An Isotopic Study of Northeast Everglades National Park and Adjacent Urban Areas

Third Interim Technical Report for Isotope Study, Phase I

Prepared for Everglades National Park
as per scope of services dated June 12, 1997

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ABSTRACT

As part of a comprehensive project evaluating the hydrology of the West Wellfield/L-31N site, an isotopic study was initiated to evaluate the sources of water to the wellfield and the potential impacts of rock mining lakes on water flows within the area. The site incorporates northeast Everglades National Park, including the eastern edge of Shark River Slough, as well as the western extent of sub-urban Miami. As per scope of services with four different funding agencies (SFWMD, USGS, ENP, and Kendall Properties and Investments), a total of 580 water samples were collected from January 1996 through December 1998. Samples were analyzed for their isotopic composition (^{18}O and D) using standardized methods which are based upon the conversion of oxygen and hydrogen into a form that can be measured by a mass spectrometer. Data collected early during this study confirmed that the isotopic composition of water was a suitable tracer of Everglades water given that differences were observed between water found deep within the Everglades and recharge within urban areas.

Results from this study indicate that the majority of water within the study site originates from local rainfall, with additional inputs from Water Conservation Areas located immediately to the northwest of the site. Surface waters within the Everglades side of the study site are generally evaporated as evidenced by their high isotopic values (^{18}O > 1.0 and D > 6). Heavy Everglades surface water is the source of shallow and deep groundwater in the Everglades. At one location adjacent to Levee 31N, it was found that surface water infuses very rapidly presumably due to a local geologic disturbance. This rapid infusion of water results in a "conduit" of isotopically light water (after large rain events) that travels along with the southeasterly groundwater flow pattern, gradually mixing with the surrounding groundwater. Upon nearing Levee 31N, Everglades groundwater flows in a more easterly direction within a series of geologic layers within the Biscayne aquifer which appear to be semi-confined. Groundwater within the urban side is generally very light (similar to that of un-evaporated rainfall) at shallow depths and relatively heavy (similar to that of Everglades water) at large depths. Lakes within the study site serve as "breaks" between the geologic layers causing deep groundwaters (which originate from the Everglades) to mix with shallow groundwater (which originate from recharge within the urban side of the site). Water from both the lakes and the deep groundwater continue to migrate toward the east until the operations of the municipal pumping wells at the West Wellfield causes this water to be drawn to the intakes.

Two box models were developed through this study to quantify flows between different regions within the study site. The models, one called the "simple" model and another called the "complex" model, were based upon water and isotopic balances. The simple model indicates that more than 60 percent of the water pumped by the West Wellfield, ultimately originates from within the Everglades; the proportion of Everglades water to the West Wellfield increases during drier weather conditions. Results from the complex model indicate that Everglades waters move preferentially through deeper groundwater layers within the Biscayne aquifer. Water within these deeper groundwater layers move east until they reach the rock mining lakes where the majority of the deep groundwater flows through the lakes. Water from both the lake and the lowest groundwater layers then migrate eastward and a portion of this water is drawn by the municipal wellfield.

PROJECT STATUS AND FOCUS OF THIS REPORT

The University of Miami project investigating the West Wellfield/L-31N site is separated into two phases: an isotope study (phase I) and a hydrologic modeling effort (phase II). This report presents the results from the isotope study (phase I) which includes analysis of: surface water, groundwater and rainwater collected from within Everglades National Park, groundwater and rainwater from the West Wellfield, and canal water from L-31N. Two earlier reports on the isotope portion of the study have been prepared. The first one titled, "Sources of Water to the West Wellfield," and dated July 10, 1998 summarizes the isotope data corresponding to the first 150 samples analyzed. A second report titled, "An Isotopic Study of Two Rock Mining Lakes," dated March 8, 2000 focused on establishing the physical, physico-chemical, and isotopic characteristics of two rock mining lakes located between the West Wellfield and northeast Everglades National Park and corresponds to another 110 samples that were collected from the two rock mining lakes. It was found during the analysis of the lake data that negligible variations in isotopic composition were observed with depth. Therefore, in the report included herein, the lake data corresponds to the depth average.

The hydrologic modeling effort (phase II) is funded by the U.S. Geological Survey (USGS). The focus of the hydrologic model was to estimate seepage below Levee 31N and to develop an algorithm for estimating real-time seepage rates. The final report documenting these results has been approved for publication by the USGS as Water Resources Investigations Report 00-4066. Copies of the USGS publication will be distributed to interested parties once it is available.

Funding for the isotope portion of the West Wellfield/L-31N study was received from four different agencies: the South Florida Water Management District (SFWMD), Kendall Properties and Investments Inc., the USGS, and Everglades National Park (ENP). ENP and the USGS funded the analysis of the last 320 samples and the results presented herein includes an analysis of all the isotopic data (580 samples) collected. Earlier reports (Solo-Gabriele 1998; Solo-Gabriele and Sternberg 1998) included a more thorough description of the motivation for the West Wellfield/L-31N study, more details concerning the characteristics of the study site, justification for use of stable isotopes as tracers for water flow in the area, and a description of the quality control program for the isotope analysis. Please refer to the earlier reports for these details.

ORGANIZATION OF REPORT

This report is separated into two chapters: administrative background (chapter I) and technical results (chapter II). A chapter on administrative background was considered necessary due to the fact that four different funding agencies provided financial support for this study, each with its own contractual requirements. A summary of agency funding as well as contractual obligations associated with sample analysis are included within the first chapter. For additional details concerning the technical content of this study please refer to Wilcox 2000.

ACKNOWLEDGMENTS

We thank Tom Van Lent of ENP for facilitating funding for this portion of the project.

DISCLAIMER

Opinions and recommendations provided within this report do not necessarily represent the views shared by the agencies that funded this project.

CHAPTER I
ADMINISTRATIVE BACKGROUND

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I.1 SCOPE OF WORK

As per scope of work provided by ENP dated June 12, 1997, the remaining samples (of 580 total) were analyzed for their isotopic (oxygen-18 and deuterium) composition. The isotopic data were utilized in conjunction with water balance models to determine the amount of Everglades water contributing to the West Wellfield and to obtain a better understanding for water flows within the area.

I.2 SAMPLES COLLECTED AND ANALYZED

A total of 580 samples for isotopic analysis have been collected and analyzed. These analyses meet the contractual requirements for agreements with SFWMD, Kendall Properties and Investments, Inc., ENP and the USGS. Among the 580 samples, 110 were collected from rock mining lakes and 470 were collected from the remaining sampling sites which included shallow and deep groundwater monitoring wells, municipal pumping wells of the West Wellfield, canal water from L-31N, rain water, and surface water from within the Everglades. This report summarizes the results from all 580 samples.

I.3 FUNDING SOURCES

A total of $113,150 was received for the project as a whole. Of this amount, $48,750 were received for the isotope portion of this study (Phase I). Refer to table 1 for more details concerning funding and contractual obligations. In-kind contributions were received from the U.S. Geological Survey in the form of core drilling and analysis, from the South Florida Water Management District in the form of well drilling, and from Miami-Dade Water and Sewer Department through the provision of a rain sampler enclosure.

Funding Source	Phase I		Phase II	Contract End Date	Contract Status
	Funds Received	# Samples per Contract	Funds Received		
South Florida Water Management District	$12,500	147		May 31, 1998	Completed
Kendall Properties and Investments Inc.	$12,500	138		July 31, 1999	Completed
U.S. Geological Survey	$10,000	118	$64,400	Sept. 30, 1999	Report Drafted for Hydrologic Model. Report Drafted for Isotope Analysis.
Everglades National Park	$13,750	162		April 2000	Report Drafted
TOTAL	$48,750	565	$64,400		
Grand Total for Phase I and II = $113,150					

Table 1: Funding Sources

I.4 PROJECT PERSONNEL

Dr. Helena Solo-Gabriele, Assistant Professor in the University of Miami's Department of Civil, Arch., and Environmental Engineering, supervised the research project. Dr. Leonel Sternberg, Professor of the Department of Biology, supervised isotope analysis. The following students (in order of graduation dates) were supported on the project.

Name: Gudrun Ibler
Degree: Earned Equivalent to a U.S. Master's Degree from Technical University Graz, Austria. Thesis Work Completed at U.Miami. Academic Specialization in Infrastructure and Environmental Management.
Thesis Title: A Hydrologic Analysis of the West Wellfield and Vicinity Using Stable Isotopes as Tracers
Research Tasks: Stable Isotopes
Dates of Support: August 1997 to February 1998

Name: Mark Nemeth
Degree: Ph.D in Civil Engineering (Environmental Specialization), University of Miami. January 2000.
Thesis Title: Use of the Reach Transmissivity Leakage Relationship to Quantify the Exchange Between Groundwater and Surface Water.
Research Tasks: Seepage Meter Tests and Model Development for Levee 31N
Dates of Support: July 1997 to December 1999.

Name: Alberto Herrera
Degree: Master of Science in Civil Engineering (Environmental Specialization), University of Miami. July 2000 (Expected)
Thesis Topic: The Limnology of Two Rockmining Lakes
Research Tasks: Stable Isotopes, Lake Studies
Dates of Support: December 1997 to August 15, 1999

Name: Walter Wilcox
Degree: Master of Science in Civil Engineering (Environmental Specialization), University of Miami. July 2000 (Expected)
Thesis Topic: A Stable Isotope Study of East Everglades National Park and the West Wellfield
Research Tasks: Stable Isotopes, L31N Canal, West Wellfield, and East Everglades
Dates of Support: September 1998 to December 1999.

Several undergraduate students were also involved on the project assisting with field and laboratory work. These students include: Jennifer Loschak, Naila Hosein, and Timothy Desmarais. Timothy has since graduated with his Bachelor's degree in environmental engineering degree and is working as a graduate student at the University of Miami. Jennifer has graduated with a Bachelor's in environmental science (conservation management specialization). Naila completed her Bachelor's degree in environmental science specializing in environmental engineering and is working as a graduate student at the University of Miami. Both Jennifer and Naila utilized the project as their academic internship which was a requirement for their undergraduate degree.

I.5 REPORTS, PAPERS, AND PRESENTATIONS DEVELOPED FROM THIS STUDY TO DATE

Reports and Papers

Solo-Gabriele, H.M., 1998. *Sources of Water to the West Wellfield*. Interim Technical Report for Isotope Study, Phase I. Submitted to the South Florida Water Management District, West Palm Beach, FL.

Solo-Gabriele, H.M., and Sternberg, L., 1998. "Tracers of Everglades Waters." *WEFTEC'98, Proceedings of the Water Environment Federation 71th Annual Conference & Exposition, Orlando, FL.* Volume 4: 323-333.

Solo-Gabriele, H.M., Sternberg, L., Ibler, G., and Nemeth, M., 1998. "A Seepage Study of the East Everglades." *Abstracts of the 1998 Spring Meeting of the American Geophysical Union, Boston, Massachusetts, EOS Supplement, April 28, 1998*. p.S93.

Solo-Gabriele, H., and Nemeth, M., 1999. "Methods for quantifying ground-water seepage beneath Levee 31N, Miami-Dade County, Florida, Abstract." *Proceedings of the First Annual South Florida Restoration Science Forum, Boca Raton, Florida, May 17-19, 1999*. p. 106-107.

Ibler, G., Solo-Gabriele, H., and Sternberg, L., 1999. "A Hydrologic Analysis of the West Wellfield and Vicinity Using Stable Isotopes as Tracers." *Proceedings of the International Symposium on Isotope Techniques in Water Resources Development and Management, Vienna, Austria, May 10-14, 1999.* IAEA-SM-361, p. 152-153.

Solo-Gabriele, H., and Herrera, A., 2000. *An Isotopic Study of Two Rock Mining Lakes.* Second Interim Technical Report for Isotope Study, Phase I. Submitted to Kendall Properties and Investments.

Nemeth, M., Wilcox, W., and Solo-Gabriele, H., 2000. *Water Resources Investigations Report 00-4066 Quantification of Ground-Water Seepage Beneath Levee 31N, Miami-Dade County, Florida.* U.S. Geological Survey.

Presentations

"A Hydrologic Analysis of the West Wellfield and Vicinity Using Stable Isotopes as Tracers." May 1999, International Symposium on Isotope Techniques in Water Resources Development and Management, Vienna, Austria

"Tracers of Everglades Waters." October 1998, Water Environment Federation National Conference, Orlando, Florida.

"Sources of Water to the West Wellfield." July 1998. South Florida Water Management District, West Palm Beach, Florida. (Invited).

"A Seepage Study of the East Everglades." May 1998. American Geophysical Union, Boston, Massachusetts. Poster Session.

"New Insights into the Hydrology of the West Wellfield and Eastern Everglades, Miami-Dade County, FL." May 1998. Miami Geological Society, Miami, Florida. (Invited).

CHAPTER II
TECHNICAL RESULTS

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II.1 DESCRIPTION OF SITE

The West Wellfield/L-31N site (figure 1) incorporates northeast Everglades National Park and the western extent of suburban Miami. Major roadways within the site include Tamiami Trail (S.W. 8 Street), Krome Avenue (S.W.177 Avenue), and Kendall Drive (S.W. 88 Street). The area (42 mi^2 or 110 km^2) is characterized by generally flat topographic relief. Ground elevations within the site range from 4 to 8 feet above mean sea level. The site includes three groundwater pumping wells (combined flow of 23 ft^3/s or 0.66 m^3/s) which draw water from the Biscayne aquifer. The two lakes (lakes RL1 and RL3) that were the focus of the earlier lake study are located in the central portion of the study site between Levee 31N and the municipal production wells.

The primary canal system within the interior of the site is the L-31N Canal, which lies 2 miles (3 km) to the west of the wellfield. The L-31N Canal is roughly 100 feet (30 m) wide and has a maximum depth of 20 feet (5.2 m). Immediately to the east is a discontinuous levee system which permits for rapid drainage of the areas east of L-31N Canal. Throughout most of the site the groundwater table is at a depth of 3 to 6 feet from the ground surface, and the canal intersects the upper portion of the aquifer permitting a permanent hydraulic connection.

A long range monitoring program has been implemented by local government agencies to determine groundwater and surface water impacts resulting from pumpage of the West Wellfield. Data are generally collected in hourly time increments and are readily available through either the USGS, SFWMD, or ENP. As observed from figures 1 and 2, the inner portion of the West-Wellfield site is extensively monitored. All of the shallow (10 foot depth) groundwater monitoring wells east of L-31N have been operational since April 1994 and shallow wells located within 1 mile west of L-31N have been operational since October 1995; a few shallow wells have a longer period of record dating back to the 1950s. Five deep (> 45 feet deep) wells were installed during 1997-1998 as part of the study plan reported herein. One of these wells, G3660, was instrumented for continuous water level measurements.

Five flow monitoring stations are located along the length of the L-31N Canal and are spaced at either 1 or 2 mile intervals (1M1, 2M3, 3M4, 4M5, 5M7). These stations are fitted with stage recorders and acoustical velocity meters which have been calibrated extensively by the USGS (Swain, 1992). Several surface water control structures are located within the study site. Stage is monitored at most of these structures; flow is monitored only at the major structures. Rainfall is measured continuously at three locations within the site using tipping-bucket rain gages (S338, G3553, S336). A weather station is located at Miami International Airport, 10 miles east of the site and at Tamiami Trail located approximately 15 miles west of the site. The data collected at these weather stations are suitable for estimating rates of potential evapo-transpiration.

Site Geology

The portion of the Biscayne aquifer located in the study area consists of highly permeable limestone having a very high hydraulic conductivity (values as high as 3 x 10^6 ft/day) and includes three formations: the Tamiami Formation, the Fort Thompson Formation, and Miami Limestone (Fish and Stewart, 1991). The base of the Biscayne aquifer slopes from a high point of approximately 44 feet below mean sea level in the northwest corner of the study area down to an elevation of roughly 84 feet below sea level in the southeast corner. Only the top highly permeable

portion of the Tamiami Formation is included within the Biscayne aquifer. The top of this formation slopes from 32.5 feet below sea level in the northwestern corner of the study area to 52.5 feet below sea level in the southeastern corner. The Fort Thompson Formation is between the Tamiami Formation and the Miami Limestone. Both the Fort Thompson Formation and the Tamiami Formation of the Biscayne aquifer have estimated hydraulic conductivities of at least 20,000 ft/d. Land surface within the study area is approximately 6 to 8 feet above sea level. The Miami Limestone generally is found from surface elevation to about 8 to 12 feet below ground level (Causaras 1987). The overall hydraulic conductivity of the Miami Limestone (1000 ft/d to 5000 ft/d) is generally lower and more variable than that of the Fort Thompson Formation and the portion of the Tamiami Formation above the base of the Biscayne aquifer.

