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Use of stable isotopes to quantify flows between the Everglades and urban areas in Miami-Dade County Florida

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Abstract

An isotopic study was performed to assess the movement of groundwater for a site located in Miami-Dade County, Florida. The site encompasses portions of a protected wetland environment (northeast Everglades National Park) and suburban residential Miami, incorporating municipal pumping wells and lakes formed by rock mining. Samples of ground, surface, and rainwater were analyzed for their isotopic composition (oxygen-18 and deuterium). Various analytical and graphical techniques were used to analyze this data and two conceptual box models were developed to quantify flows between different regions within the site. Results from this study indicate that the aquifer underlying the study site (the Biscayne aquifer) is highly transmissive with the exception of two semi-confining layers of reduced hydraulic conductivity. Everglades surface water infiltrates into the aquifer and migrates east toward residential areas. In these urban areas, 'shallow' groundwater (above the deeper semi-confining layer) is substantially affected by urban rainfall while 'deep' groundwater (below the deeper semi-confining layer) maintains a composition similar to that of Everglades water. Rock mining lakes in the area provide 'breaks' in the semi-confining layers that allow for mixing of shallow and deep groundwater. As water travels eastward, municipal well intakes, screened to a depth below the deeper semi-confining layer, draw upon not only shallow urban water (predominantly comprised of urban rainfall) and lake water (having influences from both urban rainfall and Everglades water) but also deep water that originated in the Everglades. Results from one of the box models estimate that over 60% of the water being removed by municipal pumping originated in the Everglades. These conclusions suggest that Everglades water, both directly through deep groundwater flow and indirectly through mixing with rock-mining lakes, is being drawn into the operating municipal wellfield.

Keywords: Oxygen isotopes; Hydrogen isotopes; Everglades; Water sources; Water exploitation

1. Introduction

In South Florida, urban and agricultural expansion have caused an ever-growing need for fresh water. At

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the same time, this expansion has put a strain on the existing fresh water supply by draining wetland areas for other uses and facilitating saltwater intrusion into the aquifer system through municipal pumping. In response to increased water and land demands, the municipal wellfields of Miami-Dade County have progressively moved away from the coast. This expansion has raised concerns relating to the effect that municipal wellfields have on the sensitive ecological system of nearby Everglades National Park. Already, nearly 50% of the historic Everglades have been destroyed or drained (McCally, 1999). Since, the municipal wells draw water from a highly transmissive aquifer, they could, depending on pumping rates, impact the hydrology in the Everglades.

In order to analyze this relationship, a stable isotope study was performed with the primary goal of determining whether Everglades water is being drawn into municipal pumping wells. Stable isotopes ($\delta^{18}O$ and δD) have been used extensively throughout the world to evaluate hydrometerological processes (Grobe et al., 2000; Yoshimura et al., 2001; Mikalsen and Sejrup, 2000; Noon et al., 2003; Harvey et al., 2002) and sources of water to various water bodies including aquifers (Gosselin et al., 2001; Alyamani, 2001; Criss and Davisson, 1996; Harvey and Sibray, 2001), rivers (Winston and Criss, 2003; Frederickson and Criss, 1999), lakes (Ojiambo et al., 2001; Knöller and Strauch, 2002), springs (Criss et al., 2001; Rose et al., 1996; Cartwright et al., 2000), and mines (Hazen et al., 2002). Specifically in Florida, stable isotopes have been used to evaluate the source of salinity to groundwater aquifer systems (Meyers et al., 1993; Schmerge, 2001), to evaluate seepage rates from lakes (Katz et al., 1995), sources of groundwater recharge (Price, 2001), recharge rates to aquifers (Swancar and Hutchinson, 1995; Krukikas and Giese, 1995) and the degree of evaporation experienced by surface waters (Swart et al., 1989). For these reasons, the isotopic ratios of $^{18}O/^{16}O$ and $D/^{2}H$ were chosen for study to evaluate flowpaths and sources of water to the wellfield within the present study. These isotopic ratios are suitable tracers in this area because an isotopic difference can be observed between water derived from the Everglades and water that is recharged in urban areas. Surface water in the Everglades is shallow and experiences considerable heat and solar radiation. As it is subjected to isotopic fractionation processes due to evaporation, this surface water (and, therefore, Everglades groundwater that is recharged by seepage from evaporated surface water) becomes enriched with deuterium and oxygen 18. In contrast, urban groundwaters are recharged by relatively isotopically depleted rainwater that infiltrates quickly through the unsaturated zone. As a result of this rapid recharge, urban waters maintain isotopic characteristics similar to that of rainwater and remain isotopically depleted relative to waters found within the Everglades. This difference allows us to trace the flow of Everglades water through urban areas (Solo-Gabriele and Wilcox, 2000).

Additional site-specific assessments were made during the study regarding the effect of rock-mining lakes on area hydrology, the magnitude of seepage under the levee separating Everglades waters from urban land and the extent to which a canal adjacent to the levee acts as a hydrologic boundary between the Everglades and urban groundwater. These assessments were made by modeling and analyzing data collected during the study period.

2. Site description

The study area (Fig. 1) is located in the western part of Miami-Dade County, Florida and is comprised of a wetland region in the northeastern corner of Everglades National Park as well as residential and agricultural areas of suburban Miami. The site is divided longitudinally by Levee 31N (L-31N) into what will be referred to as 'Everglades' in the west and 'urban' in the east. The major structure of importance to this study on the Everglades side of L-31N is gate S333. This gate is located northwest of the study site on a canal (Tamiami Canal) bounding the northern portion of the site. When in operation, gate S333 can deliver up to 38.2 m^3/s from water conservation areas to the north into the Tamiami Canal. This water is ultimately transferred through a series of outlet structures on the canal into a major shallow waterway (the Shark River Slough) that runs through the western edge of the study site.

The urban (eastern) side of the study site encompasses the West Wellfield of Miami-Dade County. This wellfield draws water from the Biscayne

