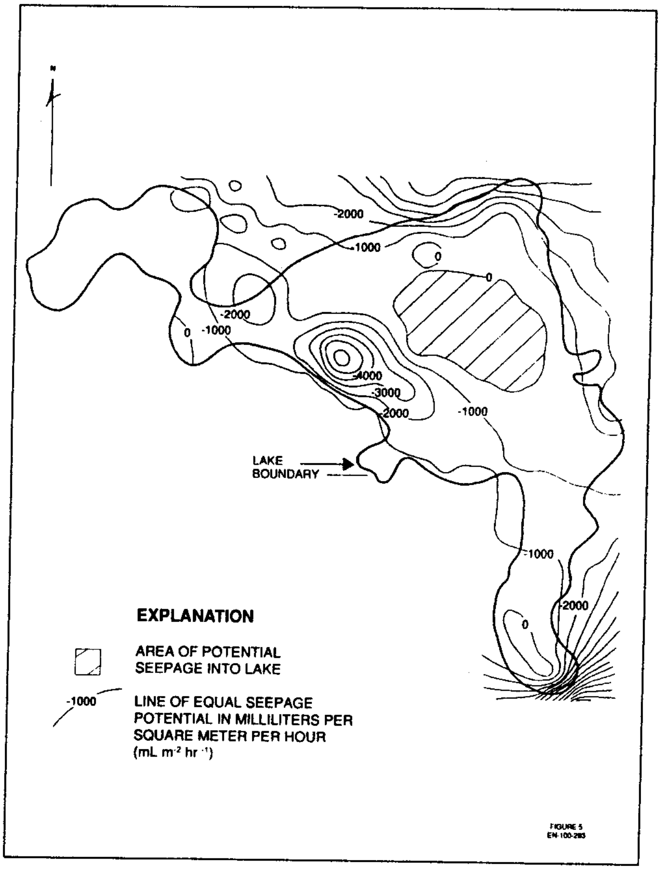

Figure 5.—Contour map of lake seepage rates (contour intervals = 1000 mL m^{-2} hr^{-1}.)

The contour map of average seepage rates during the study (Fig 5) generally agrees with the water table contour map (Fig. 6) developed from average well water level data. The water table contour map indicates lateral flow only, and apparent contradictions between groundwater inflow and outflow areas on the seepage map and the water table contour map may be due to vertical hydraulic connections between the surficial and Floridan aquifers in these areas.

Leakage rates are generally controlled by water table configuration and sediment hydraulic leakance (sediment vertical hydraulic conductivity/thickness). Seepage meter data indicated strong leakage, as expected from the sinkhole topography in the area and the downward head differences between the majority of the lake and the surficial/Floridan aquifer system. The greatest outseepage generally occurred in three areas near the lake perimeter where steep outflow gradients existed and where lakebed sediments were sandy: 1) at the end of the narrow cove on the south side of the lake, 2) in the northeast corner of the lake, and 3) near the south side of the lake (1.8-2.2 m of water; Figs. 5 and 6). Positive seepage rates (inseepage) primarily occurred in deep areas in the center of the lake. This area, bounded by the zero contour interval (Fig. 5), represented approximately 15% of lake area and coincided with the deepest area of the bathymetric map. In the study site region, sinkhole features frequently coincide with bathymetric lows; this has often been confirmed by seismic surveys (Patton 1984, Barcelo et al. 1988).

In the Mountain Lake vicinity, the Floridan aquifer exists as a distinct upper and lower unit. Low-permeability units which confine the limestones and give them separate identities are unevenly distributed and may or may not be found in the exact Mountain Lake area. If an upper unit of the Floridan aquifer were present, it could have a pronounced potentiometric head unrelated to either the surface aquifer or lower Floridan aquifer heads. Therefore, if this lake is of sinkhole origin, as we strongly believe, a hydraulic connection may exist that is reflected in positive seepage from deep water seepage meters due to upward pressure. Reduced sediment leakance, due to silty organic sediments in these areas, probably contributes to low seepage rates.

Flow-Net Analysis

The annual average water table contour map for the groundwater basin (Fig. 6) indicates that groundwater flowed into Mountain Lake along the northwest and southwest shorelines, and outflow occurred toward the northeast and southeast. Slug test data showed large variability in surficial aquifer hydraulic conductivity (5.19-0.43 m d^{-1}). Assuming a thickness of the surficial aquifer of 15.2 m, the average hydraulic conductivity was 2.28 m d^{-1}. Well nests showed a divergence of flow with the upper 15.2 m of the surficial aquifer, indicating this depth contributes flow more or less horizontally. This aquifer depth (15.2 m) was also indicated by the relationship of stratigraphic units which underlie the site (Kirkner 1991).