Recently, geologic study in the area has turned to determining the existence of semi-confining layers within the Biscayne aquifer. In the study area, there are two semi-confining layers of low-permeability limestone (Figure 3). The shallower 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. From a compilation of existing data, it has been determined that this layer begins about 10 ft below ground elevation and is roughly 2 feet thick, extending to a depth of 12 ft below ground elevation. This layer is very consistently found at this depth within the focus area of the study site and can be taken to be horizontal with only very localized variations.

The deeper semi-confining layer was not found to be as regularly horizontal as the first. On average, the layer is 5 feet thick and begins at a depth of 35 to 40 feet below ground surface elevation (and approximately 30 to 35 feet below mean sea level) in the focus area. Across the entire study site, this deeper layer slopes from a top elevation of 22.5 ft below sea level in the northwestern corner of the area to 42.5 ft below sea level in the southeastern corner and is taken as five feet thick. From available data, this layer appears to have roughly the same slope as the contact between the Tamiami Formation and the Fort Thompson Formation, as outlined by Causaras (1987). This seems reasonable as the contact of the Tamiami Formation and the Fort Thompson Formation is only five feet deeper (approximately) than the bottom of the semi-confining layer.

Wilcox, 2000, provides a detailed summary of geologic data supporting the existence of these hard layers. A considerable amount of very recent geologic data has been collected and analyzed through Kevin Cunningham of the USGS Miami Subdistrict Office whose work focuses on establishing the areal extent and inter-connected nature of these hard layers.

Groundwater Flow / Seepage

Ground-water flow characteristics for the area are available in several forms. Regional water table maps indicate a ground-water flow pattern from west to east within the study area (Fish and Stewart, 1991). However, as the site incorporates the West Wellfield of Miami-Dade County, ground-water flow in the area is affected by operation of the wells. In addition, the several lakes formed as a result of rock mining may also affect flow patterns throughout the region. A representative example of ground-water elevations in the study area is provided in Figure 4.

Seepage meter tests were performed by Nemeth et al., 2000, at 6 sites in the vicinity of the L-31N Levee. These sites were located from 1.5 miles west to 0.2 miles west of Levee 31N within northeast Everglades National Park. The seepage meter tests showed that seepage generally increases as the levee is approached from the west. The largest seepage values were found at G3577 and at a point midway between G3577 and Levee 31-N.

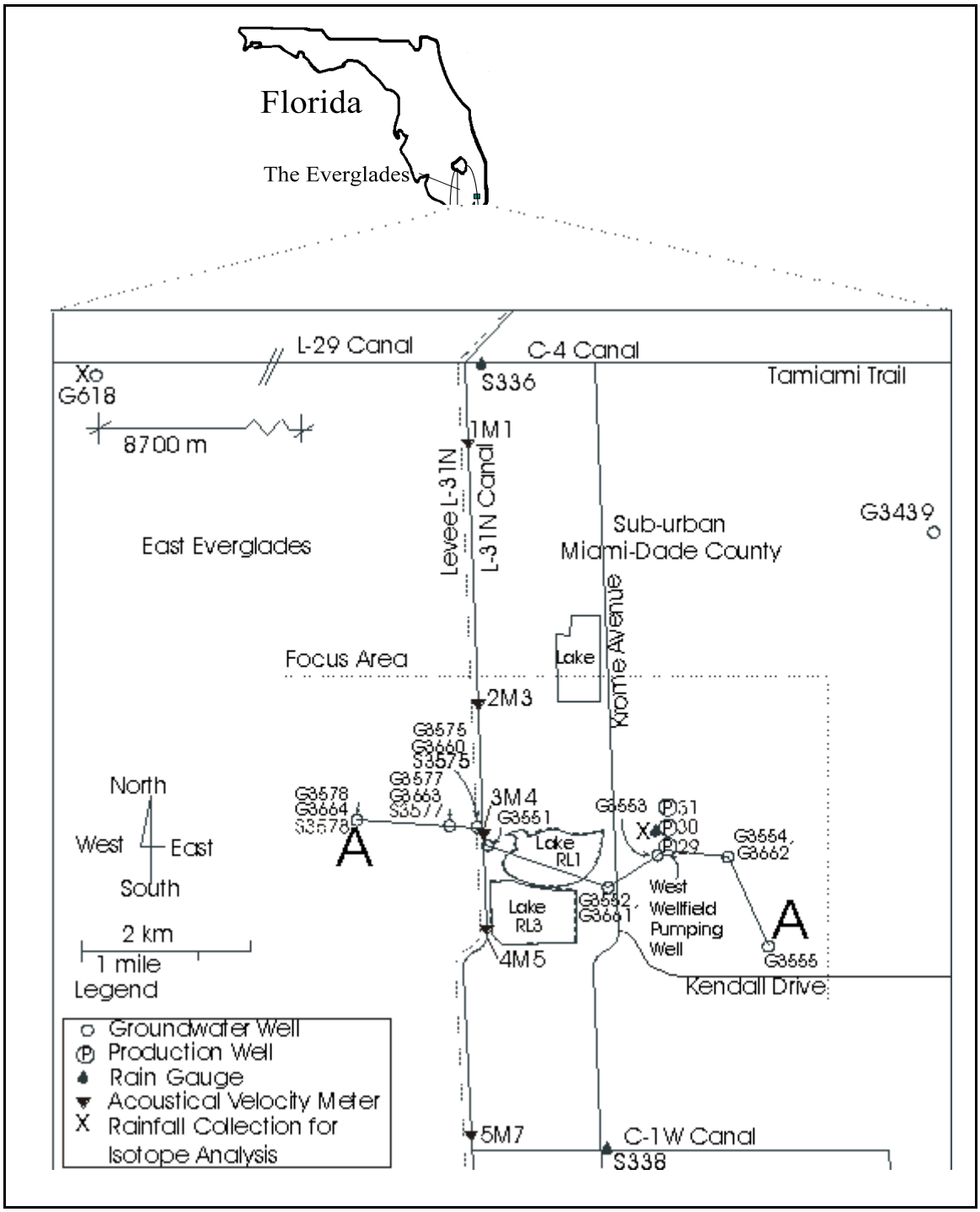

Figure 1: Location of the West Wellfield/L-31N Site

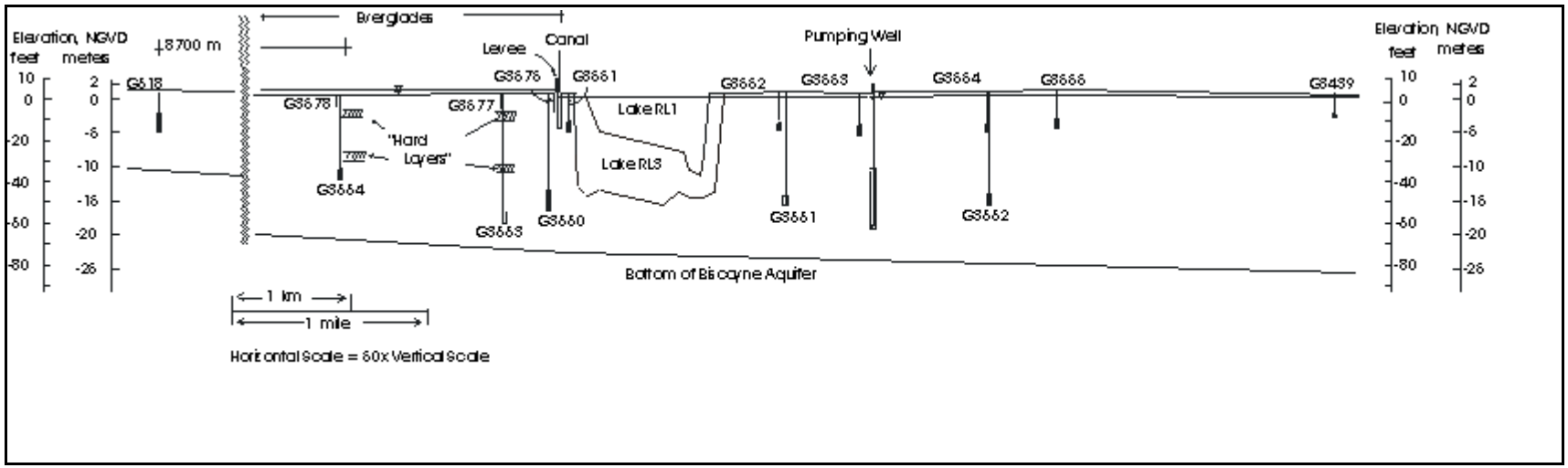

Figure 2: Cross Section A-A. See figure 1 for section location.
Note the screened or open interval of a well is given by the box near the bottom of each well.

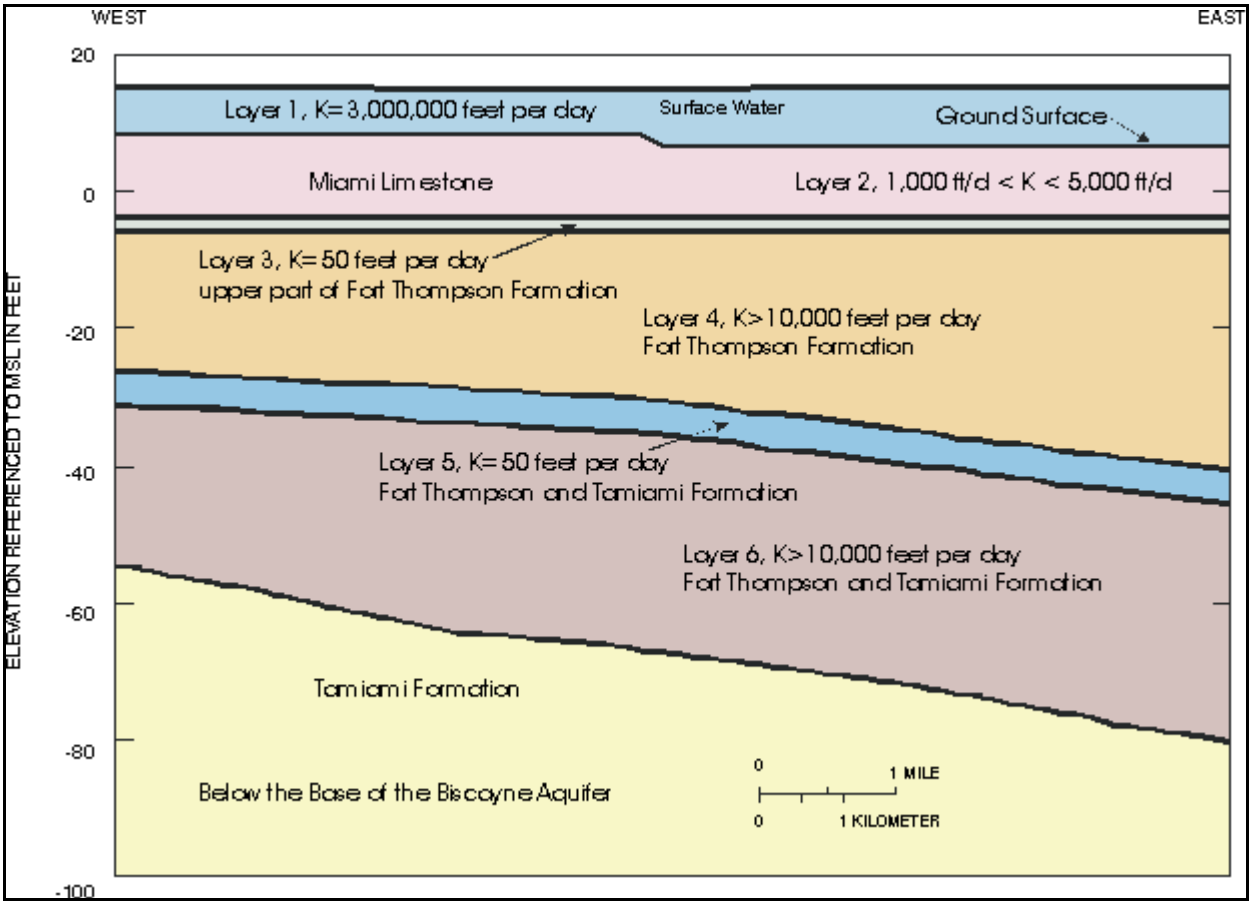

Figure 3: Geologic Map of Site (from Nemeth et al. 2000)

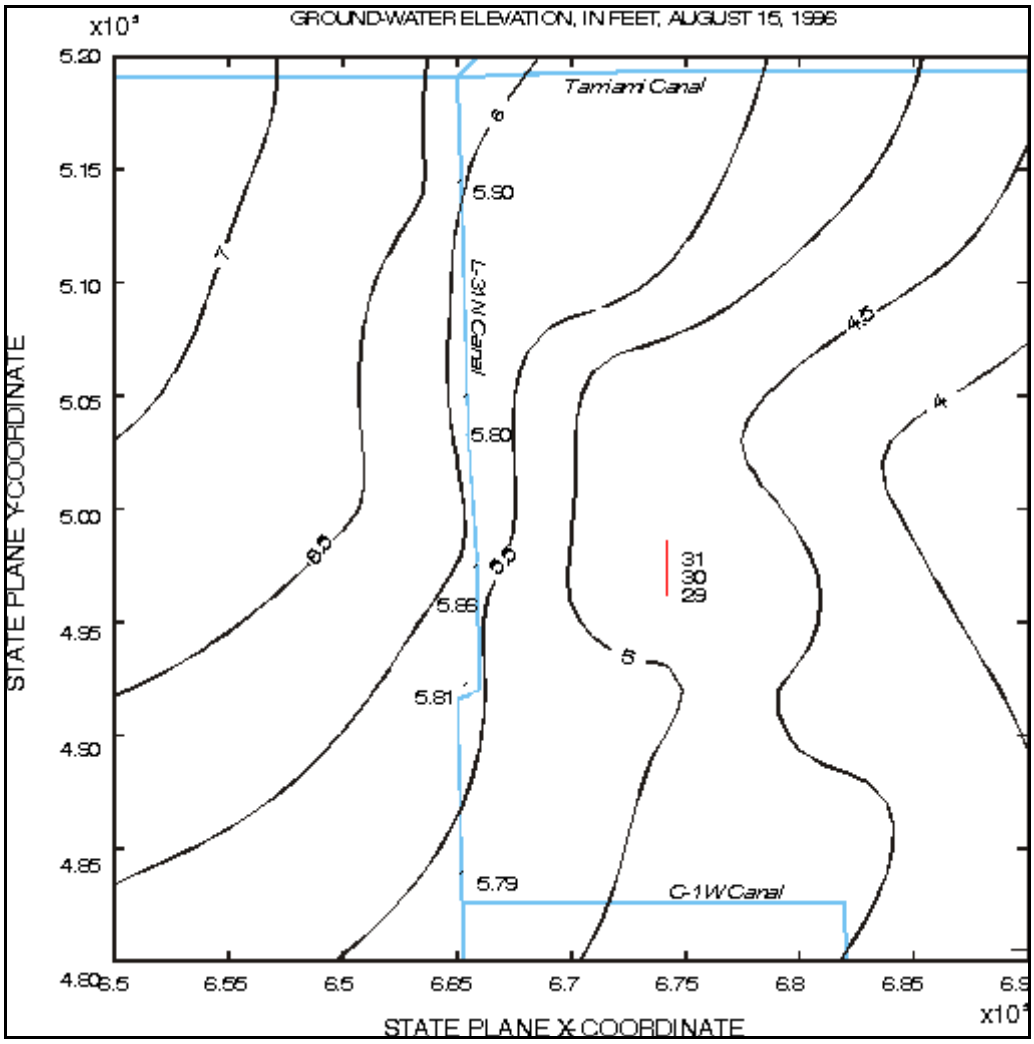

Figure 4: Groundwater Contours at Levee 31N Site (August 15, 1996)

II.2 Sample Collection and Isotope Analysis

Samples were collected during a period ranging from January 1996 to December 1998. The monitoring network (figure 1) was modified over time with an emphasis placed on sites within the focus area. Early during the sampling program only a few sites were tested on a non-regular basis. Beginning in February 1997, samples were collected on a regular monthly schedule. Furthermore it is important to note that as the research continued, sites were continually added until the completion of sampling. Overall, 580 samples were collected at 26 different sites, which included the two lakes. A summary of the isotope monitoring site characteristics is provided in Table 2. For a complete set of isotope data for all sites (except for the lakes), please see Appendix A.