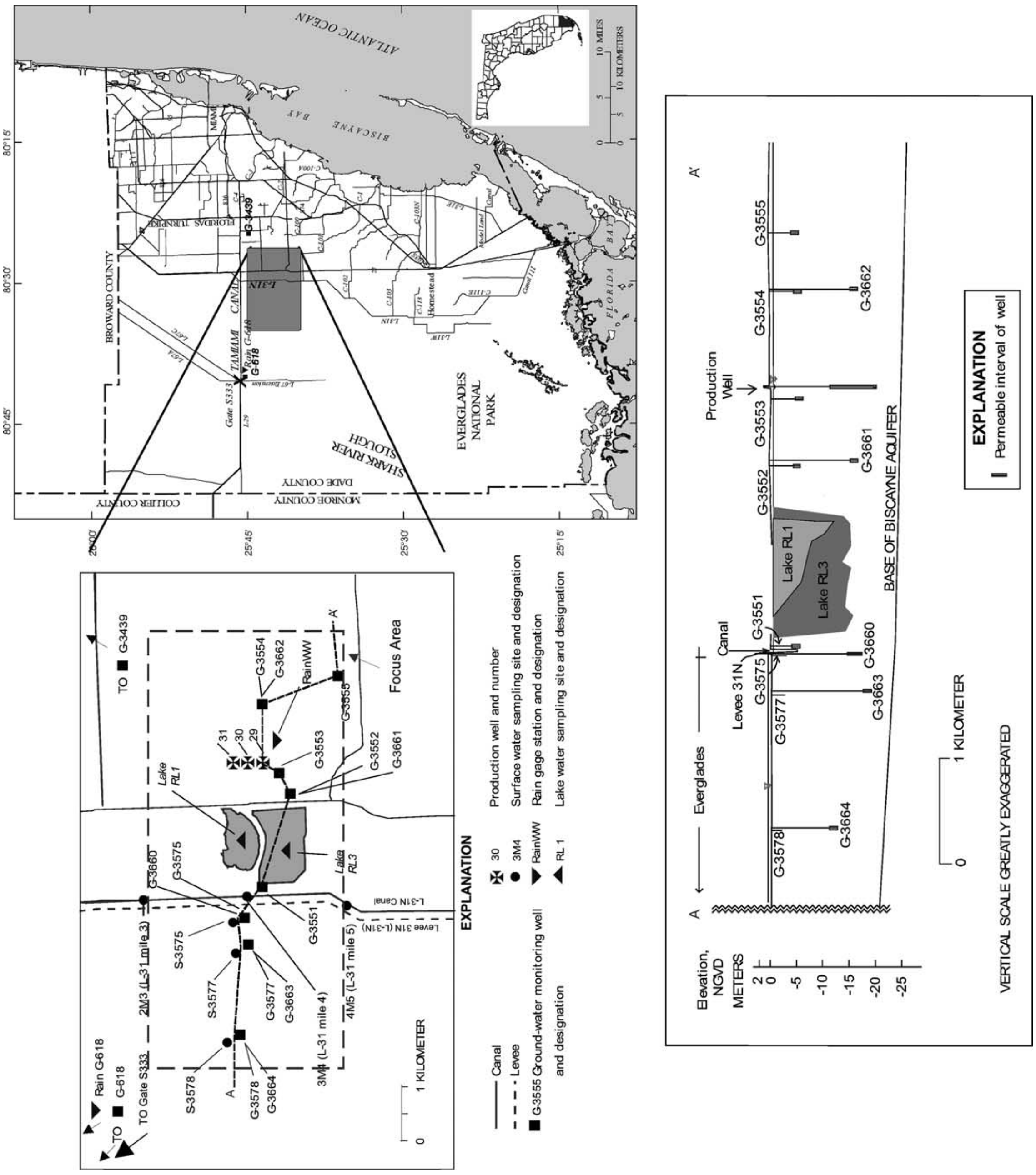

Fig. 1. Study site.

aquifer at depths between 12.2 and 21.3 m below land surface and is comprised of three pumping wells referred to as #29, #30 and #31. The wells are permitted for pumping rates of 37,850, 18,925 and 3,785 cubic meters per day, respectively. The three wells are usually not operated simultaneously. The L-31 N Canal is located just to the east of the levee and flows from north to south. This canal, having a depth of about 6.1 m and a top width of about 30.5 m, is the primary surface water canal within the study area. The stage of the canal generally does not vary by more than 0.9 m. Several lakes are also present in the urban side of the study area. For the purposes of this investigation, two lakes, designated RL1 and RL3 in Fig. 1, were examined. Both of these lakes are the result of rock mining. Lake RL1 is characterized by an average and maximum depth of approximately 8 and 13 m, respectively. Lake RL3 is characterized by an average and maximum depth of approximately 15 and 17 m, respectively. Reference will be made in later sections to the 'focus area' of the study site. This area is used to refer to the highly instrumented area near the center of the site. The focus area stretches from L-31N mile 3 to L-31N mile 5 and encompasses the West Wellfield and its immediate surrounding urban areas, lakes RL1 and RL3 and the easternmost portions of the Everglades extending roughly 3.2 km west of Levee 31N (Fig. 1).

The surficial aquifer system underlying South Florida extends to a depth of approximately 54.9 m below mean sea level in the study area. In the Miami area, the unconfined Biscayne aquifer, the most important aquifer in the South Florida area from a water supply perspective, is found in the upper part of this surficial aquifer system. The base of the Biscayne aquifer in the study site slopes from a high point of approximately 13.4 m below mean sea level in the southwest corner of the study area down to an elevation of roughly 25.6 m below sea level in the northeast corner (Causaras, 1987). The portion of the Biscayne aquifer located in the study area mostly consists of highly permeable limestone having a very high hydraulic conductivity and includes three formations: the Tamiami Formation, the Fort Thompson Formation, and Miami Limestone (Fish and Stewart, 1991). The Fort Thompson and Miami Limestone are of Pleistocene age, whereas the Tamiami Formation is of the Pliocene and late Miocene ages (Randazzo and Jones, 1997). Both the Fort Thompson Formation and the Tamiami Formation of the Biscayne aquifer are composed of highly permeable material and have estimated hydraulic conductivities of at least 6100 m/d. The overall hydraulic conductivity of the Miami Limestone is estimated at 300–1500 m/d (Fish and Stewart, 1991). In the study area, there are two semi-confining layers of low-permeability limestone (Fig. 2). The more shallow of these layers is located near the top of the Fort Thompson Formation, just below the Miami Limestone, and is most likely the result of surface exposure caused by sea-level regression following the deposition of the formation. This layer is consistently found at a depth of about 3 m below ground elevation (Sonenshein, 2001) and is roughly 0.6 m thick. The deeper semi-confining layer is 1.5 m thick. The top of this layer slopes from a beginning depth of 11 m below ground surface elevation (and approximately 9 m below mean sea level) in the west of the focus area to a beginning depth of 12 m in the east (Reese and Cunningham, 2000; Cunningham et al., 2001).

3. Materials and methods

An isotope monitoring network was established with an emphasis placed on sampling locations within the focus area. Initially, in early 1996, only a few sampling locations were tested on a non-regular basis. However, as the research continued, locations were continually added until the completion of sampling in December 1998. A total of 580 samples were analyzed from 26 sampling locations. Sampling locations within the focus area are shown in plan view in Fig. 1. Samples were collected from groundwater ('shallow' monitoring wells, 'deep' monitoring wells and production wells used for public water supply), surface water (Everglades ponded water, canals and lakes), and rainfall collection monitoring locations. All samples were collected in duplicate using glass scintillation vials wrapped with a layer of parafilm to prevent evaporation. Upon sample collection vials were rinsed three times with the water sample.

Groundwater well samples were collected using a portable pump. A minimum of three well casing

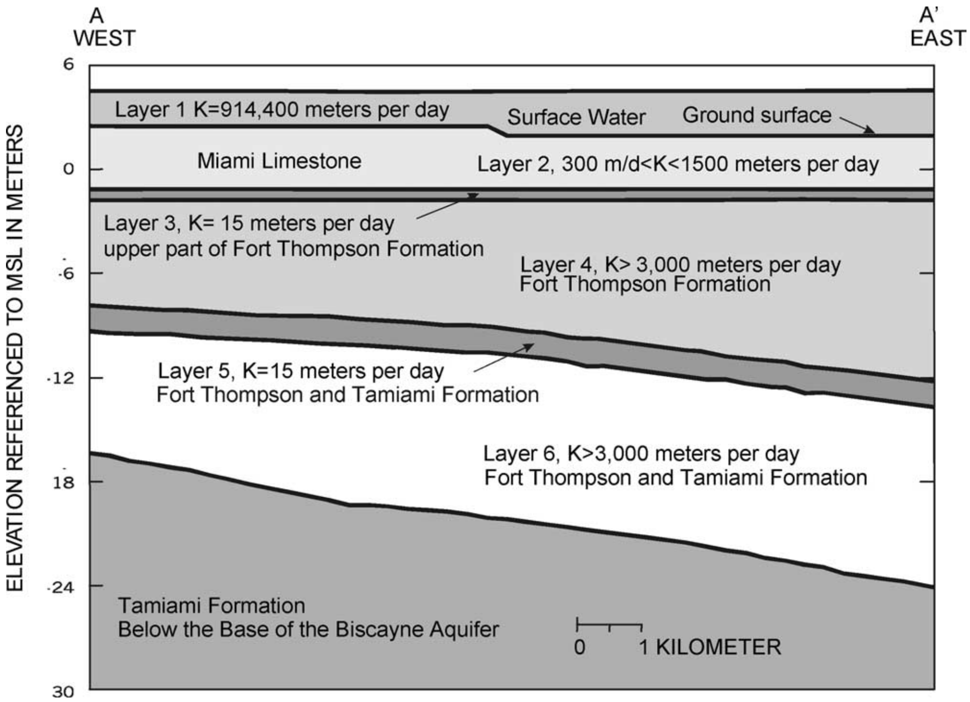

Fig. 2. Hydrogeologic layers of the Biscayne aquifer with hydraulic conductivities and layers as modeled for the study site by Nemeth et al. (2000).

volumes of water were removed from each well prior to sample collection to assure that a representative sample of surrounding groundwater was collected. The production well samples were taken directly from a spigot attached to the pumping well. These samples were obtained from either Well 29 or Well 30 at the West Wellfield, depending upon which pump was in operation on the day of sampling.