Water table elevation gradients and horizontal hydraulic conductivity data were used in equation 1 to determine the flow through defined corridors, shown in Fig. 7. These flows are presented as fluxes (Table 5) calculated from the average water table gradient and the average of the monthly fluxes. The head difference between Mountain Lake and Gate Lake (0.9 m described previously) mounded the water table around Gate Lake and created a water table gradient toward the western shoreline of Mountain Lake. In contrast, steep outflow gradients occurred along the northeast and southeast shorelines of the lake. The outflow gradient toward the southeast (Fig. 5) was probably due to a sinkhole immediately south of the lake, and was approximately equal to the lateral seepage to Mountain Lake from Gate Lake. The sink probably causes an enhanced hydraulic connection between the surficial and Floridan aquifers in this area. The cause of the steep gradient observed in the northeast corner was

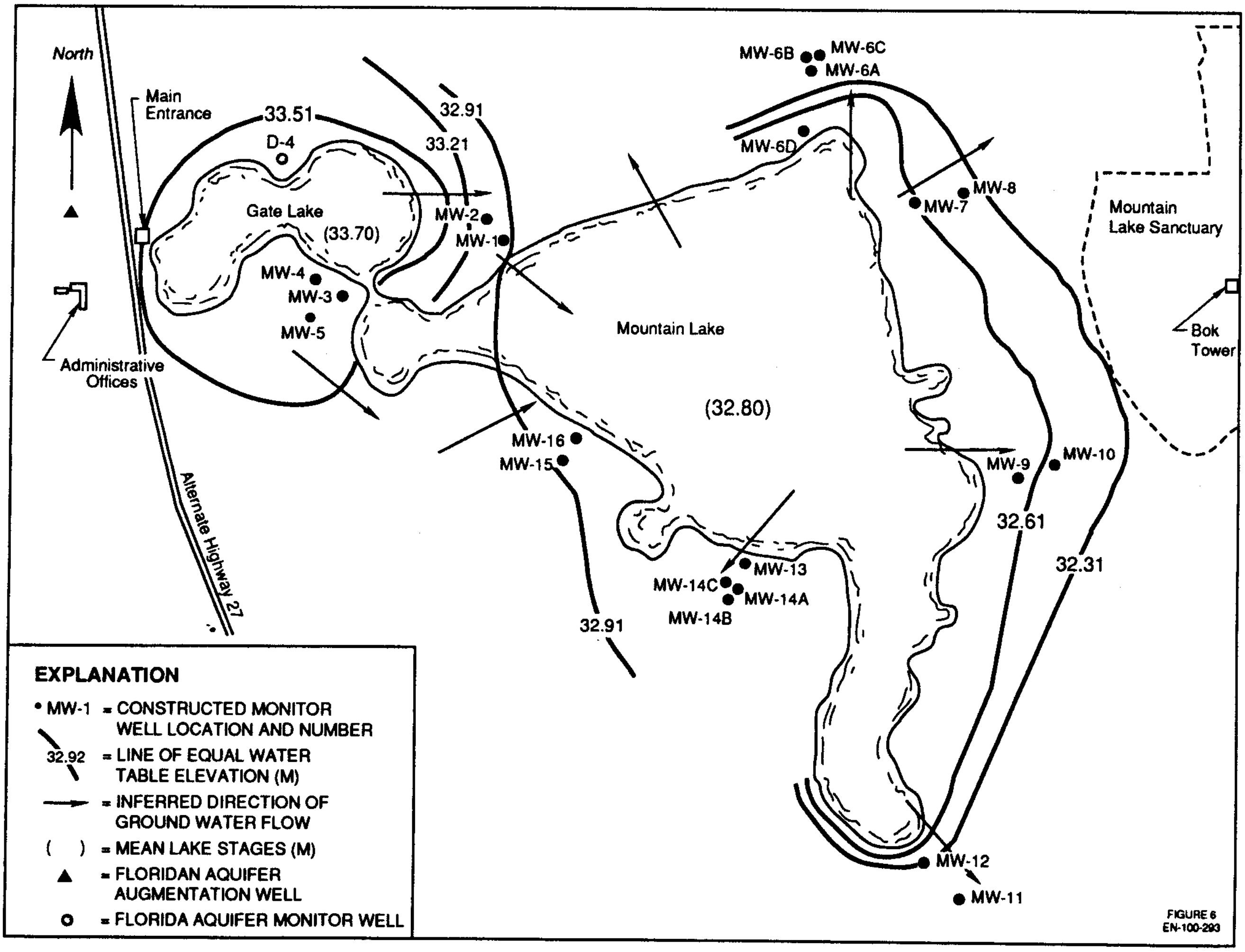

Figure 6.—Water table contour map (contour intervals = 0.30 m).

less obvious, but could be related to similar sinkhole structures.