Sample Collection

All samples were collected in duplicate using glass scintillation vials. These vials were filled to the top with sample water and sealed with a screw-on top. A layer of parafilm was then wrapped around the vials in order to prevent evaporation. Samples were collected from groundwater, municipal pumping wells, surface water (including lakes), and rainwater. Groundwater samples were collected using a portable pump connected to a 12-volt battery. The intake end of the pump hose was lowered into the well casing while the outflow end was allowed to flow into the scintillation vial for sample collection. For shallow wells, the pump was allowed to draw water from the well for five minutes prior to sample collection to assure that a representative sample was collected. For deep groundwater sites, the well was purged for fifteen minutes. 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 from the Everglades and canal sites were collected by immersing the scintillation vials below the water surface. At the lakes, a submersible pump was used to collect water from ten-foot depth intervals from the approximate center of each lake. These samples were analyzed by Herrera, 2000. Herrera found that the isotopic composition did not vary significantly with depth and therefore only the depth averaged values were utilized in this study. Rainwater collection for isotope analysis provided a somewhat unique problem, as collected rainwater must be shielded from evaporation effects. In order to accomplish this, 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, preventing rainwater interaction with the air and insuring the isotopic integrity of the sample. Once the rainwater was collected, a syringe was used to transfer the rainwater from below the mineral oil layer into the scintillation vials.

Sample Analysis

Oxygen-18 analysis included a CO_2 equilibration procedure utilizing a syringe as described by Matsui, 1980. This syringe technique was compared with the more traditional CO_2 equilibration procedure (Epstein and Mayeda 1953) with good results (Standard deviation 0.18). Samples for deuterium determinations were processed using one of two methods. The first method utilized a uranium furnace as outlined by Bigeleisen et al.1952. The second method involved the use of a chromium furnace (Gehre et al. 1996). Results from the chromium and uranium furnace were found to be statisically the same. After initial processing, samples were subject to mass spectrometry (Prism, Micromass, Inc.) for ^{18}O and D determinations. "Del" or " " values are given by

$$\delta R_1 = \left(\frac{(R_1 / R)_{sample}}{(R_1 / R)_{reference}} - 1 \right) \bullet 1000 \qquad \text{(equation 1)}$$

where R_1/R is the ratio of the "heavier" isotope to its more abundant "lighter" form. For example, for oxygen-18, the ratio is given by $^{18}O/^{16}O$. The reference is the ratio of $^{18}O/^{16}O$ or D/H of Vienna Standard Mean Ocean Water (VSMOW) provided by the National Bureau of Standards. Units are provided in "per mil" or "‰."

A considerable effort was provided for quality assurance and quality control. Details concerning these efforts is provided in the report titled, "An Isotopic Study of Two Rock Mining Lakes." This report is dated March 8, 2000 and authored by Solo-Gabriele and Herrera.

Basics Concerning Isotope Theory

Isotopes serve as conservative tracers of different water sources as long as distinct differences are observed in the isotopic composition of each source. Water bodies that have undergone extensive evaporation will be enriched in heavier isotopes (i.e. larger ^{18}O and D values). Liquids formed by the condensation of gases, such as rainfall, tend to be enriched in the lighter isotope which result in lower values of ^{18}O and D. Furthermore, rainfall is also characterized by a universal relationship between deuterium and oxygen-18, commonly called the meteoric water line and described by the equation: D= 8 ^{18}O + 10 (Craig 1961). The relationship between oxygen-18 and deuterium for water bodies that have undergone evaporation, on the other hand, are predicted by the following equation: D= M ^{18}O + I where M<8. Thus evaporative water can be identified on the basis of its D and ^{18}O values and its deviation from the meteroic water line.

Site	Type of Station	Latitude	Longitude	State Plane X Coordin-ate	State Plane Y Coordin-ate	Agency	Station Identification Number	Land Surface Elevation (feet above sea level)	Drilled Depth (feet below land surface)	Casing Depth (feet below land surface)	Casing Diameter (inches)
G3551	Shallow Well	25°41'58"	80°29'45"	666017	496749	USGS	254158080294501	6.57	18.3	13.3	5
G3552	Shallow Well	25°41'38"	80°28'44"	671605	494752	USGS	254153808284401	7.41	19.4	14.4	5
G3661	Deep Well	25°41'38"	80°28'44"	671605	494752	USGS	254138080284401	7.41	55.0	50.0	2
G3553	Shallow Well	25°41'52"	80°28'21"	673703	496173	USGS	254152080282101	6.23	19.9	14.9	5
G3554	Shallow Well	25°41'52"	80°27'45"	676996	496187	USGS	254152080274501	7.36	20	15	5
G3662	Deep Well	25°41'52"	80°27'45"	676996	496187	USGS	254152080274501	9.40	55.0	50.0	2
G3555	Shallow Well	25°41'11"	80°27'25"	678843	492055	USGS	254111080272501	8.25	19	14	5
G3439	Deep Well	25°44'21"	80°26'02"	686353	511268	USGS	254421080260201	5.79	12	10	4
Well 29/30	Production Well	25°41'56"	80°28'18"	673978	496195	Miami-Dade WASA	BA-2, BA-3	6.50, 6.48	67, 70	39, 41	54, 54
G618	Shallow Well	25°45'40"	80°36'00"	631648	519043	USGS	254500080360001	7.40	20	11	6
G3575	Shallow Well	25°42'06"	80°29'47"	665831	497556	USGS	254206080294701	5.94	9.0	9.0	4
S3575	Surface Water	25°42'06"	80°29'47"	665831	497556	-	-	5.94	-	-	-
G3660	Deep Well	25°42'06"	80°29'47"	665831	497556	USGS	254229080294801	-	57.0	47.0	6
G3577	Shallow Well	25°42'07"	80°30'02"	664459	497652	USGS	254207080300201	6.00	8.0	8.0	4
S3577	Surface Water	25°42'07"	80°30'02"	664459	497652	-	-	6.00	-	-	-
G3663	Deep Well	25°42'07"	80°30'02"	664459	497652	USGS	254207080300201	6.00	62.0	57.0	1.5
G3578	Shallow Well	25°42'10"	80°30'48"	660250	497939	USGS	254210080304801	6.00	6.0	6.0	4
S3578	Surface Water	25°42'10"	80°30'48"	660250	497939	-	-	6.00	-	-	-
G3664	Deep Well	25°42'10"	80°30'48"	660250	497939	USGS		6.00	41.0	36.0	1.5
2M3 (L-31N Canal mile 3)	Surface Water	25°43'02"	80°29'50"	665535	503208	USGS	02290765	-	-	-	-
3M4 (L-31N Canal mile 4)	Surface Water	25°42'06"	80°29'46"	665923	497556	USGS	02290766	-	-	-	-
4M5 (L-31N Canal mile 5)	Surface Water	25°41'09"	80°29'50"	665244	483521	USGS	02290767	-	-	-	-
Rain G618	Rain Water	25°45'40"	80°35'14"	635857	519043	-	-	-	-	-	-
RainWW	Rain Water	25°41'56"	80°28'18"	673978	496195	-	-	-	-	-	-
RL1	Lake	25°42'06"	80°29'15"	668811	497556	-	-	-	-	-	-
RL3	Lake	25°41'38"	80°29'15"	668811	494752	-	-	-	-	-	-

Table 2: Isotope Monitoring Station Site Descriptions

II.3 RESULTS

II.3.a Plots of ^{18}O Versus D

Rainfall Analysis

A regression analysis was performed on the rainfall data collected at the RainWW and RainG618 sites (Figure 5), in order to compare rainfall data collected through the current study with the universal meteoric water line (MWL) (Hoefs 1997). A regression analysis on the rainfall data collected resulted in the following equation:

$$D = 7.9550 \ ^{18}O + 8.9211 \qquad \text{(equation 2)}$$

as compared to the universal MWL equation of:

$$D = 8 \ ^{18}O + 10 \qquad \text{(equation 3)}$$

Specific ^{18}O and D values were found to be within acceptable ranges as ^{18}O values were found to vary between –4.70 $^{o}/_{oo}$ to –0.29 $^{o}/_{oo}$ and D values ranged from –32.93 $^{o}/_{oo}$ to 8.78 $^{o}/_{oo}$. It is also seen graphically that the fitted rain line is nearly identical to the universal meteoric water line (Figure 5). Since the two lines are so close to each other, the universal MWL was used in analysis of other meteoric plots developed through this study.

Analysis of All Data

A plot of ^{18}O vs. D of all collected samples excluding those from rainwater sites is provided in Figure 6. This plot is of over 430 data points. All the values on this plot fall below the MWL, showing that the samples were enriched in ^{18}O values as compared with deuterium values. This would indicate that the waters within the study site were subjected to an evaporative process. In order to further examine the structure of the collected data, the average delta values of all sites were plotted (Figure 7). As can be seen, rainwater is significantly lighter than the other water samples collected. Of the other sites (Figure 8), G3555 and G3439 are the lightest. These sites are the furthest east and consequently the most removed from the Everglades. G618 and S3577, both located in the Everglades, are the heaviest. In agreement with the data points on the extremities, an overall pattern is observed from relatively heavy to relatively light as the sites progress geographically from west to east. To emphasize this point wells have been grouped into Everglades wells (those west of L-31N) and urban wells (those east of L-31N) (Figure 9). With the exception of G3663, the Everglades wells are in general heavier than the urban wells. This is due to the impact of evaporation within the Everglades which results in its waters to be enriched in the heavy isotopes. In urban areas, water infiltrated more quickly into the ground thus maintaining isotopic characteristics closer to that of rainfall. Figure 10 compares the impact of well depth on groundwater isotopic composition. In this figure wells located at the same horizontal coordinates have been given the same color. Shallow groundwater was assigned a square symbol whereas deep groundwater was assigned a diamond shape. The results show that at specific geographic locations the deep wells are in most cases heavier than the shallow wells. This especially holds true on the urban (eastern) side of the Levee 31N where, for example, G3662 plots heavier than G3554, even though both wells are located at the same horizontal

location. The primary exception to this general trend occurs at G3577/G3663 where the deeper well is significantly lighter than the shallow well. Further discussion of these observations is incorporated into the following sections.

A regression line that incorporates the average values of the specific sites was developed to further examine the effects of evaporation on the isotopic composition of waters in the study area. An intersection of the regression line with the MWL would indicate that the rainfall feeding the system came from a location having an isotopic composition similar to the intersection point. In Figure 11, it can be seen that rainfall within the study area (the RainWW and RainG618 sites) falls within the 99% confidence limits. The assertion that local rainfall strongly contributes water to the system becomes even more convincing when 95% confidence bars are shown for the averaged values of individual sites (Figure 12). The confidence bars of the rainfall data and the confidence bounds of the regression line overlap greatly.

The fact that the sampled rainfall plots near the outer bounds of the confidence limits of the regression line suggests, nevertheless, that there may be another, slightly lighter source of water to the site in addition to local rainfall. The other potential source flows through control gate S333. S333 controls the flow of water to northeast Everglades National Park from an Everglades conservation area located to the north. This conservation area collects water from rainfall points further north as well as more inland. While no isotope data is available in this area, it is conceivable that due to Raleigh distillation effects (Hoefs 1997), this water would trace back to a point that was lighter on the meteoric water line. This infusion of water could therefore have an influence on the sampling points in the study area and affect the regression line. However, it is important to make a distinction here that while the evaporation regression may point to a supplemental, lighter initial source of water (lighter rainfall) to the conservation area, this does not mean that water entering the study area through the gate is light. This water is in fact very heavy as a result of evaporation effects. In other words, while the regression analysis gives insight into the initial source of water (e.g. rainfall location) to a system, it does not indicate the state of the water in the system at a given time. Water that may have initially been isotopically light rainfall could in fact be heavy at a given time due to evaporation effects.