Surface water samples for sites other than the rock mining lakes were taken by immersing the scintillation vials below water surface in order to collect the samples. At the lakes, a pump was used to collect water from 10-foot depth intervals from the approximate center of each lake, resulting in the collection of 3–5 samples per lake depending upon which lake was sampled. No specific trend in the isotopic composition of the lake water was noted with depth so only the depth averaged values were used in this study. In order to shield collected rainwater from evaporation effects, rainwater collection bottles were filled with a two-inch deep layer of mineral oil prior to use. These bottles were fitted with a collection funnel and an air release port. As rain entered the collection apparatus, the buoyant mineral oil floated on top of the collected rain, minimizing rainwater interaction with the air thereby limiting evaporation of the sample. At collection time, a syringe was used to transfer the rainwater from below the mineral oil layer and deposit the sample into scintillation vials. Collection basins were then replaced with fresh bottles with mineral oil for the next sampling period.

A mass spectrometer (Prism, Micromass, Inc) was used to determine the hydrogen and oxygen isotope ratios of collected water samples. Isotope ratios are quantified as δ values in which

$$\delta = [(R_{\mathrm{SAMPLE}} - R_{\mathrm{STANDARD}})/R_{\mathrm{STANDARD}}]1000‰ \quad (1)$$

and R is defined as D/H for δD values and $^{18}O/^{16}O$ for δO values. These δ values are relative in nature and represent the positive or negative deviation from the standard which in this study was Vienna Standard Mean Ocean Water. Oxygen isotope ratios were measured by the carbon dioxide equilibration syringe method proposed by Matsui (1980) in which carbon dioxide is equilibrated with sample water and then isolated from water vapor and other trace gases prior to injection into the mass spectrometer. Two different methods were used to prepare samples for deuterium analysis in the mass spectrometer. Both methods involve reducing sample water into elemental hydrogen through use of a heated furnace packed with oxidizable material. The first method employed involved the use of a uranium furnace as outlined by Bigeleisen et al. (1952). The second method (Gehre et al., 1996) is similar in conception, but relies on the use of a chromium furnace rather than a uranium furnace.

Data quality was checked through an internal laboratory calibration of standards (Coplen et al., 1991) at the Biology Department's isotope research laboratory at the University of Miami and a split sampling exercise with the US Geological Survey (USGS) Isotope Laboratory located in Reston, Virginia. Results from this effort indicate that the standard deviation of the oxygen analysis was 0.19‰. For hydrogen analysis, the standard deviation was 1.64‰. The variability of the analysis was observed to be Gaussian distributed, so the 95% confidence limits were calculated as 1.96 times the standard deviation. The results from split samples between the two laboratories were statistically equivalent at 95% confidence.

4. Results and discussion

4.1. Comparison to the meteoric water line

The name 'meteoric' refers to water that has gone through at least a portion of the meteorological cycle (i.e. evaporation, condensation, precipitation, etc.). All water in this study is considered to be meteoric water. Meteoric water is characterized by an observed relationship between hydrogen and oxygen isotope ratios that can be quantified by what is known as the global meteoric water line (MWL) (Craig, 1961). Stable isotopic data for the two rainfall stations utilized in this study show that local rainfall for the study site is consistent with the global MWL (Fig. 3). Such results are consistent with data collected by others in Florida (Swart et al., 1989; Katz et al., 1995; Krukikas and Giese, 1995; Swancar and Hutchinson, 1995; Price, 2001; Harvey et al., 2002). Samples collected from ground water and surface water on the other hand (Fig. 4) plot below the MWL with a slope of 5.8, indicating that these waters were subjected to an evaporative process and possibly mixing of evaporated waters with rainwater. Of all the groundwater and surface water sampling locations,

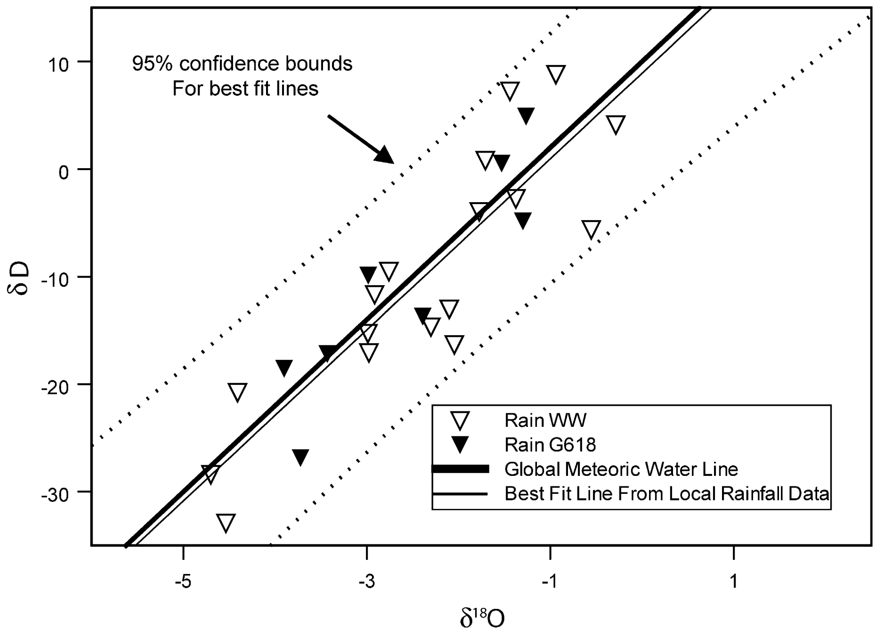

Fig. 3. δD versus $\delta^{18}O$ for rainfall samples.