Hydrologic Budget

Pumpage volume is the largest term in the estimated water budget for Mountain Lake (Table 2). It is also the most accurate and precise component and tends to overwhelm the error found in the other terms of the budget. Calculated vertical leakage (3.2×10^6 m^3 yr^{-1}), was 18 times lateral seepage (1.8×10^5 m^3 yr^{-1}), implying the large estimation error in this parameter is not a major issue. Total annual measured outseepage (seepage meter) rate of 3.7×10^6 m^3 reflects both leakage losses and lateral outflow through the surficial aquifer. Average measured outseepage (leakage) between 6/90 and 12/90 was used to calculate this measured value. Total outseepage was determined through water budget analysis to be 3.4×10^6 m^3 yr^{-1}, and shows close agreement with the measured value (within 10%). Total outflow was 9.3% greater than pumped augmentation water (3.11×10^6 m^3 yr^{-1}), and was four times greater than evaporation losses and six times greater than precipitation contributions (Table 2). Overall, the budget indicates that leakage from the lake is substantial and in 1990 was approximately equal to the amount pumped from the augmentation well.

Discussion

Errors in the various water budget parameters are related to measurement or calculation based on instrument precision, collection procedures, methodology applied, and other factors. Winter (1981*b*, 1983) has published several noteworthy papers on recognition of errors in water budget analysis. The choice of indirect techniques or direct measurement (i.e., seepage meters) to estimate groundwater seepage depends on objectives and constraints of the study. Seepage meter limitations must be understood and are related to measurement and sampling errors in