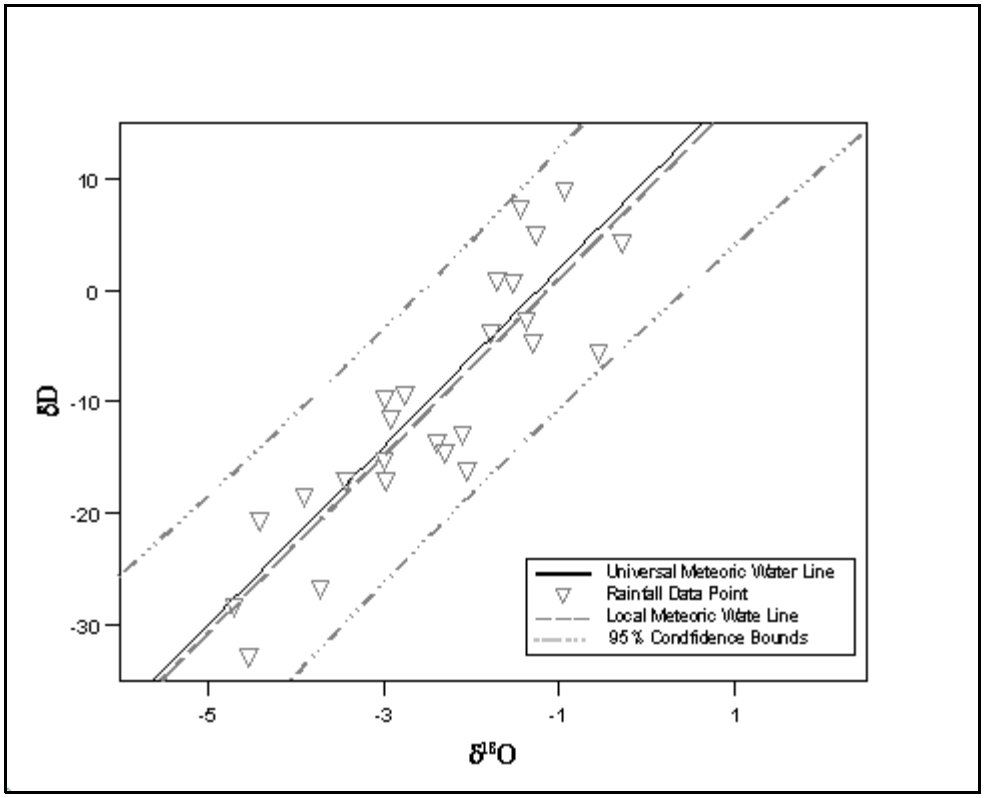

Figure 5: Local MWL Versus Universal MWL

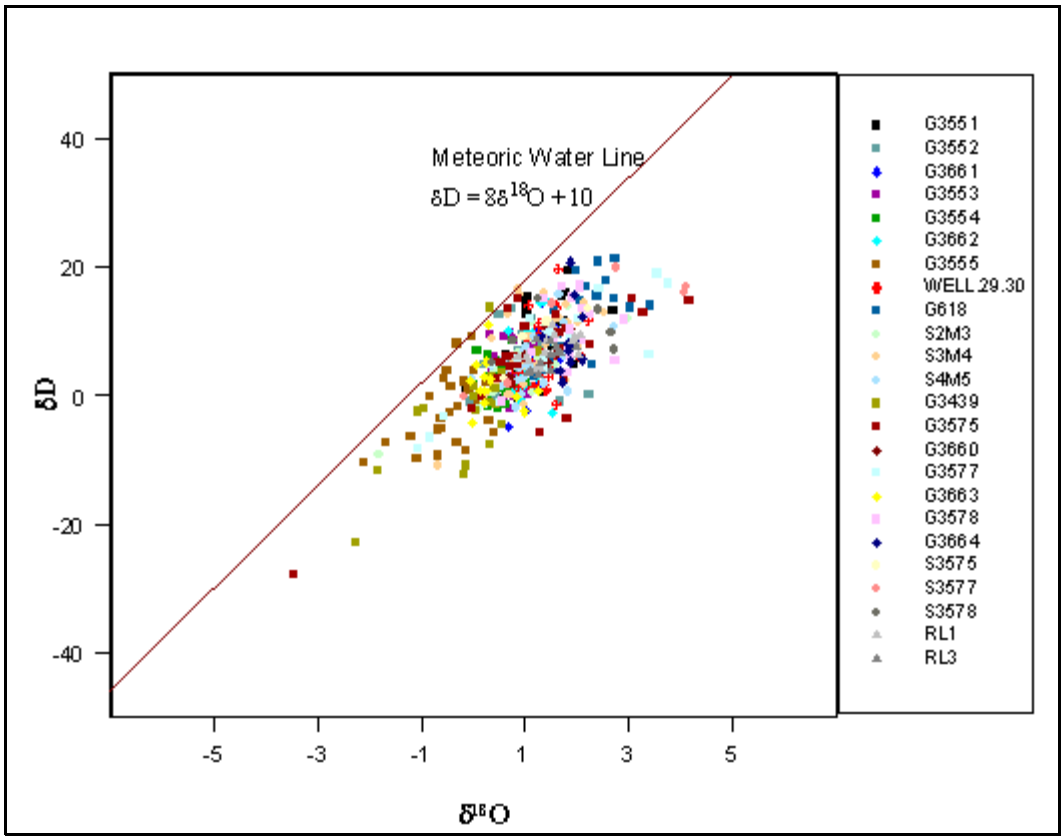

Figure 6: All Data Points Excluding Rainfall

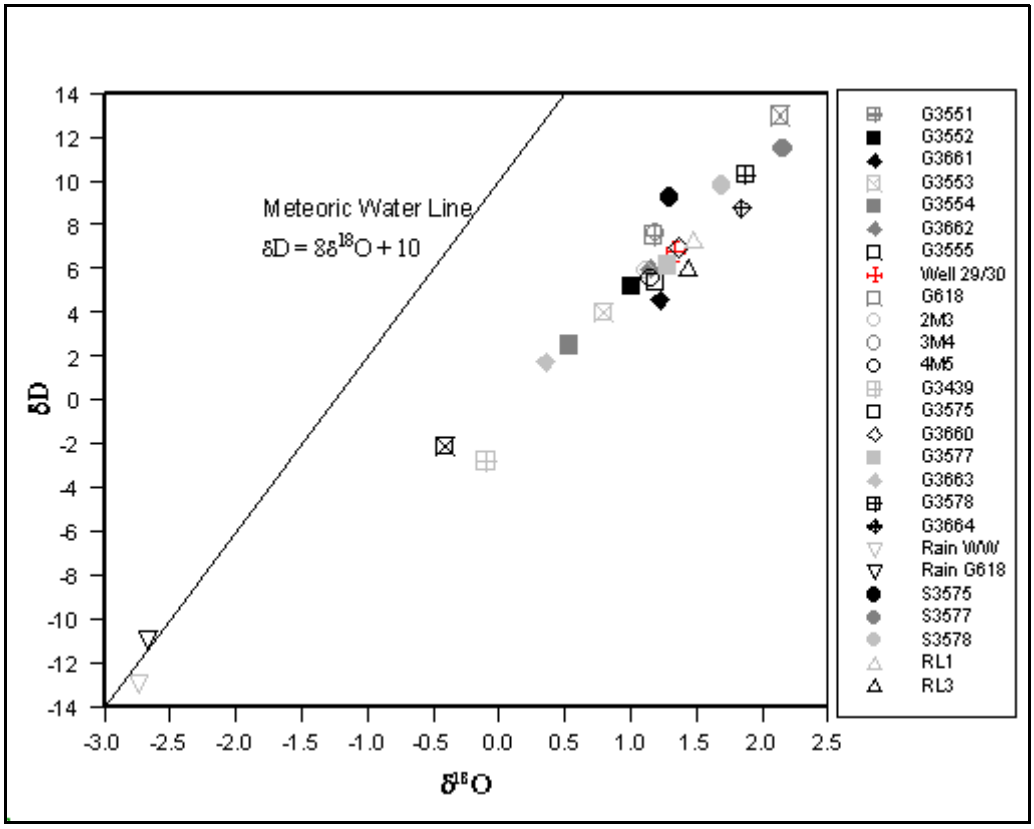

Figure 7: Average Values of Study Sites Including Rainfall

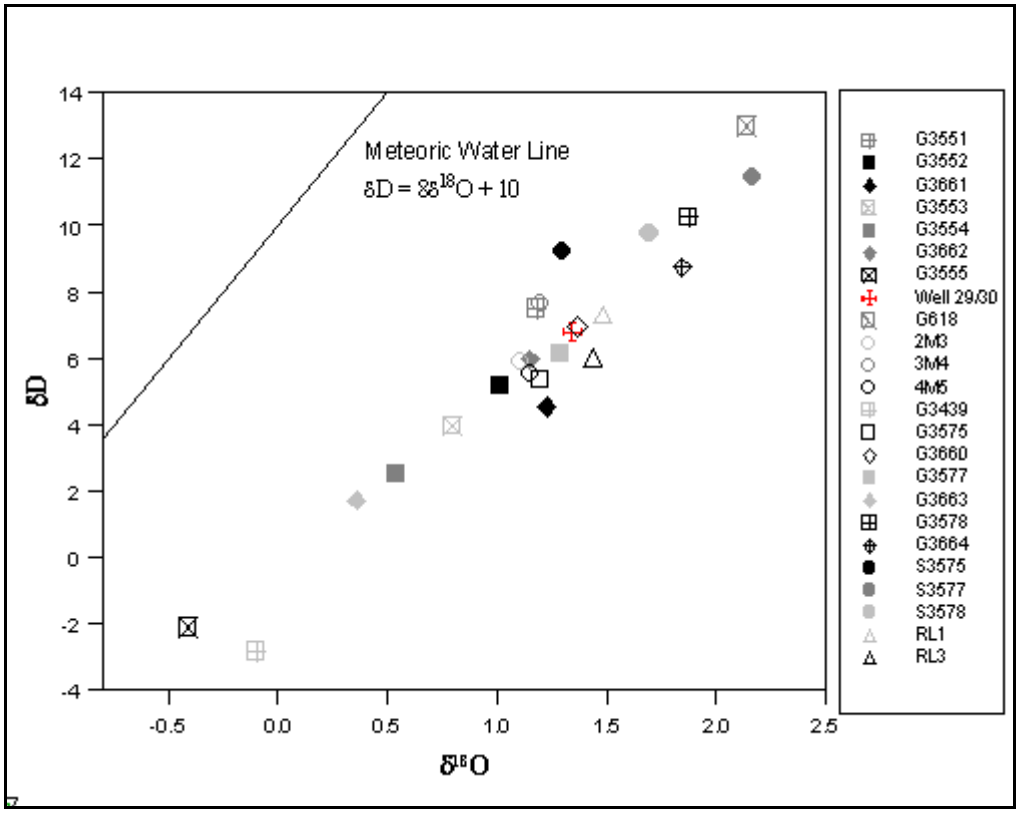

Figure 8: Average Values of Study Sites Excluding Rainfall

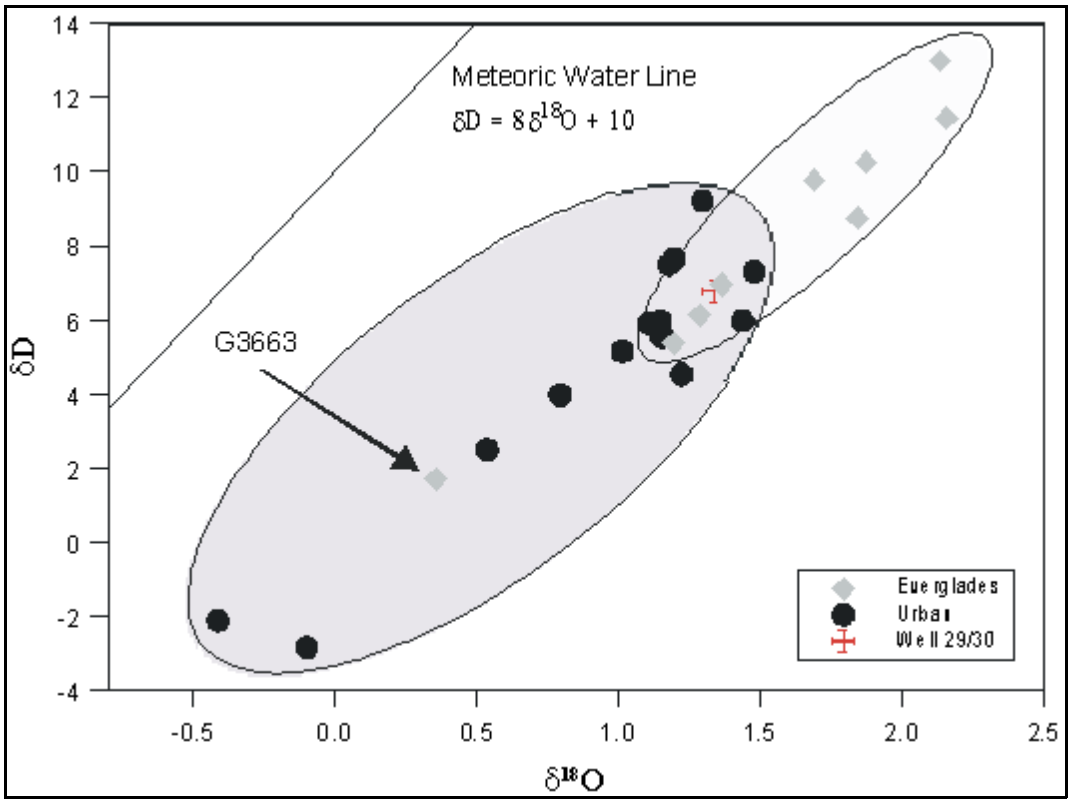

Figure 9: Everglades Wells Versus Urban Wells

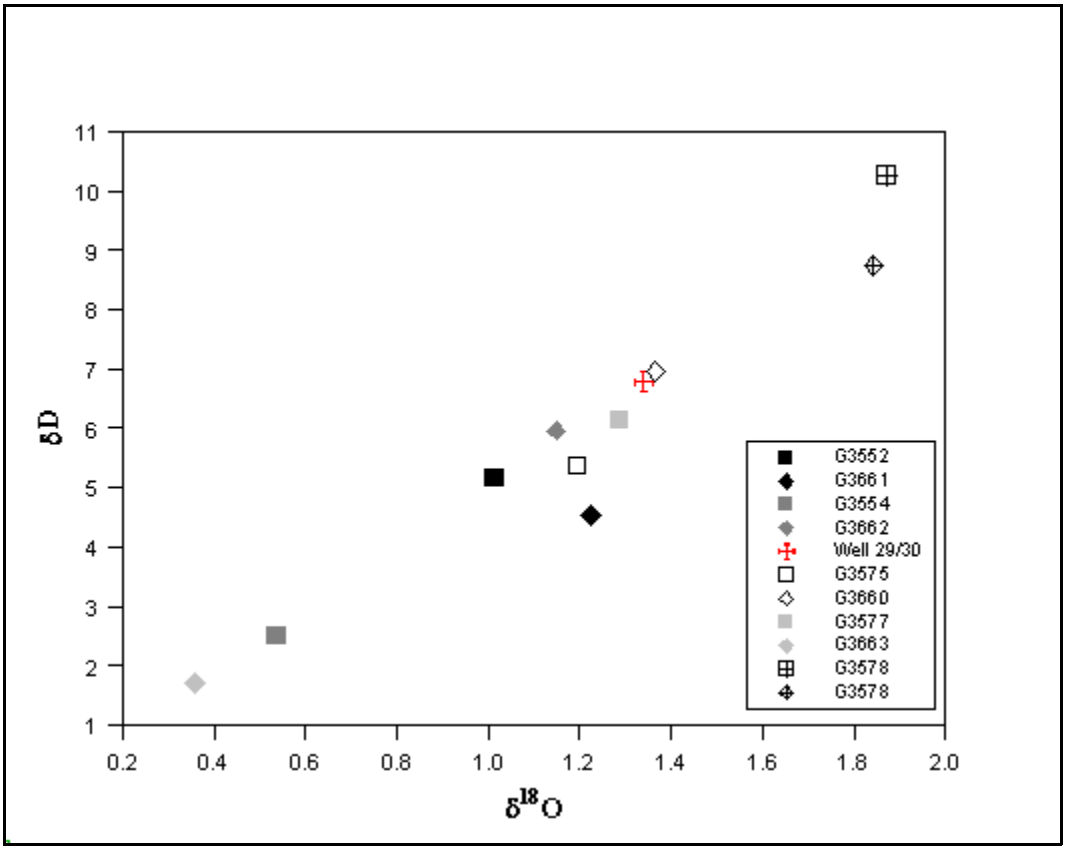

Figure 10: Shallow Wells (Squares) Versus Deep Wells (Diamonds)