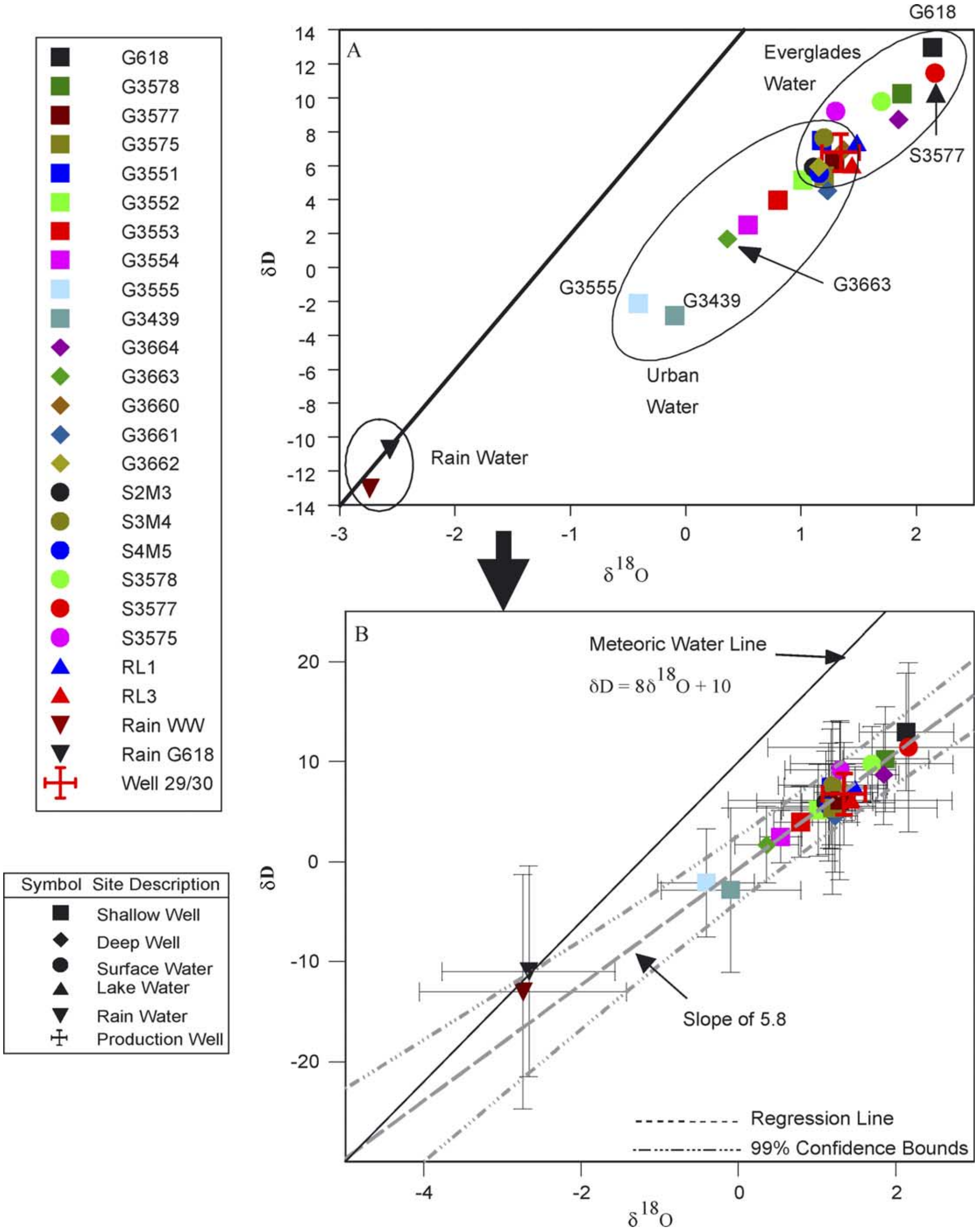

Fig. 4. Average δD versus δ^{18}O for each site (A) with 95% confidence bounds superimposed (B).

groundwater from wells G-3555 and G-3439 have water that is the most depleted in ^{18}O and D. These locations are the furthest east and, consequently, the most removed from the Everglades. Groundwater well G-618 and surface water station S3577, both located in the Everglades, have water that is the most enriched in ^{18}O and D. An overall pattern is observed from relatively enriched waters to relatively depleted waters as the sampling locations progress geographically from west to east. Given this trend, sampling locations have been grouped into Everglades water (those west of L-31N) and urban water (those east of L-31N). With the exception of water extracted from G-3663, the Everglades sampling locations are in general more isotopically enriched than the urban locations. The value for the pumping wells plots in the area of intersection between Everglades and urban groupings indicating that it is most likely drawing water from both sources (Fig. 4a).

In addition to giving insight to water movement within the study site, comparison to the MWL can point to an ultimate source of water to the area from a more regional perspective. Rainfall collected at the RainWW and Rain G-618 locations within the study area fall within the 95% confidence limits of the regression line derived from the study site's ground and surface water samples (Fig. 4b). This observation indicates that local rainfall is a strong contributor to the area's water supply and is further validated by the fact that 95% confidence bounds of the rainfall data and the regression line confidence bounds overlap greatly. The 95% confidence limits include the seasonal variability of the results at each sampling station.

4.2. West to east spatial analysis

To further emphasize the spatial effect of west to east water migration on isotope values within the study area, a plot of average $\delta^{18}O$ values vs. distance from pumping wells was produced (Fig. 5). Ninety-five percent confidence intervals have been incorporated into the plot to show the effect that seasonal variations can have on delta values. The plot shows a general trend of decreasing $\delta^{18}O$ values when moving from west to east in the focus area. This trend is due to the mixing of isotopically depleted groundwater (primarily from urban areas) in the eastern end of the transect with isotopically enriched Everglades water on the western end of the transect. Infiltrated

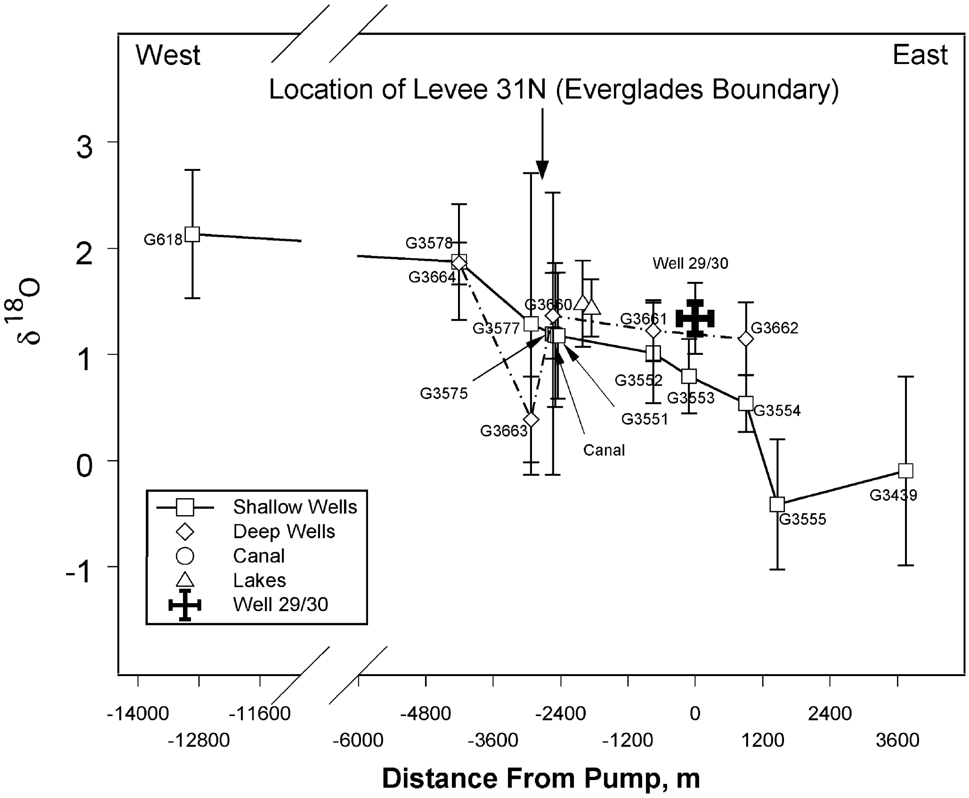

Fig. 5. $\delta^{18}O$ versus distance. Length of error bars corresponds to the 95% confidence bounds of the measurements at each sampling station.

water is more depleted on the urban side due to rapid drainage of rainwater. This rapid drainage occurs through an infrastructure of canals and groundwater infiltration trenches designed to prevent flooding of these areas and possibly through vertical conduits in the unsaturated zone of the Biscayne Aquifer due to karst-like conditions within the aquifer. Infiltrated water is enriched on the Everglades side due to evaporation effects on the standing surface water west of Levee 31N. The mixing of these two water sources results in the δ^{18}O values becoming more isotopically depleted with distance from the Everglades. The predominant portion of this trend is seen in the vicinity of L-31N, along the border between the Everglades and urban areas. In the Everglades, the trend is much less pronounced once far removed from this border as evidenced by the relatively small change from G-618 to G-3578 over a large distance. The average value for L-31N canal sampling points is seen to lie immediately between G-3575 and G-3551, the shallow wells immediately west and east of the canal, respectively. This illustrates that canal water is not significantly different from the shallow wells. This observation which is consistent with the local hydraulic gradient, indicates that the canal water is mixing with surrounding groundwater.

Also evident is that deep groundwater on the urban side is isotopically enriched relative to shallow water (Fig. 5). The deep water begins to diverge isotopically from shallow water at G-3575/G-3660, the easternmost of the Everglades wells. This divergence can be explained due to the mixing effect of isotopically depleted rainwater that rapidly infiltrates into the Biscayne Aquifer on the urban side of Levee 31N. While the shallow wells are significantly impacted by this infusion of rainfall, the deep wells do not show this effect as strongly (although, a decreasing delta trend is still evident with eastward migration). The primary exception to the deep groundwater trend was observed at G3663, which is isotopically depleted given its location. This exception is discussed in greater detail within Section 4.3.

Rock mining lakes and the pumping wells have water that is isotopically enriched for both their location and depth. One explanation for this observation at the lakes is isotopic enrichment at the surface of the lakes by the process of evaporation. The lakes also are influenced by the inflow of deep isotopically enriched water that originated in the Everglades since evaporation effects alone would not result in as large an enrichment as that observed. The importance of groundwater inflow on the isotopic composition of the lakes can be readily computed from an isotopic mass balance model established for the lakes (Herrera, 2000) which show that the dominance of the groundwater inflow is partly due to the relatively large depth of the lakes given their surface area. The pumping wells mirror the isotopic enrichment of the lake water supporting the hypothesis that water is being drawn into the wells from the rock mining lakes directly west of the wellfield. The only other source of such enriched water to the pumping wells could be Everglades water and it is unlikely that the municipal wellfield is drawing water directly from locations such as G-3578 and G-3664. This is not to say that water from these locations does not migrate to the wellfield. However, the time required for this migration would result in at least some mixing with more depleted, rain influenced water as is observed in the deep wells trendline. As such, results support the hypothesis that lake water is being drawn into the pumping wells (Fig. 5).