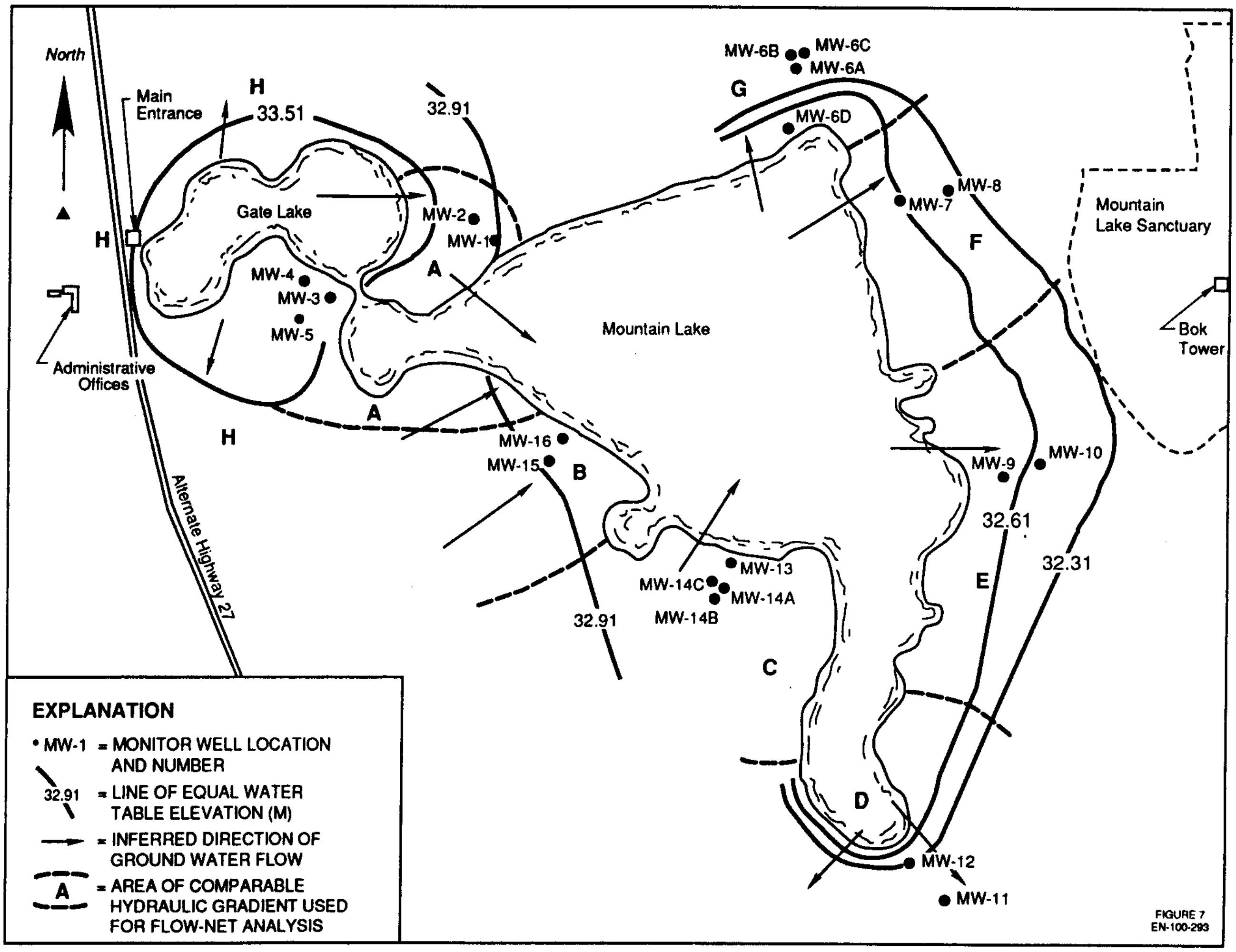

Figure 7.—Flow corridors (areas of comparable hydraulic gradient) used in the flow-net analysis and determined from water table elevation gradients and horizontal hydraulic conductivity data.

the field (cf. Belanger and Montgomery 1992). Seepage meter spatial errors far outweigh measurement (device) errors due to variability and complexity of groundwater-surface water interactions in single waterbodies. Because of this, extrapolation of seepage data from a limited number of seepage meters to an entire waterbody requires special care (Belanger and Montgomery 1992). Although spatial errors may be significant, adequate numbers of properly placed meters can accurately portray distribution and quantity of seepage and improve groundwater seepage estimates, but this approach is very labor intensive. Water quantity estimates from indirect techniques also can be accurate if hydrogeologic conditions are sufficiently known. In this study, the two approaches agree; in another example, average measured seepage rate across the Indian River Lagoon ($0.12\ m\ d^{-1}$) calculated using numerous seepage meters over a 7-month period—was considerably higher than a previous modeling estimate ($3.0 \times 10^4\ m\ d^{-1}$) by Montgomery (1990) who used the U.S. Geological Survey (USGS) 3-D finite difference MODFLOW model. Extremely high horizontal and vertical hydraulic conductivities were needed for modeling results to agree with the measured seepage rate. However, historical data indicate faulting may have occurred beneath the lagoon (Lichtler 1960, Almasi 1983, Miller 1986, and Schiner et al. 1988), and high seepage rates resembling springs have been

Table 5. Comparison of net lateral seepage through surficial aquifer flow corridors, Mountain Lake[1] ($m^3\ d^{-1}$).

Flow Corridor	Flux, calculated	
Average of	using average gradient	monthly flux
A	−29	−33
B	−12	− 17
C	−4	− 1
D	+ 159	+ 213
E	+ 9	+ 7
F	+ 49	+ 42
G	+ 155	+ 138
H	+ 175	+ 203
Net Outflow	500	552

[1] + = Outflow from lake system; - = Inflow to lake system

found in localized areas in the lagoon (Belanger and Walker 1990); so leakage through the Hawthorne Formation is a likely explanation for high seepage rates. This demonstrates the importance of direct measurement studies to verify model predictions.

Conclusions

This study illustrates usefulness of seepage meter measurements in determining inseepage or leakage patterns in surface waterbodies and in verifying model or flow-net results. A check of the accuracy of the leakage term in this study was addressed through comparison with seepage meter data. The comparative analysis shows close agreement.

This study also indicates usefulness of water budget analysis as a management tool. The Mountain Lake water budget (Table 2) shows that augmentation and leakage are the biggest components, and supports the contention that the lake recycles groundwater, as over 90% of pumped water returns to the groundwater system. This indicates that augmentation in the Mountain Lake-Gate Lake system is not a wasteful practice, except from an energy standpoint. The hydrogeology of this study site is very unique and these results cannot be freely extrapolated to justify the practice of lake augmentation in other areas.