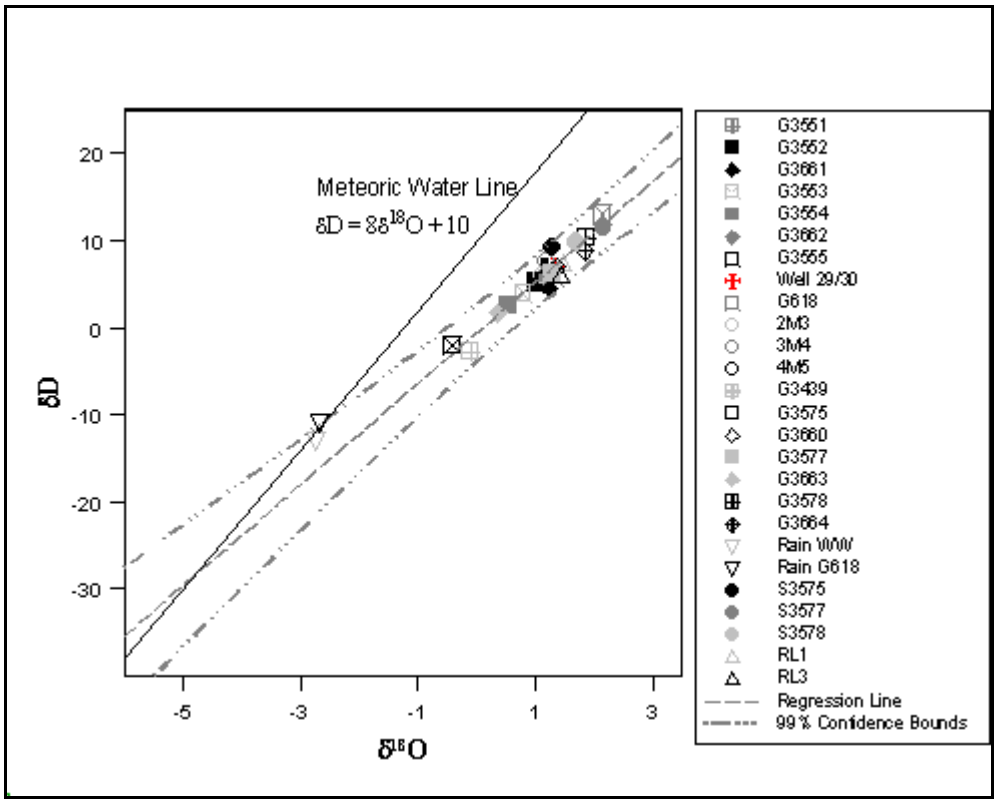

Figure 11: Regression Analysis

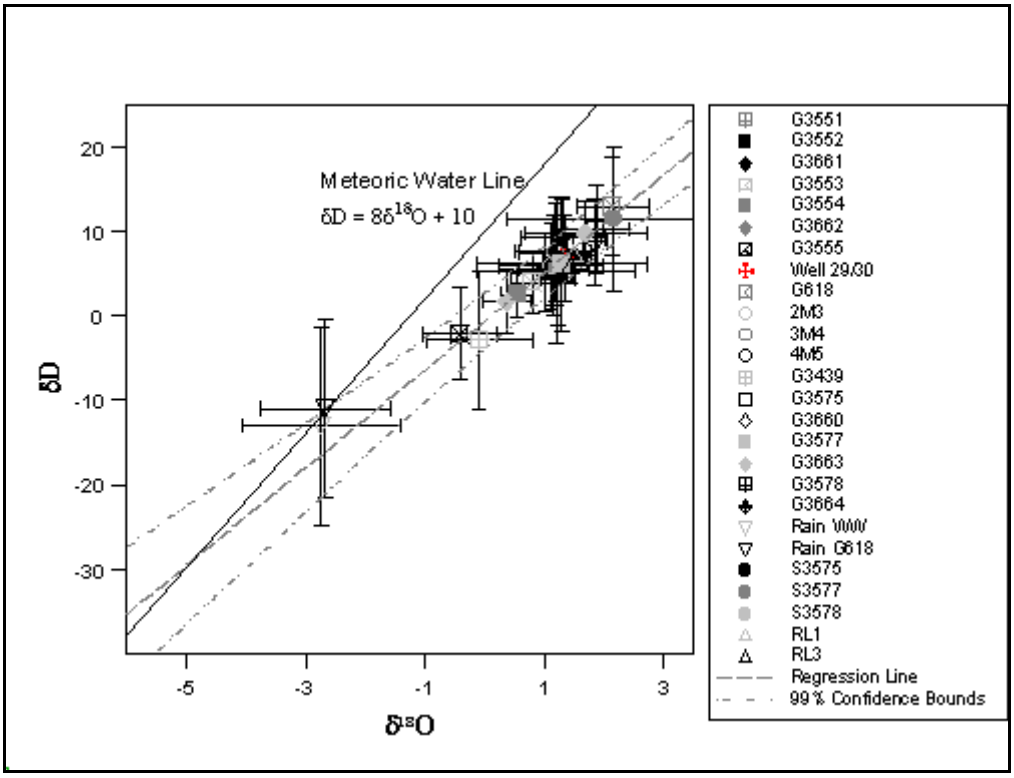

Figure 12: Confidence Boundaries

II.3.b ^{18}O versus Distance

Plots of ^{18}O values versus distance from pumping wells emphasize the spatial effect of west to east flows on isotope values in the study area (Figure 13). Each symbol corresponds to the average ^{18}O for a particular sampling station. The vertical bars correspond to the 95% confidence limits in the ^{18}O measured at that station, which include the effects of different antecedent conditions and seasonal variations. The figure shows a general trend of decreasing ^{18}O values when moving from west to east in the study site. This trend is due to the mixing of isotopically light infiltration with evaporated Everglades water as the water migrates from west to east. Infiltration is lighter on the urban side due to rapid drainage of rainwater through an infrastructure designed to prevent flooding of these areas. Water is heavy on the Everglades side due evaporation of the standing surface water west of Levee 31N. The mixing of these two water sources results in the ^{18}O values becoming lighter with distance from the Everglades. The predominant portion of this trend is seen in the vicinity of Levee 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 G618 to G3578 over a large distance.

The plot of ^{18}O versus distance (Figure 13) also shows that deep groundwater is generally heavier than shallow groundwater east of G3575/G3660 (inclusive), presumably due to the greater influence of heavy Everglades waters and smaller impacts of surface infiltration (which is isotopically light on the urban side) at larger depths. Also, of interest is that a gradient is observed in these deep groundwater wells, with lighter values as one proceeds eastward. This gradient, however, is not as steep as the gradient observed for shallow groundwater. A different behavior is observed west of G3575/G3660. At G3578/G3664, the isotopic composition of shallow and deep groundwater is the same indicating that Everglades waters are mixed throughout the Biscayne aquifer at this point. A clear deviation from the general trend is observed at G3577/G3663, where the isotopic composition of deep groundwater at G3663 is lighter than the composition of shallow groundwater at G3577. This deviation can be explained by assuming that water at G3663 is strongly influenced by rainfall. It is likely that isotopically light rainfall infiltrates rapidly to this particular sampling point.

Further examination of Figure 13 indicates that the rock mining lakes and the pumping well are heavy for both their location and depth. The most likely reasons for this observation at the lakes are evaporation and potential input of heavy Everglades water through deep groundwater inflows. Evaporation does cause an enrichment of heavy isotopes at the surface of the lakes. However, evaporation alone cannot account for the magnitude of the enrichment observed (Herrera 2000) and thus the data support that heavy groundwater that originated in the Everglades ultimately flows into the lakes. The heavy water observed at the pumping wells supports the hypothesis that a portion of its supply comes from the rock mining lakes directly west of the wellfield. The only other source of such heavy water to the pumping wells could be Everglades water and it is unlikely that the municipal wellfield is drawing water directly from sites such as G3578 and G3664. This is not to say that water from these sites does not migrate to the wellfield. However, the distance required for this migration would result in at least some mixing with lighter, rain influenced water as is observed in the trendline for the deep wells. As such, Figure 13 supports the hypothesis that the pumping wells draw a least a portion of their supply from the lake.

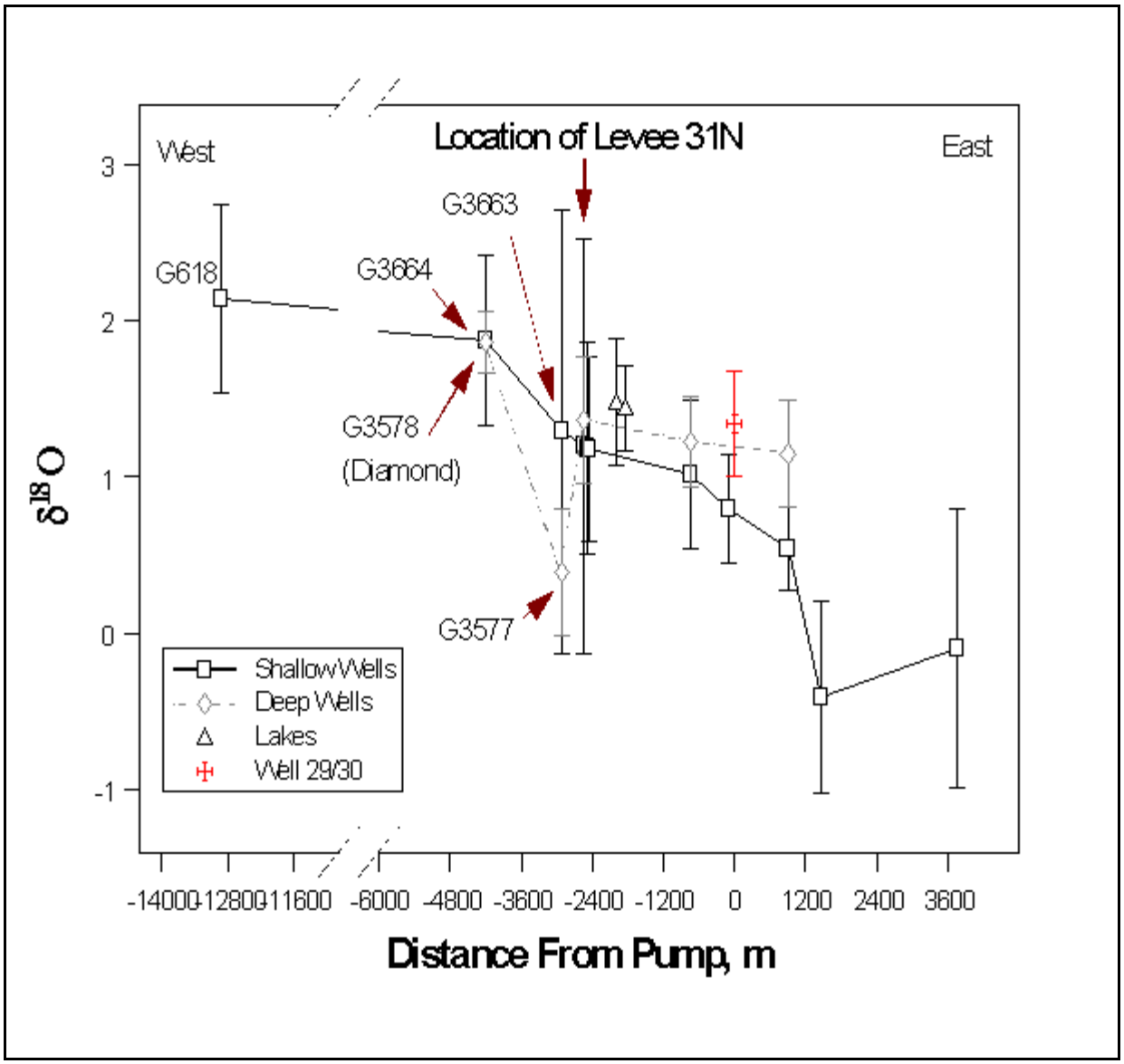

Figure 13: ^{18}O Versus Distance
Order of deep wells from west to east: G3664, G3663, G3660, G3661, G3662
Order of shallow wells from west to east: G618, G3578, G3577, G3575, G3551, G3552, G3553, G3554, G3555, G3439

II.3.c Three Dimensional plots

The relative impact of rainfall events and S333 gate operation on the isotope delta values in the study area was assessed through a series of three-dimensional plots, which included graphs of ^{18}O versus rainfall in inches versus average flow in cubic feet per second at gate S333. In order to compare short and long term effects, two sets of plots were made, one incorporating values for the previous five days and one incorporating values for the previous thirty days to sampling. Plots of this nature produce graphical surfaces that reflect the effects of both rainfall and gate operations on delta values. Heavier isotope values result in a darker color while lighter isotope values result in lighter shading. If no significant impact by these variables is observed, a nearly flat, uniformly shaded plane having very little slope or surface distortion would be produced. On the other hand, if rainfall and gate operations influenced the delta values, the graphical surface will appear to bend and distort from a planar shape and will contain both darker and lighter shadings.

The five-day graphs show several interesting features. First, the plots once more confirm that water in the west (Everglades) was in general heavier than water in the east (urban) as indicated by the darker shading on the plot for a typical Everglades well (Figure 14). Furthermore, the data show that shallow groundwater within the urban side is characterized by a distinctive "spoon shape" where lighter water is observed during antecedent wet conditions and intermediate flow values. Water within the Everglades is characterized by a more planar shape. It is also apparent from the data that shallow and deep groundwaters were affected differently in the short term by rain and gate operations (Figure 15). Deep groundwater (e.g. G3662) was not affected by short-term rain events due to the fact that travel time to the deep wells is greater than five days whereas the impacts of rainfall in shallow urban wells (e.g. G3554) is readily apparent. Flow through gate S333 did not result in fluctuations in ^{18}O values comparable to those caused by rainfall at most sites. This is observed from the large slopes in the graphical surfaces along the rainfall axis rather than the flow axis in most plots. The only plots that do show the influence of gate S333 in the short term are the Everglades surface waters. S3578 is provided as a representative plot (Figure 16).

The noticeable exceptions to the general trends occurred at G3577/G3663 and at the pumping well (Figure 17) where the immediate influence of rainfall was observed despite the fact that these waters should show a pattern similar to that observed at G618 (the characteristic Everglades well) due to their location or depth. For G3663, this divergence can be explained by the presence of a large open cavern encountered during the drilling of the well. The increased hydraulic conductivity associated with the existence of this cavern 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, ^{18}O values at G3577 and G3663 are significantly decreased by rainfall events. This observation also explains the extremely light delta values observed in the meteoric (Figure 6) and distance plots (Figure13). The influence of rainfall at the pumping well is likely due to the pump's ability to draw water vertically from more shallow areas than its open intake. The shallow urban water, given that it is influenced by rainfall, will therefore result in a rainfall influence at the pumping well. It is important to also note that while the shape of the pump's plot points to a short-term rainfall influence similar to that of urban shallow wells, the overall values are heavier than surrounding shallow wells. This suggests that the pumping well draws a mix of both shallow and deep groundwaters as well as water from the isotopically enriched lakes. Lake RL3 (Figure 18) interestingly shows a similar pattern on the three dimensional plot at the pumping wells. Such results support the hypothesis that the pump is drawing at least a portion of its supply from the lake.

The thirty-day plots are in general much more planar than the five-day plots as the greater time scale results in smaller fluctuations in rainfall and flow measurements. Overall, these plots are consistent with the ones described earlier. For example, the differences in isotopic composition between Everglades (western) and urban (eastern) groundwater (Figure 19) is readily observed by noting the height of the plane on the vertical axis. In general, Everglades and deep groundwater plot at heavier ^{18}O values than urban, shallow groundwater. Furthermore, it appears that over the larger time scale, there is a relationship between gate operations and delta values in the Everglades, where heavier ^{18}O values are observed at higher flows. In addition to the Everglades surface waters (that showed a response to flow conditions in the five-day plots), shallow Everglades groundwater such as that observed at G3575 and G3578 (Figure 20), showed an increase in ^{18}O values after a period of 30 days of high flow conditions. This observation supports the earlier interpretation of the data which indicated that waters upstream of gate S333 serve as a source of water to the study site.

The thirty-day plots for G3577 and G3663 give further insight into the movement of water in the study site (Figure 21). It has already been observed in the five-day plots that rainwater infuses very quickly at this location. The thirty-day plots are consistent with this interpretation, 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 ^{18}O values at G3577. It is also evident in this plot that at high flow conditions, ^{18}O values increase considerably indicating a correlation with operations of gate S333. It appears that the area surrounding G3577 acts as a sink for Everglades surface water. Over the larger time scale of thirty days, this collected water that infuses so rapidly is gradually mixed with the *in situ* ground water. This is evidenced by the decrease in delta values under heavy rainfall conditions observed at G3663 and other surrounding wells including G3575 and G3578 (Figure 20).

To make this concept clearer, a cartoon sketch (Figure 22) is provided. The extremely high seepage into the underground cavern near G3577 likely flows as a "conduit" of water that is isotopically different than surrounding groundwater. This "conduit" responds quickly to the composition of the surface water feeding the seepage. The predominant direction of groundwater flow in this area is from northwest to southeast. Thus it is conceivable that the "conduit" takes water to the south of the sampling sites and does not regularly affect the delta values at the adjacent wells. Only under heavy rain conditions when increased volumetric input to the "conduit" results in greater east/west spreading of surface-water influenced flow that mixing effects are observed in adjacent wells. In other words, a large infusion of surface water causes water in this "conduit," moving from northwest toward the southeast, to mix with surrounding groundwater in a direction perpendicular to the flow direction, 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.