The results also show that the pumping well on average is isotopically enriched for its location and depth indicating an influence of lake water (Fig. 5). Other sources of water to the pumping well include both deep and shallow water in its immediate location. The confidence interval of the data collected for the pumping wells clearly encompasses the deep well average line indicating that the pumping wells are influenced by deep water. The shallow water in the area also asserts an influence as evidenced by the fact that the confidence interval of data for the pumping well overlaps at least partially the confidence intervals of surrounding shallow wells G-3553 and, especially, G-3552.

4.3. Rainfall and gate operation effects

The relative impact of rainfall events and S333 gate operation on the isotope delta values in the study area was assessed through the production of three-dimensional (3D) plots. These graphs (Fig. 6) plotted δ^{18}O vs. rainfall in centimeters vs. average flow in cubic meters per second at gate S333. In order to compare short and longer term effects, two sets of

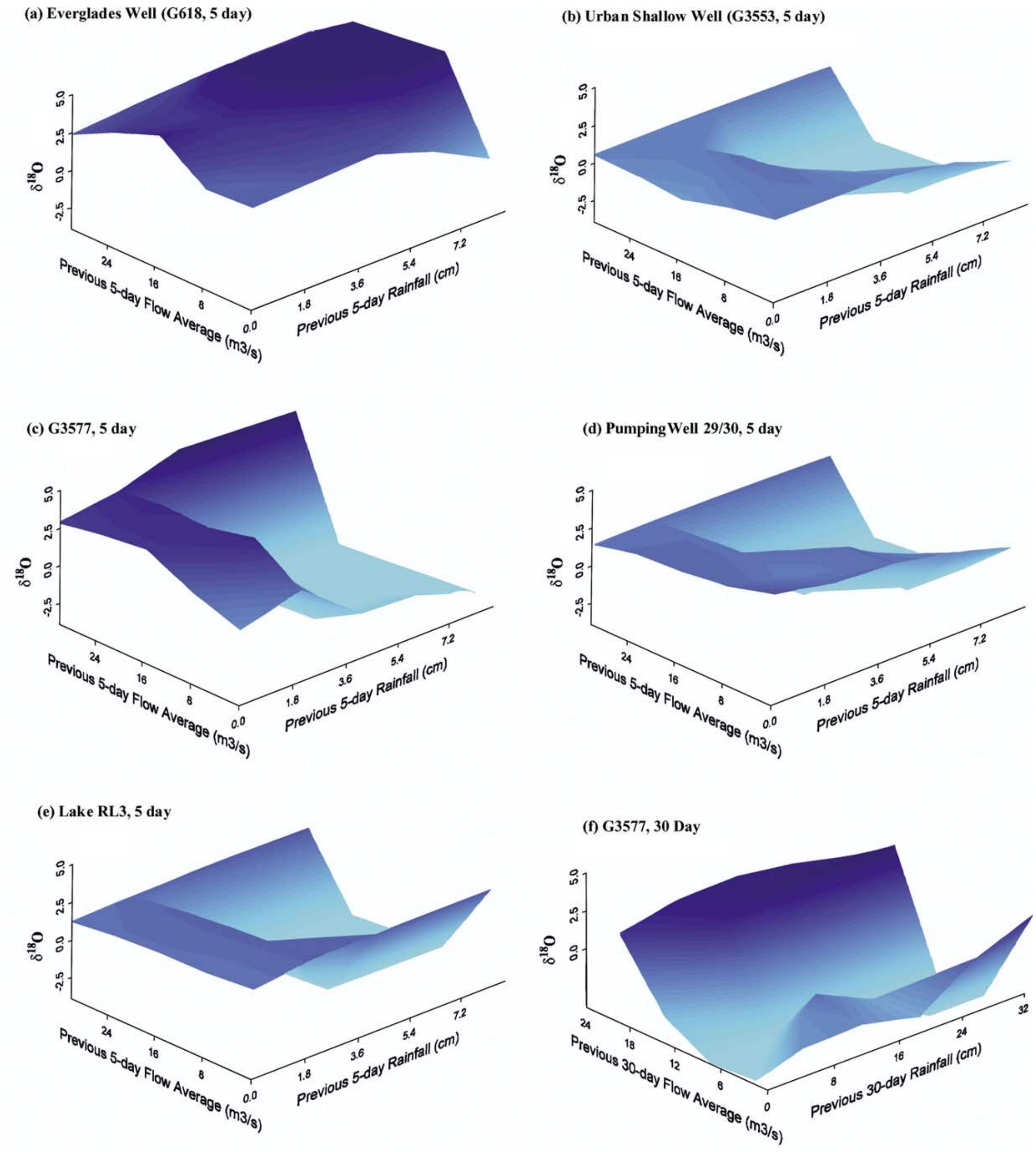

Fig. 6. Rainfall and gate operation effects on $\delta^{18}O$ values.

plots were made, one incorporating values for the previous 5 days and one incorporating values for the previous 30 days to sampling. Plots of this nature produce graphical surfaces that show the effects of both rainfall and gate operations on delta values. Enriched isotope values result in a darker color while more depleted values result in lighter shading. If no significant impact by these variables were observed, a nearly flat, uniformly shaded plane having very little slope or surface distortion would be produced (e.g. Fig. 6a). On the other hand, if rainfall and gate operations do have an influence on delta values, the graphical surface will appear to bend and distort from a planar shape and will contain both darker and lighter shadings (e.g. Fig. 6c).

In the short term, results showed that Everglades and urban sampling locations reacted differently to rainfall influences and influences from the operation of gate S333. For example, at G-618 (Fig. 6a), an Everglades shallow well, the sloping transition from dark shading to light shading towards more depleted δ^{18}O values as rainfall increases under low flow conditions indicates that at greater rainfall events, the δ^{18}O values are more isotopically depleted. However, in the presence of flow through gate S333, these rainfall influences are negated and δ^{18}O values remain isotopically enriched. A more consistent pattern is observed in urban wells and urban surface waters (the lakes and canal) where high rainfall events resulted in more depleted δ^{18}O values (Fig. 6b). This type of pattern is consistent with the expected outcome as depleted rainfall should cause a decrease in sampling location delta values as it mixes with more enriched in situ water. Additionally, the 5-day plots show that the shallow wells (Fig. 6b) and the deep wells were affected differently in the short term by rain and gate operations. The deep wells maintain a pattern similar to that of Everglades water (Fig. 6a) indicating that in the short term, they were not as affected by rainwater as the shallow wells.

The noticeable exceptions to these general trends occurred at G-3577/G-3663 (Fig. 6c) and at the pumping well (Fig. 6d) where the immediate influence of rainfall was observed despite the fact that these wells should show a pattern similar to that of G-618 due to their location or depth. For G-3663, this divergence can be explained by the presence of a large open cavity encountered during the drilling of the well. The increased hydraulic conductivity associated with the existence of this cavity supports the hypothesis that rain influenced water travels through the aquifer at this location more quickly than at other locations. As a result, in the short term, δ^{18}O values at G-3577 (Fig. 6c) and G-3663 are significantly decreased by rainfall events. This observation also explains the relatively depleted delta values for these wells observed in the meteoric (Fig. 4) and distance plots (Fig. 5). In contrast, at the pumping well (Fig. 6d), the very nature of the well itself will give insight into the variation. The fact that the well is drawing large quantities of water from the surrounding aquifer medium is the direct cause of observed differences from other deep (non-pumping) wells. The pumping well pulls water not only horizontally, but also vertically from more shallow areas than its screened intake. Although, the shape of the 3D plot points to a short-term rainfall influence similar to that of urban shallow wells, the overall values are more enriched than surrounding shallow wells. This would indicate that the pumping well draws a mix of both shallow and deep waters. Also of interest is the observation that the pumping well plot is similar to that of RL3 (Fig. 6e). Like the pumping well, RL3 exhibits a short-term rainfall influence, but overall is more enriched than shallow wells in its vicinity. This observation further confirms that the lakes have an influence on the pumping well.