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References

Almasi, N. M. 1983. Holocene sediments and evaluation of the Indian River (Atlantic Coast of Florida) PhD Thesis, Univ. Miami, Florida.

Barcelo, M. D., D. L. Slonena, S. C. Camp and J. D. Warren. 1988. Ridge II-A hydrogeologic investigation of Lake Wales Ridge. Southwest Florida Water Management District, Brooksville.

Belanger, T. V. and D. A. Mikutel. 1985. Groundwater seepage nutrient loading in a Florida lake. Wat. Res. 19:773-781.

———— and M. E. Montgomery. 1992. Seepage meter errors. Limnol. Oceanogr. 37:1787-1795.

———— and R. B. Walker. 1990. Groundwater seepage in the Indian River Lagoon, Florida. 367-375 *in* J. Krishna, V. Quinones-Aponte, F. Gomez-Gomez and G. Morris, (Eds.), Proc. Internat. Symp. Tropical Hydrology and Carribbean Wat. Resour.

Cherkauer, D. A. and M. S. McBride. 1988. A remotely operated seepage meter for use in large lakes and rivers. Ground Wat. 26:165-171.

Cooper, H. H., J. D. Bredhoeft and I. S. Papadopulus. 1967. Response of a finite diameter well to an instantaneous charge of water. Wat. Resour. Res. 3:263-269.

Erickson, D. R. 1981. The hydrology of Williams Lake, Minnesota with special emphasis on quantification of littoral ground water contributions using seepage meters and wells. MS Thesis, Univ. Minnesota. 153pp.

Fellows, C. R. and P. L. Brezonik. 1980. Seepage flow into Florida lakes. Wat. Res. Bull. 16:635-641.

Fernald, E. A. and D. J. Patton. 1984. Water resources atlas of Florida. Inst. Sci. Public Affairs. Florida State Univ., Tallahassee. 291pp.

Hvorslev, M. J. 1951. Time lag and soil permeability in groundwater observations. U.S. Army Corps. Eng. *in* Waterways Exp. Sta. Bull. 36, Vicksburg, MS.

Kirkner, R. L. 1991. Results of the water budget analysis of Mountain Lake. Report for the Mountain Lake Corporation. Wat. and Earth Sci., Inc., Lake Wales, FL.

Lee, D. R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr. 22:140-147.

Lichtler, W. F. 1960. Geology and ground water resources of Martin County, Florida. Florida Geol. Surv. J. Res. 23. 149pp.

McBride, M. S. and H. O. Pfannkuch. 1975. The distribution of seepage within lakes. U.S. Geol. Surv. J. Res. 3:505-512.

Miller, J. A. 1986. Hydrogeologic framework of the Floridan aquifer system in Florida and parts of Georgia, Alabama and South Carolina. U.S. Geol. Surv. Prof. Pap. 1403-B.

Montgomery, M. E. 1990. A comparison of direct and indirect methods for estimating seepage in the Indian River Lagoon, Florida. MS Thesis, Florida Inst. Tech., Melbourne. 148pp.

Schiner, G. R., C. P. Laughlin and D. J. Toth. 1988. U.S. Geological Survey Water Resources Investigations Report 88-4073.

United States Department of Agriculture. 1975. *Urban hydrology for small watersheds*. Soil Conserv. Serv., Tech. Release 55.

United States Environmental Protection Agency. 1988. Internal working draft, Oct. 6. A review of methods for assessing nonpoint source contaminated groundwater discharge to surface waters and their relevance to waste local allocation. Office of Groundwater Protection.

Winter, T. C. 1976. Numerical simulation analysis of the interactions of lakes and ground water. U.S. Geol. Surv. Prof. Pap. 1001. 45pp.

————. 1978. Numerical simulation steady state three-dimensional ground water flow near lakes. Wat. Resour. Res. 14:245-254.

————. 1981*a*. Effects of water table configuration on seepage through lake beds. Limnol. Oceanogr. 25:925-934.

————. 1981*b*. Uncertainties in estimating the water balance of lakes. Wat. Res. Bull. 17:82-115.

————. 1983. The interaction of lakes with variability saturated porous media. Wat. Resour. Res. 19:1203-1218.

————, J. W. LaBauch and D. O. Rosenberry. 1988. The design and use of a hydraulic potentiomanometer for direct measurement of differences in hydraulic head between ground water and surface water. Limnol. Oceanogr. 33:1209-1214.