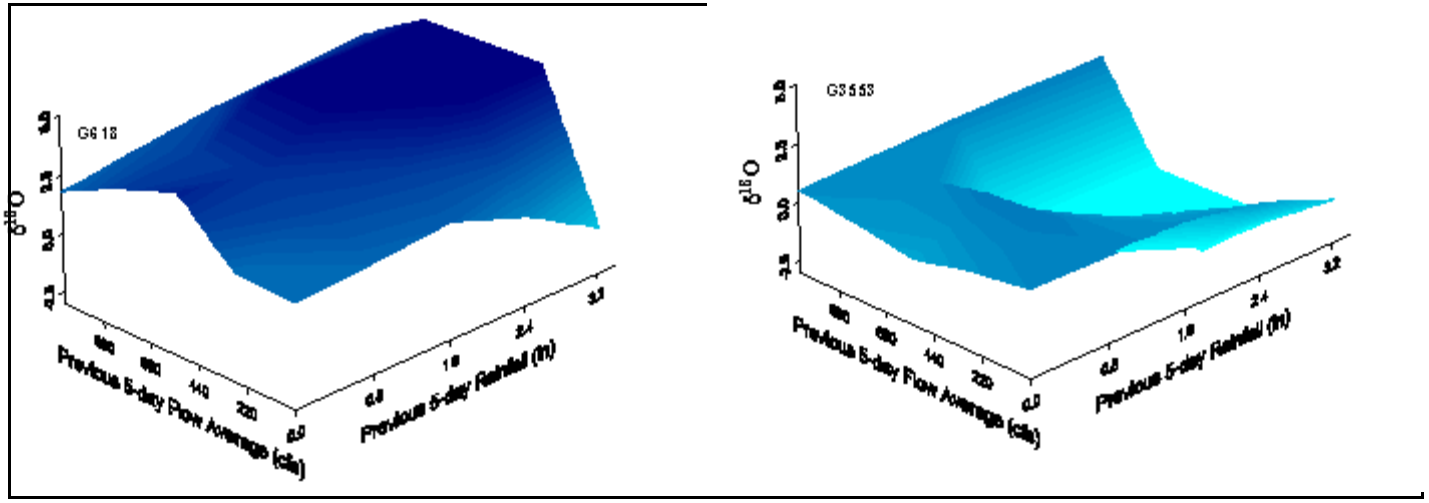

Figure 14: 5-Day Plot of Typical Everglades Well (G618) Versus Urban Well (G3553)

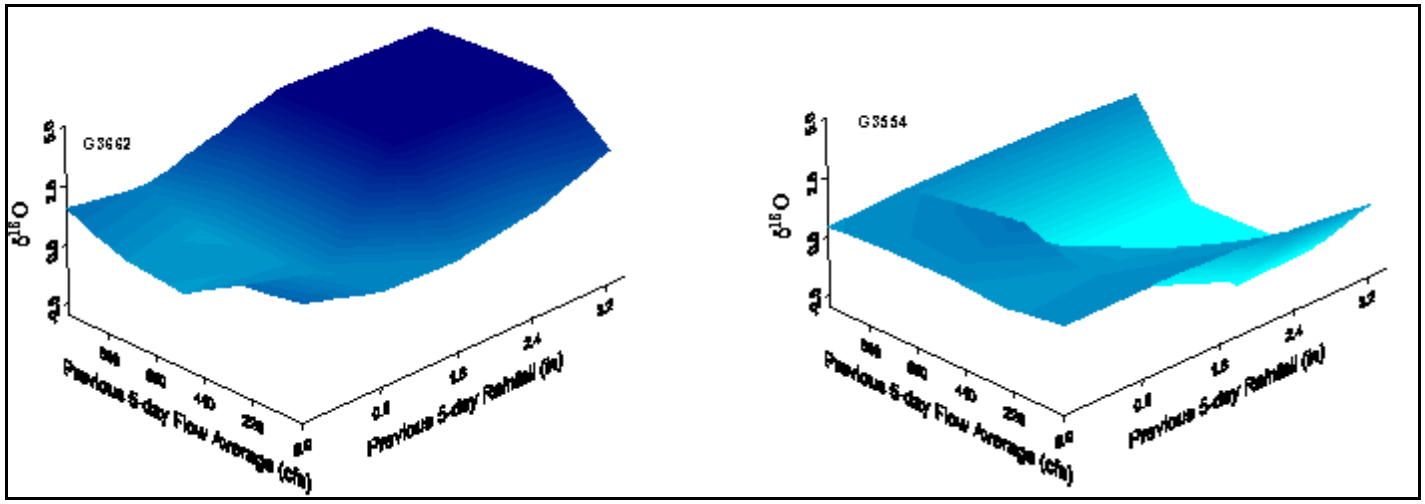

Figure 15: 5-Day Plot of Typical Deep Well (G3662) Versus Shallow Well (G3554)

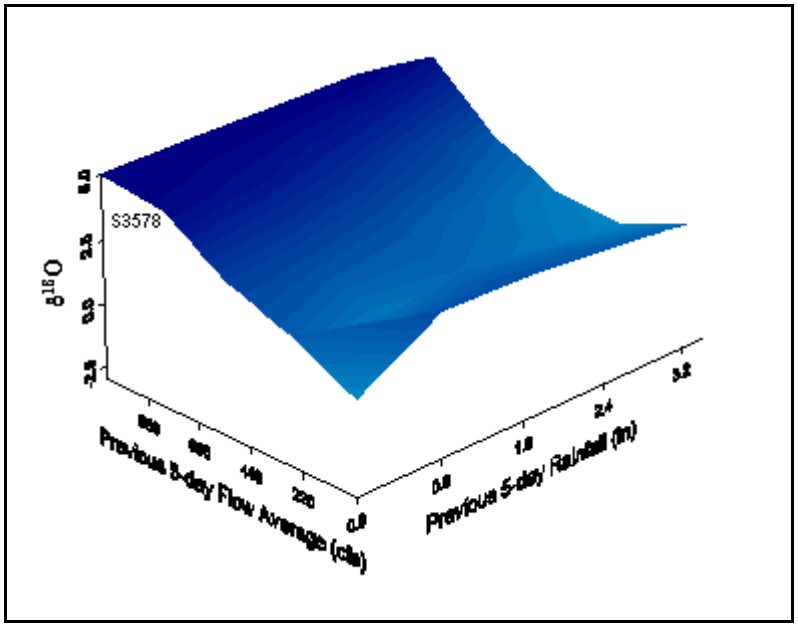

Figure 16: 5-Day Plot of Typical Everglades Surface Water (S-3578)

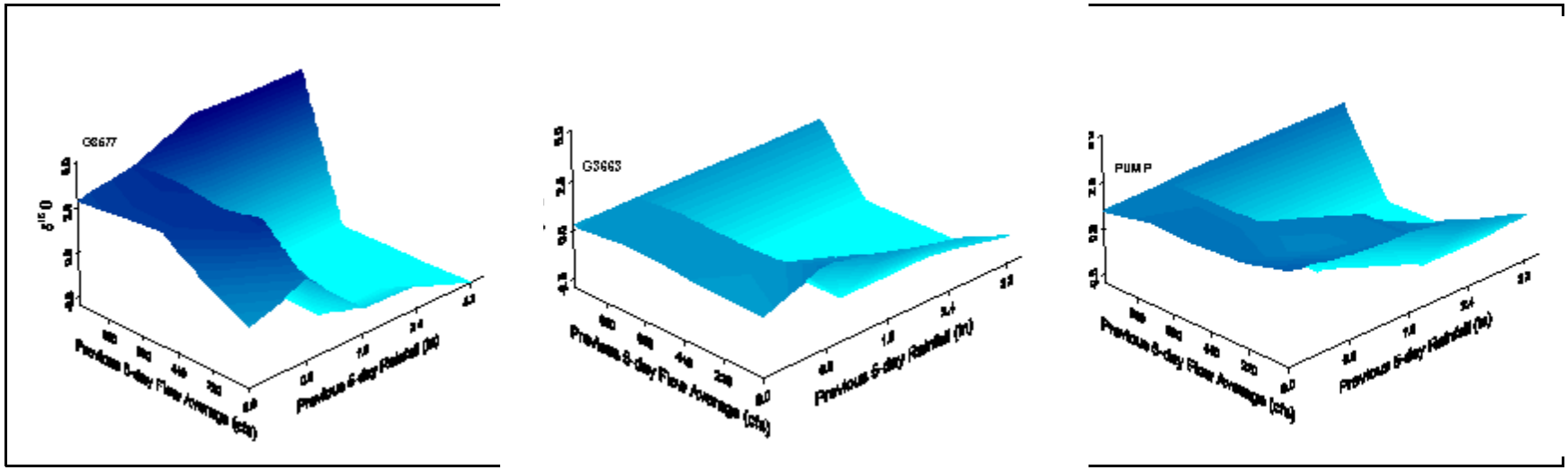

Figure 17: 5-Day Plot of G3577, G3663, and Pumping Well

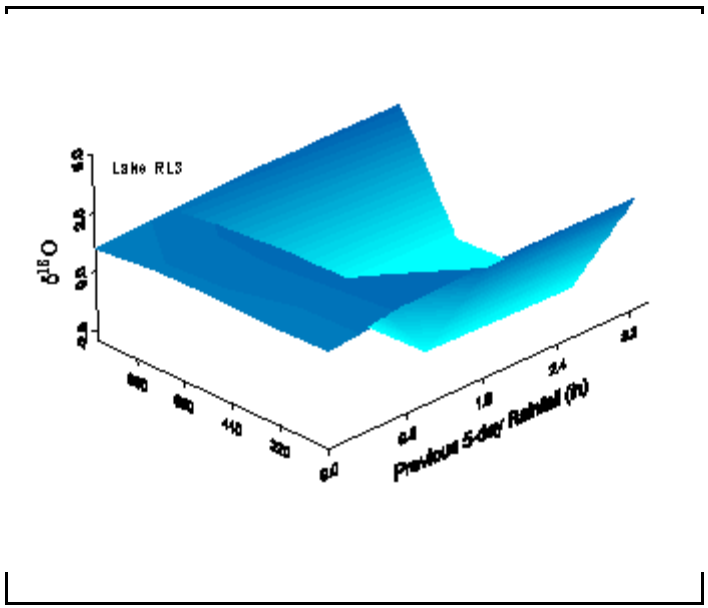

Figure 18: 5-Day Plo

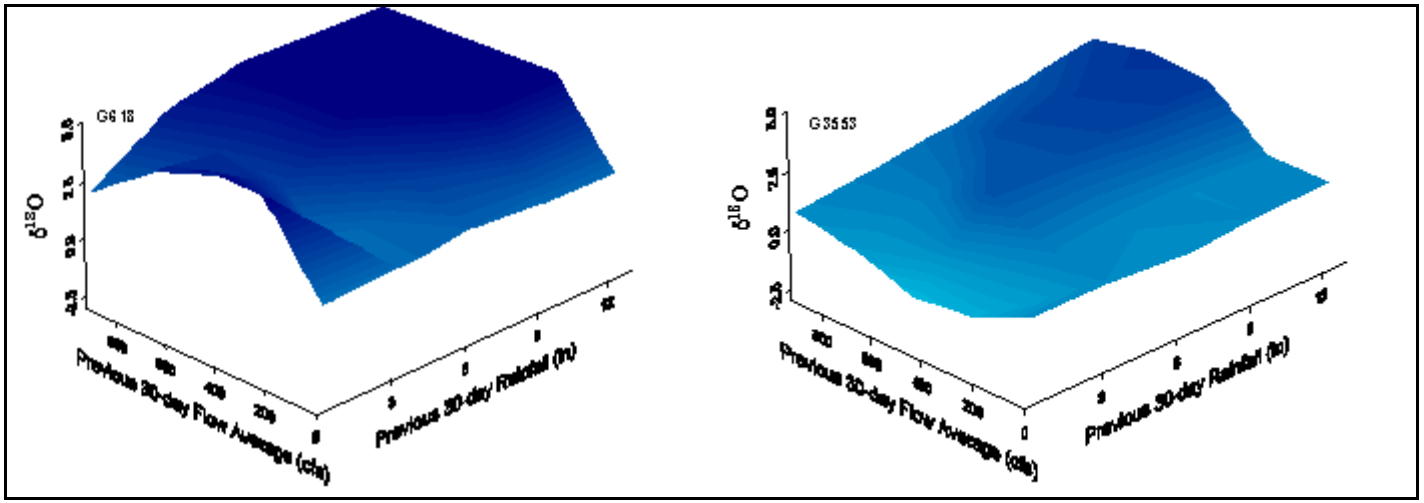

Figure 19: 30-Day Plot of Typical Everglades Well (G618) and Urban Well (G3553)

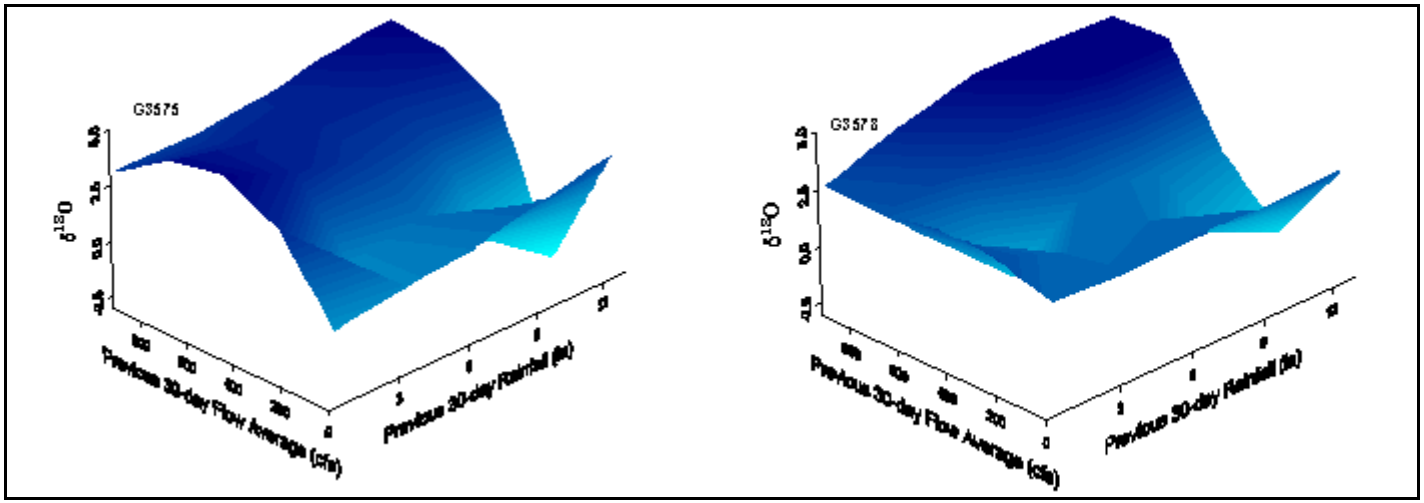

Figure 20: 30-Day Plot

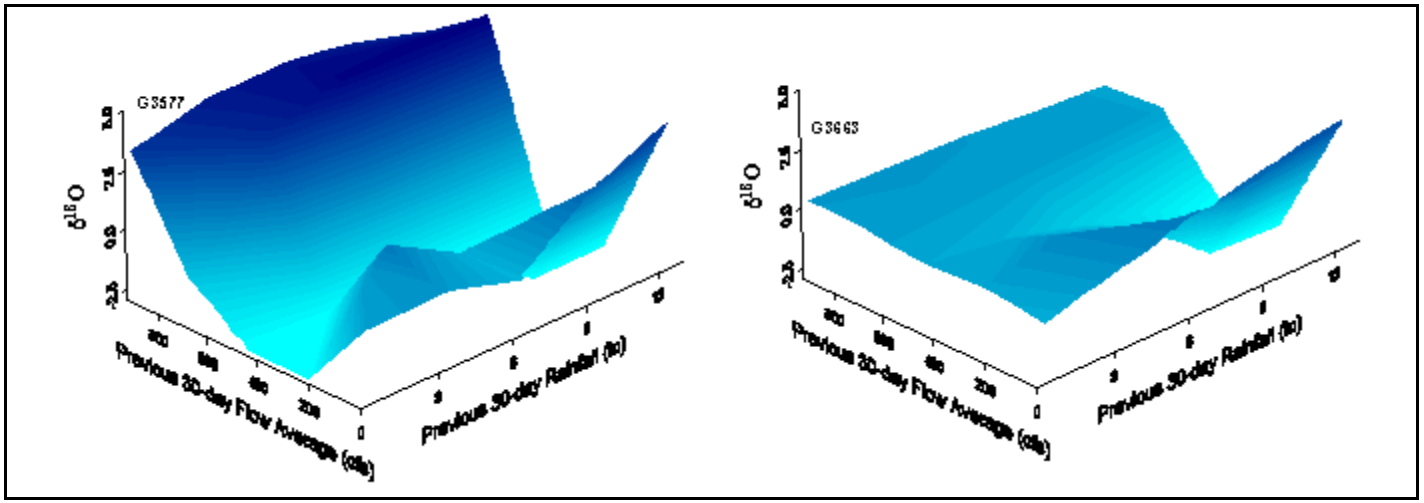

Figure 21: 30-Day Plot for G3577 and G3663

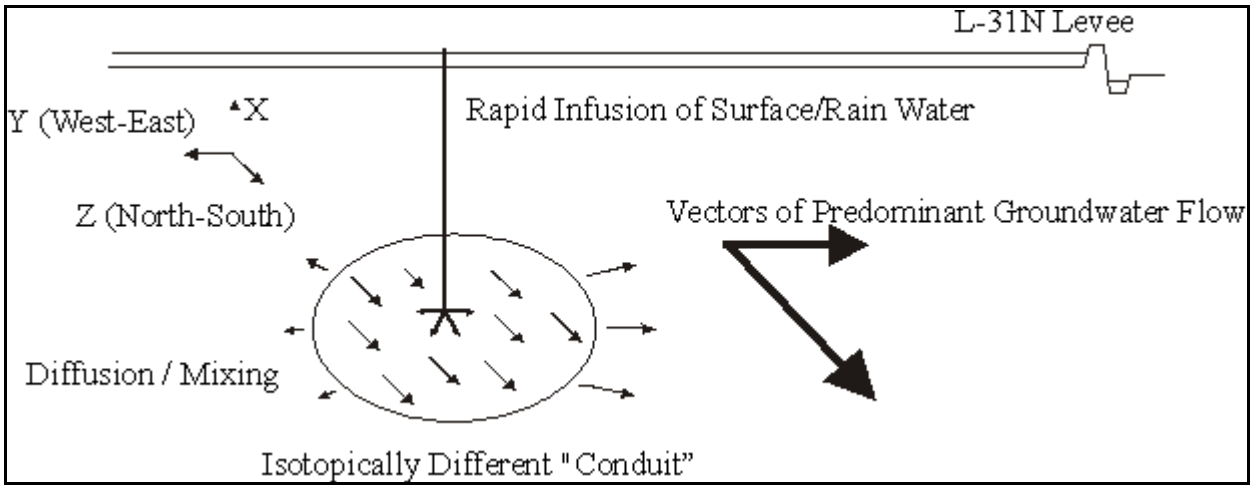

Figure 22: Cartoon Sketch of Subsurface Flow "Conduit"

II.4 BOX MODELS

Two box models were developed for this study and are referred to herein as the "simple" and "complex" box models.