The 30-day plots were in general much more planar than the 5-day plots as the greater time scale results in less drastic fluctuations in rainfall and flow measurements (not shown). While the differences in Everglades vs. urban and shallow vs. deep wells as observed in the 5-day plots can be further validated by the longer time scale, the 30-day plots are especially useful in examining the flow near G-3577 and G-3663. The rapid infiltration of rainwater at these wells has been discussed earlier through the 5-day plots. The 30-day plots of these wells (Fig. 6f) support this assertion, as for nearly any amount of rainfall and intermediate flow values (the most prevalent condition found throughout the course of the study) there is a sharp decline in δ^{18}O values at G-3577. It is also evident in this plot that at high flow conditions, δ^{18}O values increase dramatically indicating a correlation with operations of gate S333. The area directly beneath and immediately surrounding G-3577 acts as a sink for Everglades surface water. Over the larger time scale of 30 days, this collected water that infiltrates rapidly is gradually mixed with the in situ ground water. This is evidenced by the decrease in delta values under heavy rainfall conditions observed below G-3577 at G-3663 and at other surrounding wells including G-3578 and G-3575.

To make this concept clear, a schematic is provided (See bottom inset for Fig. 8). The extremely high seepage into the underground cavern beneath G-3577 flows into a 'conduit' of water that is isotopically different from surrounding groundwater. This conduit responds quickly to the composition of the surface water feeding the seepage. Over time, the predominant groundwater flow (moving from north-west to southeast) and further infusion of surface water cause water in this conduit to mix with surrounding groundwater, eventually reaching isotopic equilibrium and becoming indistinguishable from the groundwater. When the volume of seepage feeding the conduit is less, its range of influence is reduced. The predominant groundwater flow direction at this point is toward the southeast. It is, therefore, likely that this conduit takes water to the south of other sampling locations and does not regularly affect the delta values of the water extracted at these locations. In fact, it is only under heavy rain conditions when increased volumetric input to the conduit results in a greater east/west spreading of surface water influenced flow that mixing effects are observed in adjacent wells as mentioned above.

These observations are consistent with Harvey et al. (2002) who also observed groundwater of variable isotopic signatures in areas upstream of the study site, within the Everglades Water Conservation Areas. Harvey et al. (2002) observed that the source of fresh groundwater was evaporated surface waters with a few exceptions. These exceptions were characterized by groundwater with isotopic signatures similar to that of rainfall, again suggesting isolated areas where rapid infiltration occurs. Furthermore, it is emphasized that the rapid and localized infusion of rainwater at G-3663 is consistent with karst aquifer flow conditions (Celle-Jeanton et al., 2003; Gabrovšek and Dreybrodt, 2001; Siemers and Dreybrodt, 1998; and others). Jones and Banner (2003) for example found consistently among three tropical karstic aquifers that recharge occurs by rapid infiltration with little evaporation. Given the results observed within this study, recharge to the Biscayne Aquifer exhibits some karst flow behavior with rapid infiltration at discrete locations. These discrete inflows serve to augment recharge which is primarily dominated by the infiltration of evaporated surface water.

4.4. Modeling based on stable isotopes

A simple box model was created in order to estimate the contribution of Everglades water to the West Wellfield pumping stations. This model assumes that two isotopically different waters are drawn into the pumping well: Everglades type water (characterized by relatively high δ^{18}O values) and urban type water. The isotopic balance is, therefore, represented by the following two equations

$$x + y = 100\% \tag{2}$$

$$(\delta^{18}\mathrm{O_x})x + (\delta^{18}\mathrm{O}_y)y = (\delta^{18}\mathrm{O_p})100 \tag{3}$$

in which x is the percentage of Everglades water at the pumping well, y is the percentage of urban water at the pumping well, $\delta^{18}\mathrm{O}_x$ is the δ^{18}O value of Everglades water (taken as the δ^{18}O value at G-618), $\delta^{18}\mathrm{O}_y$ is the δ^{18}O value of urban water (taken as the δ^{18}O value at G-3555) and $\delta^{18}\mathrm{O_p}$ is the δ^{18}O value of water at pumping well 29/30.

This model was evaluated using different sets of input data. These sets included the overall average of all samples, the 1998 yearly data average, and the 1996/1997 combined data average. Also used as input for model runs were the averages of 'Summer' months (considered to be May through October), 'Winter' months (November through April), 'Dry' months (those having less than a total of 10.16 cm of rainfall during the thirty days prior to sampling), and 'Wet' months (those having more than a total of 10.16 cm of rainfall during the 30 days prior to sampling). The 95% confidence limits for the values of x and y from this analysis were computed as $\pm 5\%$ based upon a 95% confidence interval of 0.24‰ for the laboratory analysis of δ^{18}O.

This model, using data for the entire study period, shows that about 70% of the water pumped from the well is indicative of Everglades water while only 30% is indicative of urban water (Table 1). The simple model results also show that during dry winter conditions, when a smaller quantity of recharge is available, a greater demand is placed upon the contribution from Everglades groundwater from

Table 1
Percentages of everglades versus urban water pumped by west wellfield as estimated using a simple box model

	% Everglades water	% Urban water
Overall average	69	31
1998 average	66	34
1996-1997 average	72	28
Summer months	60	40
Winter months	86	14
Wet months	66	34
Dry months	74	26

about 60 to 85% (Table 1). This causes the percent composition of Everglades water in the pumping well to increase. The opposite trend is observed during the wet summer months. Summer months in general correlate to the wet season in South Florida during which rainfall recharges the urban system more consistently than during winter months. Consequently, a decrease in the quantity of Everglades water reaching the pumping well is observed during the wet summer conditions. The difference between the 1998 average model results and those of the 1996–1997 average is also most likely the result of rainfall differences. On average, there was less rainfall during 1996 and 1997 (128.3 cm) than in 1998 (133.2 cm) in the study area. Accordingly, the percentage of Everglades water returned by the model was higher in the drier 1996–1997 years.

While this simple box model is useful in assessing general trends, certain conceptual problems are inherent as a result of its simplicity. These include the lack of compensation for the direct isotopic influence of rainfall and inflow from water conservation areas at gate S333 on the system as well as the influence of any mixing across geologic layers in the rock mining lakes and evaporation of water at the lake surface. There is no simple way to redress these problems within the framework of this simple mass balance model. While introducing only rainfall to the model would result in a higher Everglades influence (as additional isotopically enriched Everglades water would be needed to balance the depleted rain input in the isotope balance), introducing only isotopically enriched lake water as an inflow would cause an increase in the observed urban influence. In order to address some of these problems, a more complex box model was developed.

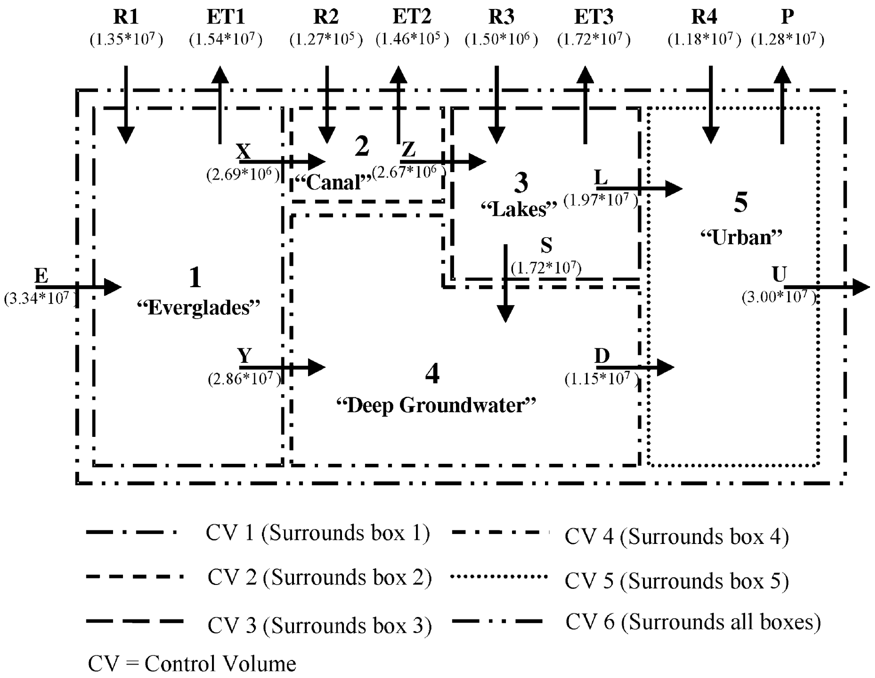

Fig. 7. Complex box model conceptualization and results. All units in m^3/year.

Table 2
Variables used for the complex box model

Box #	Box Description	Inputs [L^3/T]	Corresponding δ Values Used	Outputs [L^3/T]	Corresponding δ Values Used
1	Everglades	• Everglades water including inflow from S333 (E) • Rainfall [R1] over [A1]	• [G618] • [Rain G618]	• Evapo-transpiration [ET1] over [A1] • "Shallow" Groundwater (X) • "Deep" Groundwater (Y)	• [δ_{E1}] from Rain G618, S3575, S3577 & S3578 • [G3575] • [G3660]
2	Canal	• "Shallow" Groundwater (X) • Rainfall [R2] over [A2]	• [G3575] • [Rain WW]	• Evapo-transpiration [ET2] over [A2] • "Shallow" Groundwater (Z)	• [δ_{E2}] from Rain WW, 2M3, 3M4 & 4M5 • [G3551]
3	Lakes	• "Shallow" Groundwater (Z) • Rainfall [R3] over [A3]	• [G3551] • [Rain WW]	• Evapo-transpiration [ET3] over [A3] • "Shallow" Groundwater (L) • Seepage (S)	• [δ_{E3}] from Rain WW, RL1 & RL3 • [δ_L] from RL1 & RL3 • [δ_L] from RL1 & RL3
4	Deep Groundwater	• "Deep" Groundwater (Y) • Seepage from lakes (S)	• [G3660] • [δ_L] from RL1 & RL3	• "Deep" Groundwater (D)	• [G3662]
5	Urban	• "Shallow" Groundwater (L) • "Deep" Groundwater (D) • Rainfall [R5] over [A5]	• [δ_L] from RL1 & RL3 • [G3662] • [RainWW]	• Pumping Well [P] • Urban Water (U)	• [Well 29/30] • [G3555]

Variables in squares were measured and variables in circles were computed from the model.

For the complex box model, a 3.2 by 6.4 km rectangular area within the focus area was selected and broken into five conceptual boxes (Fig. 7), each of which were assumed to be well mixed. Specifications for these boxes are provided in Table 2. In this table, R refers to rainfall, A refers to area, ET refers to evapo-transpiration, P refers to the pumping well and subscripts to the delta notation indicate location of a collected isotopic sample (e.g. δ_{G618} would refer to the average isotopic value of samples collected at the G-618 monitoring location). $\delta_{E\#}$ (the delta value of evaporated air leaving a surface water in box '#') is calculated using the method proposed by Gonfiantini (1986) and δ_L is the average of the $\delta^{18}O$ values for RL1 and RL3. The calculation of δ_E using the method as proposed by Gonfianitini is dependent on the surface water delta value, the delta value of the air into which the water is being evaporated (obtained from a balance of the air delta value with that of collected rainfall), humidity and isotope fractionation and enrichment factors. The measured and model obtained variables in the complex box model are outlined in Table 2.

The complex model incorporates horizontal seepage flow terms between the boxes. An additional seepage term is incorporated into the lake box (box 3). This seepage term, while drawn as a vertical flow in the figure, in fact incorporates both movement through the bottom of the lakes and any inflow from the horizontal difference between the deeper semi-confining layer and the base of the lakes (approximately 1.52–3.05 m). In this regard, it is impossible for the model to distinguish between horizontal and vertical flow across the boundary between box 3 and box 4. While the lakes box incorporates an additional seepage term, the canal box does not. Canal seepage is considered to be only through the sides of the canal. This arrangement is considered to describe physically the system given that hydraulic gradients are very flat in the area of the canal resulting in horizontal flow lines.

The terms shallow groundwater and deep groundwater are used to distinguish between water moving in the Biscayne Aquifer above the deeper semi-confining layer (shallow corresponding to layers 2–4 in Fig. 2) and water moving between the deeper semi-confining layer and the base of the Biscayne Aquifer (deep corresponding to layer 6 in Fig. 2). The unknown flow values were calculated in the model by simultaneously solving equations created by performing isotopic and volumetric balances assuming steady state conditions and using six control volumes (geometric volumes in space through which fluid may flow) (Fig. 7). Take for example, the equations used in the balance of control volume one surrounding box one:

Volumetric balance:

$$E + R1 \times A1 - ET1 \times A1 - X - Y = 0 \quad (4)$$

Isotopic balance:

$$E\times\delta_{G618}+R1\times A1\times\delta_{Rain\ G618}-ET1\times A1\times\delta_{E1}-X\times\delta_{G3575}-Y\times\delta_{G3660}=0$$

For these equations, all variables are defined in Table 2. A full set of equations used are provided in Wilcox (2000).

Results of the complex box model for the overall average of the period of record (Fig. 7) indicate that water leaving the Everglades and seeping under Levee 31N preferentially moves in the layer between the deeper semi-confining layer and the base of the Biscayne aquifer. This is seen by a flow ratio of 10 to one in the deep groundwater as compared to shallow groundwater for the model run. Water in this semi-confined layer travels east until moving into the vicinity of the rock mining lakes. As the lakes cut through the deeper semi-confining layer, the model indicates nearly 60% of the deep groundwater flow travels up into the lake. Water from both the lake and deep groundwater then migrate eastward into control volume number five, the urban box. Here, the model flow terms indicate that the pumping well draws water from surrounding urban shallow groundwater, the lakes and deep groundwater.

The complex model is in many ways an improvement over the simple model. It incorporates rainfall and evapo-transpiration data. In addition, it accounts for the presence of both deep groundwater flow and the rock mining lakes. Another positive aspect of the complex box model is that it utilizes data from several of the isotope monitoring stations rather than only two as in the simple box model.

Despite all of the positive aspects of the complex box model, it is still only a conceptualization that does not fully account for north/south water migration or surficial Everglades flow. In addition, some of the sampling locations used in the complex box model were not monitored until the start of 1998 or later. As a result, at locations such as G-3660 too few data points are available to accurately perform additional model runs such as those done for the simple model that assess the impact of seasonal or conditional variations on the system. In addition, the areal size of the complex model was chosen so as to incorporate the rock mining lakes, the West Wellfield and Everglades isotope monitoring stations. As such, redefining the boundaries of the model could result in different model output.

One of the goals of creating the complex box model was to compare the results obtained from an isotopic and volumetric flow balance of the study site to the results of the existing MODBRANCH model of the site (Nemeth et al., 2000; Nemeth, 2000; Herrera, 2000), calibrated for 1997 data. MODBRANCH is a three dimensional, finite difference coupled ground and surface water model maintained by the United States Geological Survey. It can simulate steady and non-steady flow through irregularly shaped flow systems that include ponded surface water, aquifer layers of varying hydraulic conductivities and open channel reaches. Flows from the complex box model run were compared to the MODBRANCH model at two locations: the seepage under L-31N and the outflow from the rock mining lakes (Table 3). The results for the sum of the flows are both of the same order of magnitude with the seepage case having a 35% difference in the complex box model relative to the MODBRANCH model and the lake outflow case having only a 26% difference in the complex box model relative to the MODBRANCH model.