II.4.a Simple Box Model

A simple box model was developed in order to determine the percent contribution of Everglades water to the West Wellfield. This model is based upon the assumption that two isotopically different waters are being drawn to and mixed at the pumping well site (Figure 23). These waters include Everglades type water (water west of L-31N) and urban type water (water east of Levee 31N). An isotopic balance is therefore represented by the following two equations:

$$x + y = 100\ \% \qquad \text{(equation 4)}$$

$$^{18}O_x)x + \ ^{18}O_y)y = \ ^{18}O_p)100 \qquad \text{(equation 5)}$$

where x is the percentage of Everglades water at the pumping well, y is the percentage of urban water at the pumping well, $^{18}O_x$ is the ^{18}O value of Everglades water (taken as the ^{18}O value at G618), $^{18}O_y$ is the ^{18}O value of urban water (taken as the ^{18}O value at G3555) and $^{18}O_p$ is the ^{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 four inches of rainfall during the thirty days prior to sampling), and "Wet" months (those having more than four inches of rainfall during the thirty days prior to sampling). Rainfall measurements were those collected at S338. Results of the model for these data sets are provided in Table 3.

	Everglades Water	Urban Water
Overall Average	68.9	31.1
1998 Average	65.7	34.3
1996-1997 Average	72.0	28.8
"Summer" Months	59.6	40.4
"Winter" Months	86.4	13.6
"Dry" Months	73.8	26.2
"Wet" Months	66.4	33.6

Table 3: Simple Box Model Results

This model, using data for the entire study period, shows that 69% of the water being pumped from the well is indicative of Everglades water while only 31% is indicative of urban water. This supports the hypothesis that Everglades type water is reaching the pumping well and may be the major contributing source. Furthermore, for all conditions, over 50% of the water at the pumping well is Everglades type. The simple model results also show that during "dry" conditions, when

a smaller quantity of recharge is available, a greater demand is placed upon the contribution from Everglades groundwater. This causes the percent composition of Everglades water in the pumping well to increase. This observation also holds true when comparing summer and winter months. Summer months in general correlate with the wet season in South Florida during which rainfall recharges groundwater more consistently than during winter months. Consequently, an increase in the quantity of Everglades water reaching the pumping well is observed during the drier winter conditions. The difference between the "1998 Average" model results and those of the "1996-1997 Average" is also likely the result of rainfall differences. On average, there was less rainfall during 1996 and 1997 (50.5 inches) than in 1998 (52.5 inches) in the study area. Accordingly, the percentage of Everglades water returned by the model is higher during the drier 1996-1997 years.

While this simple box model is useful for assessing general trends, certain conceptual problems are inherent as a result of the simplicity of this type of model. 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 correct these problems within the framework of the simple model. While introducing only rainfall to the model would result in a higher Everglades influence (as additional heavy Everglades water would be needed to balance the light rain input in the isotope balance), introducing only isotopically heavy 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. Results of the complex model are provided in the next section.

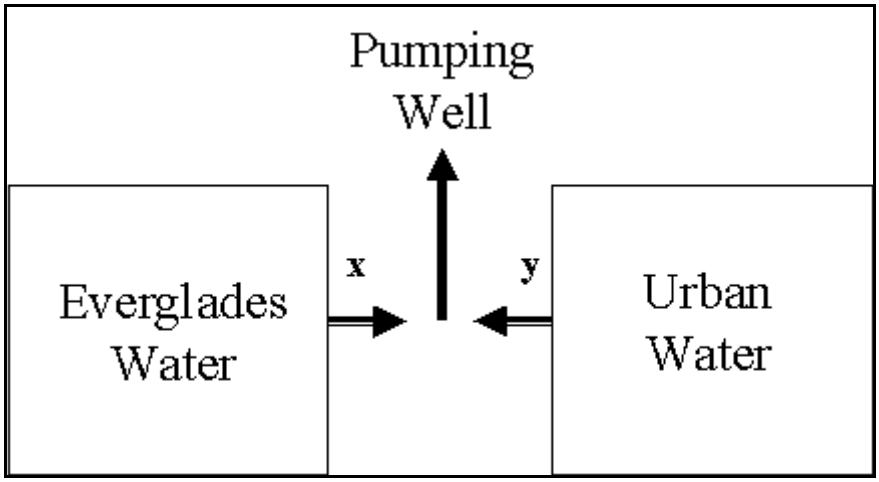

Figure 23: Simple Box Model

II.4.b Complex Box Model

For the complex box model, a two-mile by four-mile rectangular area within the focus area (down to the Biscayne aquifer) was selected and broken into five boxes which represent the Everglades area, canal, lakes, deep groundwater, and urban areas (Figures 24 and 25). A water balance and an isotopic balance were then established for each box in order to compute water flows between each of the boxes. Specifications for these boxes are provided in Table 4. Those variables which were measured versus those computed through the complex model described in this section are summarized in Table 5.

Values of $_{G618}$, $_{G3660}$, $_{G3575}$ $_{G3551}$, $_{G3662}$, $_{Well\ 29/30}$, and $_{G3555}$ utilized for the complex model were the average values measured at the corresponding well locations (given by the subscripts). Isotopic values for the rainfall were also measured directly at sampling stations located next to well G618 ($_{Rain\ G618}$) and at the West Wellfield ($_{RainWW}$). Values of $_{E1}$, $_{E2}$, and $_{E3}$ for evaporated water were calculated using the method developed by Gonfiantini (1986). The computation was a function of the values for rainfall and surface water corresponding to a particular site. Details concerning this computation are provided by Wilcox, 2000, and Herrera, 2000. The value of $_{L}$ utilized is the average of the ^{18}O values for RL1 and RL3. Herrera, 2000, showed that values of $_{L}$ for RL1 and RL3 were similar to one another and the values did not vary considerably with depth within each lake. Please refer to Herrera, 2000, or Solo-Gabriele and Herrera, 2000, for more details concerning $_{L}$ values for the lakes. The rainfall depths, R1, R2, R3, and R5, were obtained from station S336. Values of ET1, ET2, and ET3 were obtained from the Tamiami Trail weather station located roughly 15 miles west of the study site. P was obtained from chart records from each well. Charts were provided by Miami Dade Water and Sewer Department. The value used for the model was 4.53 x 10^8 cubic feet per year (9.3 mgd) which was found to be representative of the pumping well data evaluated. A1, A2, A3, and A5, correspond to the surface area of the Everglades, canal, lakes, and urban control volumes. The Everglades control volume corresponds to a surface area of 2 miles by 2 miles (A1). The canal is 2 miles by 0.02 miles in area (A2). The urban side (A5) is assumed to represent an area of 2 miles by 1.76 miles. The value of A3, which corresponds to the lakes, was determined by summing the surface area of the two rock-mining lakes included within this study (1.24 x 10^7 sq ft, Herrera 2000). Conceptually, the model accounts for the lakes as a thin strip which is 0.22 miles long and two miles wide. While the lakes actual shapes are in fact very different, for the purposes of the model flow balances, only the surface area is important.

The model incorporated a seepage term from deep groundwater into the lake control volume. This seepage term, while drawn as an input through the bottom of the lake in the figure, in fact incorporates both movement through the bottom of the lakes (vertical flow) and any inflow through the side (primarily horizontal flow) of the lake between the bottom of the canal and the base of the lakes (between 30 and 40 feet). The model does not distinguish between horizontal and vertical flow across the boundary between box 3 and box 4. Canal seepage, on the other hand, is considered to be only through the sides of the canal. This arrangement is considered to physically describe the system given that hydraulic gradients are very flat in the area of the canal resulting in horizontal flow lines. Furthermore this conceptualization is consistent with the existing MODBRANCH model of the study site (Nemeth et al. 2000). This model utilizes the a relationship which simulates canal seepage through the sides of the canal rather than the bottom.

The unknown flow values were calculated in the model by simultaneously solving a series of mass balance equations. The equations assume steady state conditions and include both volumetric and isotopic balances. Equations were developed for six control volumes (Figure 25). Details of these computations are provided in Wilcox 2000. An example of the equations utilized are provided for box 1 below:

Volumetric Water Balance:

$$E + R1*A1 - ET1*A1 - X - Y = 0 \qquad \text{(equation 6)}$$

Isotopic Balance:

$$E^*_{G618} + R1*A1^*_{Rain\ G618} - ET1*A1^*_{E1} - X^*_{G3575} - Y^*_{G3660} = 0 \qquad \text{(equation 7)}$$

For these equations, all variables are defined in Table 4. All flows are measured in cubic feet per year (cfy), all areas are in square feet (sq. ft) and rainfall/evapo-transpiration values are measured in feet per year (ft/yr).

Results of the complex box model for the 1998 and the overall average data sets (Figures 26 and 27) indicate that water leaving the Everglades and seeping under the Levee 31N preferentially moves through the deep groundwater layer. This is observed from the flow ratio of over ten to one in the deep groundwater as compared to shallow groundwater. Deep groundwater 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 that nearly sixty percent of the deep groundwater flow travels into the lake. Water from both the lake and deep groundwater migrate eastward into control volume number five, the urban box. Here the model flow terms indicate that the pumping wells draw water from surrounding urban shallow groundwater, the lakes, and deep groundwater. Furthermore, it is important to note that the results of the complex box model are consistent with those from the numerical model (MODBRANCH) developed by Nemeth et al. 2000 and later modified by Herrera 2000 to incorporate lakes. A detailed comparison between the results of the complex model and those of the numerical model are provided by Wilcox 2000. Wilcox, 2000, reports that the results are within the same order of magnitude and within only a 30 to 35% difference between the MODBRANCH and complex models.

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 has its limitations. The complex box model does not fully account for north/south water migration or surficial Everglades flow. In addition, some of the sites used in the complex box model were not monitored until the start of 1998 or later. As a result, at sites such as G3660 too few data points were available to accurately perform additional model runs such as those done in the simple box model (section II.4.a) that assess the impact of seasonal variations on the system. It is also important to note that 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.