Table 3
Seepage rates below L-31N and outflows from lakes as estimated by the complex box model and the MODBRANCH model

Location		Complex box model for overall average cumulative flow (m^3/y)	MODBRANCH model for 1997 cumulative flow (m^3/y)
Seepage under L-31N	Shallow	2.69×10^6	2.85×10^7
	Deep	2.86×10^7	2.00×10^7
	Sum	3.13×10^7	4.85×10^7
RL1 and RL3 lake outflow	Shallow	1.97×10^7	1.51×10^7
	Deep	1.72×10^6	1.38×10^7
	Sum	2.14×10^7	2.89×10^7

The most likely reason for this difference stems from the fact that the model input data differ. While the complex model is dependent on at least some data from 1998 (such as at G-3660 where no data is available before 1998), the MODBRANCH model is based on data from 1996 and calibrated to data from 1997. Differences in rainfall, evaporation rates, etc. between different years could lead to changes in the cumulative flow volumes. Despite this, the results of the complex box model and the MODBRANCH simulation do match up well, especially given that the results were derived from entirely different approaches.

5. Conclusions

Based on the modeling results, a sketch of water movement in the area of L-31N is provided in Fig. 8. Results of the hydrogeologic review indicate the presence of two semi-confining layers in the otherwise highly permeable Biscayne aquifer. From a regional perspective, meteoric water plots show that the water in the site is coming from local rainfall (both Everglades and urban) with additional water the result of infusion of water at gate S333 from northern water conservation areas. Within the study area, it is known from regional water table maps, measured head differentials, and MODBRANCH modeling simulations that water moves in general from northwest to southeast on the Everglades side of L-31N and from west to east on the urban side of L-31N.

Isotopically enriched Everglades surface water, primarily comprised of water that has been affected by evaporation, infiltrates into shallow and deep water flow layers present in the Biscayne aquifer underlying the Everglades. Results show that that localized geologic disturbances can cause the rapid infiltration of isotopically depleted water, such as in the vicinity of USGS monitoring wells G-3577 and G-3663. Localized rapid infiltration of rainfall results in the formation of karstic-like ‘conduits’ of isotopically depleted water that travel along with the predominant groundwater flow pattern, gradually mixing with the surrounding groundwater until it comes into isotopic equilibrium. Such observations collectively indicate

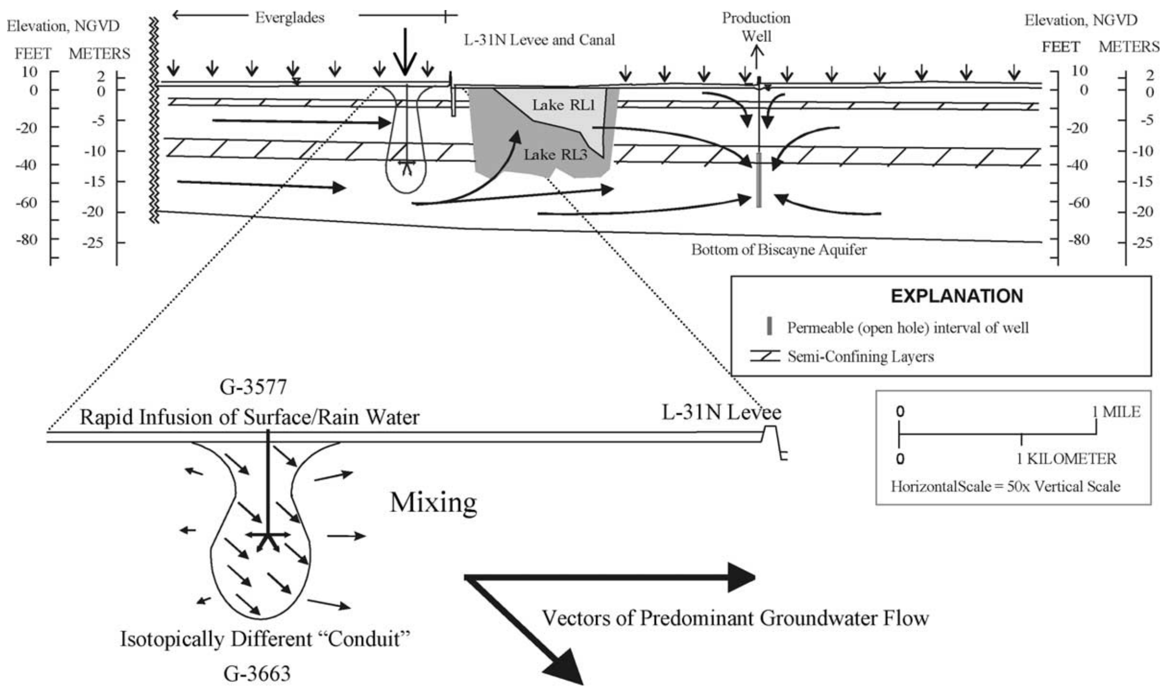

Fig. 8. Conceptualization of water movement for study site (cross section view).

that recharge of evaporated surface water to the Biscayne aquifer is augmented by discrete inflows of isotopically depleted water (e.g. rainwater) at discrete locations.

Upon nearing Levee 31N, Everglades groundwater begins to travel in a more easterly pattern, moving nearly horizontally with very little vertical migration in the geologic layers comprising the Biscayne aquifer. The results of the complex box model (and the MOBRANCH model) indicate that on the order of 30 million cubic meters of water per year is seeping under the portion of L-31N between mile 3 and mile 5 (adjacent to the West Wellfield) into the urban side of the study site. This water moves in the both the shallow flow layer above the deeper semi-confining layer (Layer 5, Fig. 2) and the deep flow layer between the deeper semi-confining layer and the base of the Biscayne aquifer. Isotopic and volumetric balances suggest that Everglades water is preferentially moving into the deep flow layer prior to seeping under the Levee. This indicates that the L-31N canal, which cuts through a portion of the shallow groundwater flow, does not act as a hydrologic boundary between Everglades and urban waters. Additionally, the relative isotopic similarity between canal water and surrounding shallow groundwater on both the Everglades and urban sides of L-31N seem to indicate that the canal is mixing with groundwater rather than acting as a boundary.

Once on the urban side of L-31N, rainwater rapidly infiltrates into the shallow flow layer, progressively mixing with groundwater and making it more isotopically depleted as it travels east. The plot of $\delta^{18}O$ values vs. distance from the pumping wells shows that this effect is also seen in the deep flow layer, however not as drastically. Near the lakes, the ‘breaks’ in the semi-confining layers that are a by-product of rock mining allow deep Everglades water to mix with the lake water, thus providing a hydraulic connection between the lakes and deep groundwater. The inflow of deep water in conjunction with the evaporation effects evident in the plot of $\delta^{18}O$ values vs. distance (Fig. 5) make the lakes isotopically enriched. Results of the complex box model agree with this assertion, illustrating that some water is indeed moving up into the lakes from a deep groundwater source.

Water from both the lakes and the deep groundwater continue to migrate to the east until the operations of the municipal pumping wells at the West Wellfield causes some of this water to be drawn into the production well intakes. These intakes are screened to a depth well below the deeper semi-confining layer and, consequently, draw upon not only shallow urban water (predominantly comprised of urban rainfall) and lake water (having influences from both urban rainfall and Everglades water) but also deep water that originated in the Everglades. Results of the simple box model indicate that more than 60% of the water being pumped by the West Wellfield ultimately originates in the Everglades. Additionally, during drier weather conditions, the proportion of Everglades water at the West Wellfield is seen to increase as urban rainfall is not as readily available to recharge the Biscayne aquifer. The combined examination of the hydrogeology, isotopic characteristics, and water migration patterns in the immediate vicinity of L-31N and the West Wellfields of Miami-Dade County leads to the conclusion that Everglades water, both directly through groundwater flow in deep semi-confined units of the Biscayne aquifer and indirectly through mixing with rock-mining lakes in the area, is indeed being drawn into the operating municipal wellfields.

The conclusions presented in this paper point to the need for further research near the West Wellfield and Everglades National Park. While, this research clearly indicates that Everglades water is being pulled into municipal pumping wells and that rock mining practices in the area serve to mix groundwater vertically, a more in-depth isotopic study of the region would be useful in further evaluating groundwater movement in the region. In particular, it would be of interest to determine the additional amount of seepage from the Everglades induced by rock-mining and well pumping activities. Such studies would be useful in analyzing the impacts of the pending Comprehensive Everglades Restoration Project that seeks to alter the surface water flow pattern through the Everglades.

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