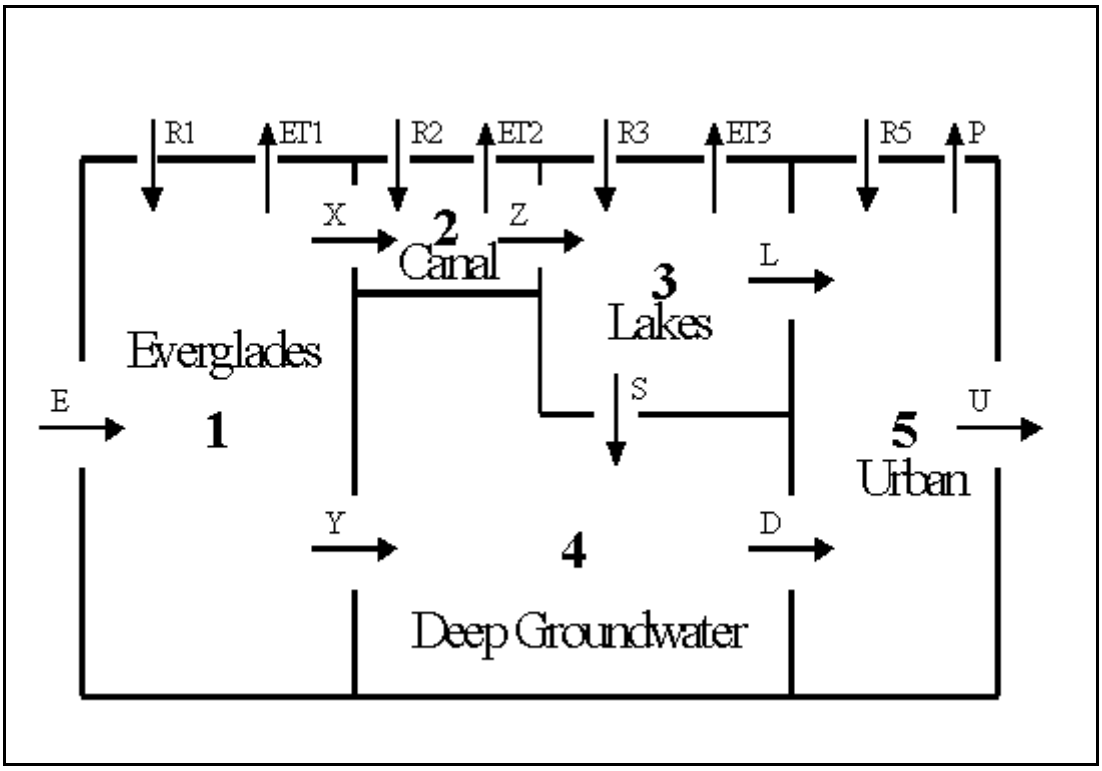

Figure 24: Flow Terms Used in Complex Model

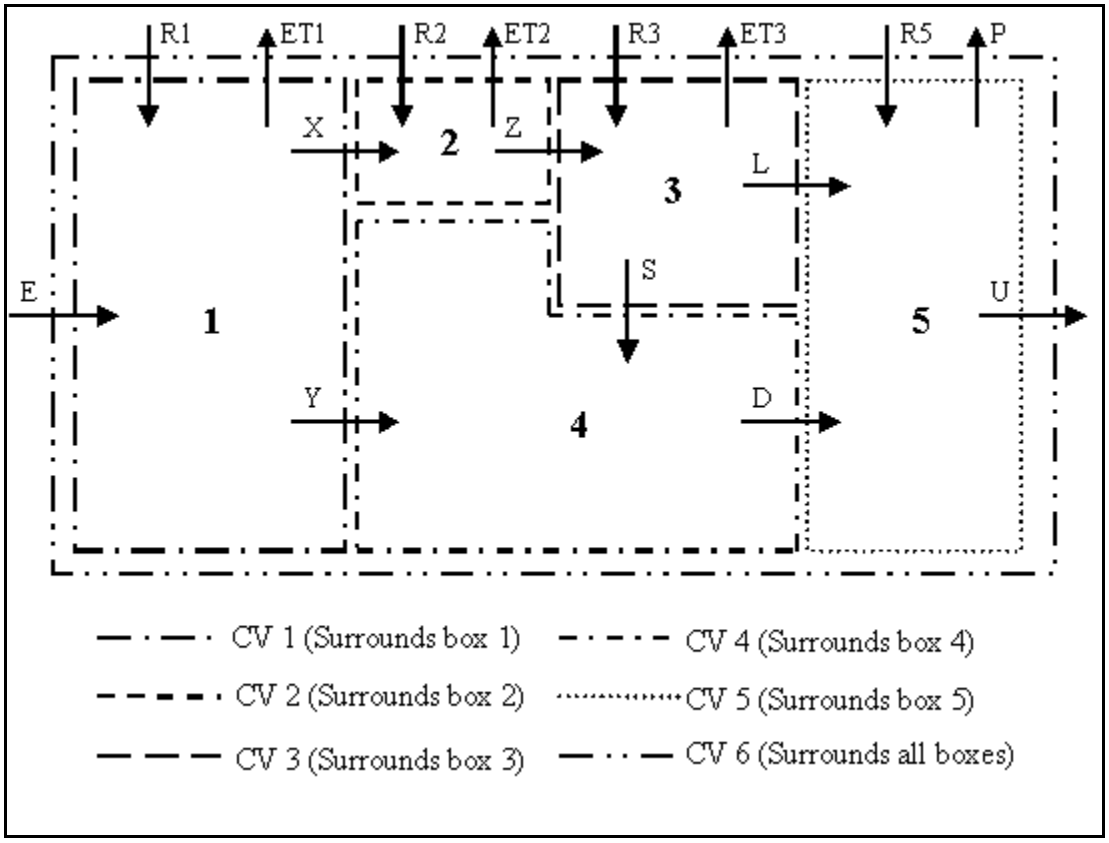

Figure 25: Control Volumes Used for Complex Model

Box #	Box Description	Inputs	Corresponding Values Used	Outputs	Corresponding Values Used
1	Everglades	Everglades water including inflow from S333 (E) Rainfall (R1) over A1, a 2.00 mile by 2.00 mile area	G618 Rain G618	Evapo-transpiration (ET1) over A1, a 2.00 mile by 2.00 mile area Shallow Groundwater (X) Deep Groundwater (Y)	$_{E1}$ from Rain G618, S3575, S3577 & S3578 G3575 G3660
2	Canal	Shallow Groundwater (X) Rainfall (R2) over A2, a 2.00 mile by 0.02 mile area	G3575 Rain WW	Evapo-transpiration (ET2) over A2, a 2.00 mile by 0.02 mile area Shallow Groundwater (Z)	$_{E2}$ from Rain WW, 2M3, 3M4 & 4M5 G3551
3	Lakes	Shallow Groundwater (Z) Rainfall (R3) over A3, a 2.00 mile by 0.22 mile area	G3551 Rain WW	Evapo-transpiration (ET3) over A3, a 2.00 mile by 0.22 mile area Shallow Groundwater (L) Seepage (S)	$_{E3}$ from Rain WW, RL1 & RL3 $_{L}$ from RL1 & RL3 $_{L}$ from RL1 & RL3
4	Deep Groundwater	Deep Groundwater (Y) Seepage from lakes (S)	G3660 $_{L}$ from RL1 & RL3	Deep Groundwater (D)	G3662
5	Urban	Shallow Groundwater (L) Deep Groundwater (D) Rainfall (R5) over A5, a 2.00 mile by 1.76 mile area	$_{L}$ from RL1 & RL3 G3662 RainWW	Pumping Well (P) Urban Water (U)	Well 29/30 G3555

Table 4: Complex Box Model Parameters

Box #	Measured Variables	Calculated Variables
1	R1, ET1, A1, G618, Rain G618, E1, G3575, G3660	E, X, Y
2	R2, ET2, A2, G3575, Rain WW, E2, G3551	X, Z
3	R3, ET3, A3, G3551, Rain WW, E3, L	Z, L, D
4	G3660, L, G3662	Y, S, D
5	R5, A5, P, L, G3662, Rain WW, Well 29/30, G3555	L, D, U

Table 5: List of Measured and Calculated Parameters in Complex Box Model

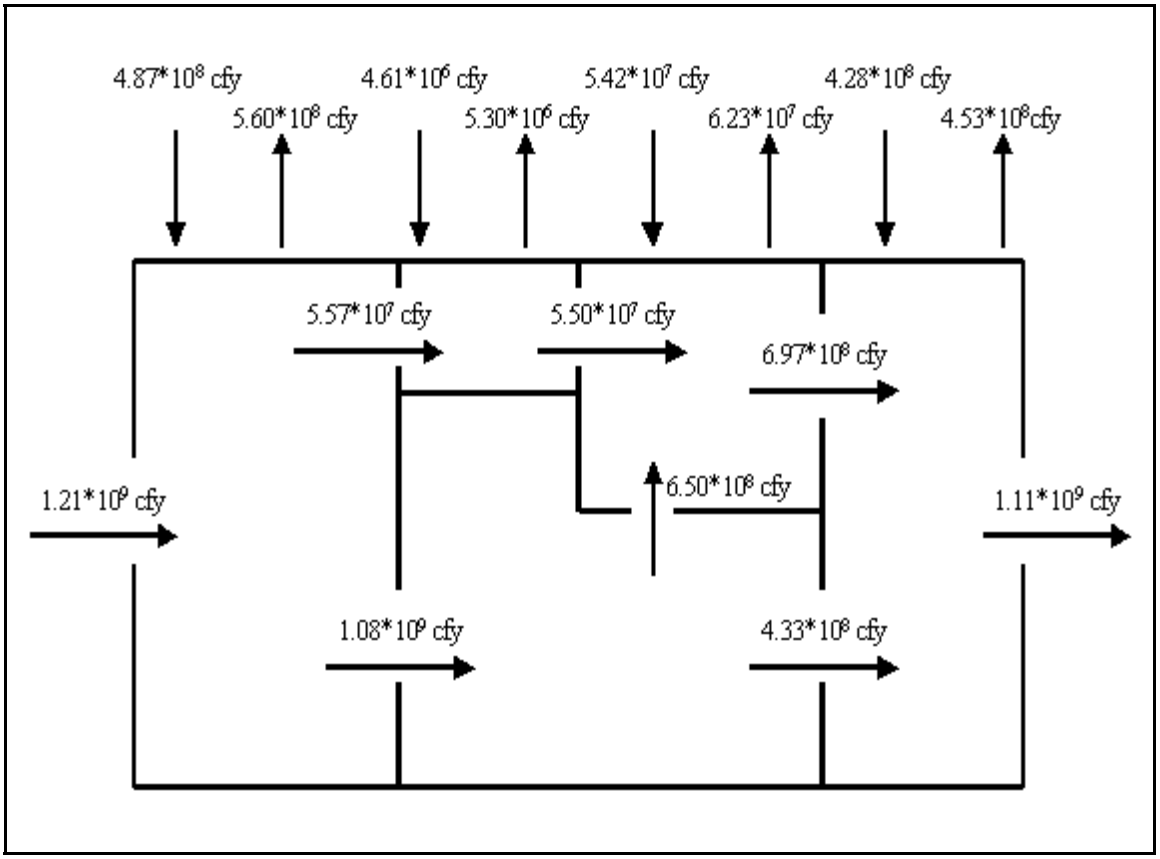

Figure 26: Complex Model Results Using Isotopic Data from 1998

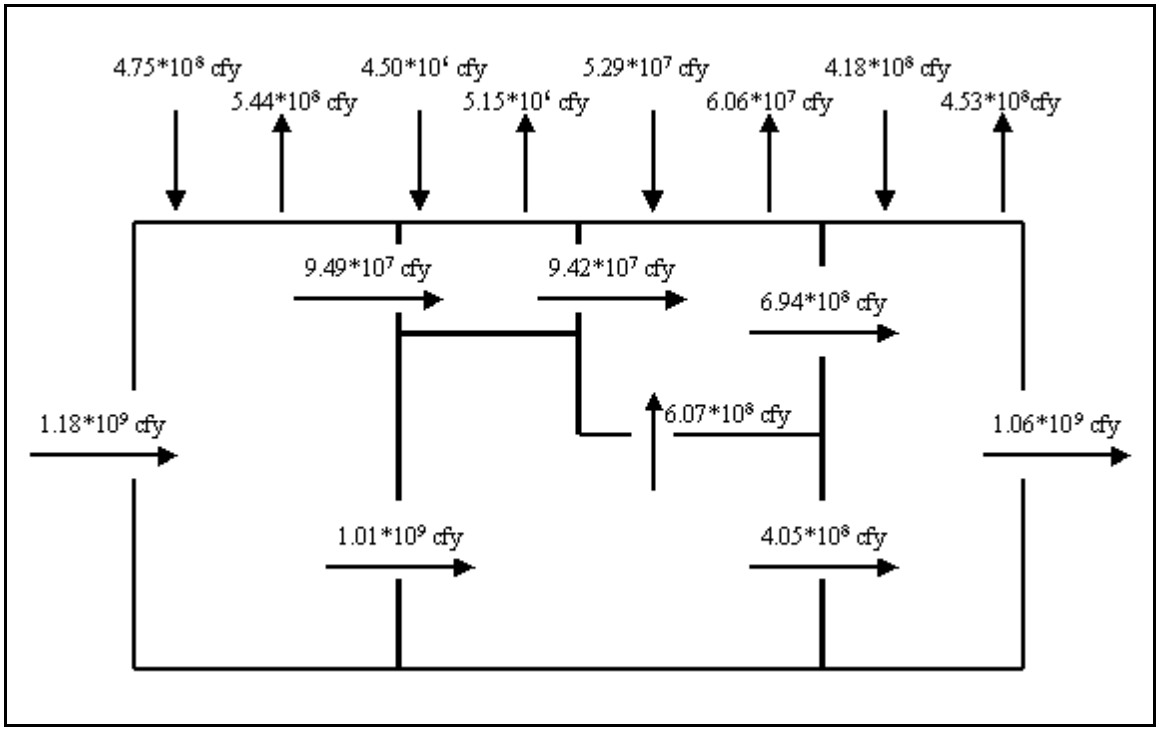

Figure 27: Complex Model Results Using Entire Isotopic Data Set

II.5 Discussion and Conclusions

Why are Isotopes Suitable for Tracing Flows At the Levee 31N Site?

Stable isotopes can be used to trace the flow of water at the West Wellfield/L-31N site, since an isotopic difference can be observed between water derived from the Everglades and water that is recharged in urban areas. Water in the Everglades is subject to considerable evaporation, given that it is shallow and experiences considerable heat and solar radiation. Therefore water within the Everglades is enriched in the heavier isotopes, e.g. oxygen-18 and deuterium. Water that recharges within the urban areas infiltrates into the groundwater system relatively quickly given the extensive drainage network in these areas. These "urban" waters therefore have isotopic characteristics similar to that of rain waters which are lighter than the evaporated waters found within the Everglades. Therefore, heavy water is found within the Everglades and light water is found within urban areas. This difference in isotopic composition can be used to trace the flow of Everglades water through urban areas.

One exception to this general rule occurs in the Everglades, immediately adjacent to the levee. During some hydrologic conditions light water is found at this location. The hydrologic condition corresponds to a period immediately after a heavy rain event and when flows of evaporated waters from upstream conservation areas are "shut-off"(when S333 is closed) from the site.

Conclusions from Data

The data indicate that the majority of water within the study site is coming from local rainfall with additional water most likely the result of infusion of water at gate S333 from northern water conservation areas. It is known from regional water table maps, measured head elevations, and MODBRANCH modeling simulations of the area (Nemeth et al. 2000) that groundwater in the study site moves in general from northwest to southeast on the Everglades side of Levee 31N and from west to east on the urban side of Levee 31N. Heavy Everglades surface water, primarily comprised of evaporated rainfall and water from the conservation areas, infuses into shallow and deep groundwater flow layers in the Everglades. At certain points, such as in the vicinity of G3577/G3663, localized geologic disturbances cause this infusion to occur very rapidly. This rapid infusion results in the formation of "conduits" of isotopically light water (after rainfall events) that travel along with the predominant groundwater flow pattern, gradually mixing with the surrounding groundwater until it comes into isotopic equilibrium.

Upon nearing Levee 31N, Everglades groundwater begins to travel in a more easternly direction, moving nearly horizontally in the geologic layers comprising the Biscayne aquifer. The results of the complex box model indicate that the majority of the water seeping under Levee 31N moves in flow layers between the bottom of the L-31N canal and base of the Biscayne aquifer. At the lakes, the "breaks" in the hard layers cause some of this deep Everglades water to mix with the lake water. This combines with evaporation at the lakes' surfaces to enrich the isotopic composition of the lakes. 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 this water to be drawn into the intakes. These intakes are screened both above and below the deeper semi-confining layer and consequently draw upon not only shallow urban water and lake water but also deep water that originated in the Everglades (Figure 28).

The combined examination of the hydrogeology, isotopic characteristics, and water migration patterns in the immediate vicinity of Levee 31N and the West Wellfield 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.

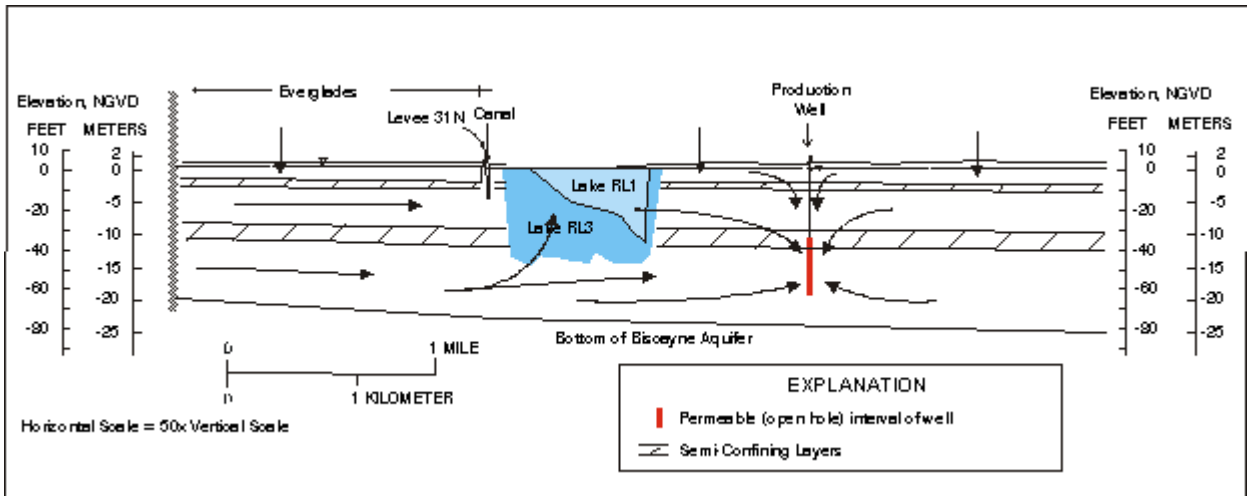

Figure 28: Cartoon Sketch of Water Movement in Study Site

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Appendix A: Isotopic Data

All Data Provided Except For Lakes Where the Depth Averaged Values Are Provided Only

Site	1/31/ 1996	3/26/ 1996	4/19/ 1996	6/24/ 1996	8/28/ 1996	10/1/ 1996
G3551	1.96	1.73		1.76	1.04	1.55
G3552	1.67	0.92		0.87	1.52	0.70
G3553	1.08	0.70		0.67	1.82	0.41
G3554				0.55	0.94	0.29
G3555		0.66		0.25	-0.05	-0.09
WELL 29/30		1.27			2.21	1.34
2M3	1.43	1.61		0.98		
3M4	1.78	1.78	2.14	0.44	1.39	1.67
4M5	1.38	1.66		0.59		
G3575	2.10	2.27		-0.02	1.71	1.52
G3577			2.43			

Table A.1: 1996 Oxygen-18 Data

Site	1/31/ 1996	3/26/ 1996	4/19/ 1996	6/24/ 1996	8/28/ 1996	10/1/ 1996
G3551	4.70	15.42		11.64	7.85	11.06
G3552	-1.00	3.16		7.00	4.63	4.96
G3553	3.70	-2.01		1.69	6.50	5.97
G3554				4.39	3.14	-1.81
G3555		9.25		2.08	0.73	0.99
WELL 29/30		11.26			11.74	10.22
2M3	10.90	4.71		6.45		
3M4	2.20	14.01	14.46	1.97	7.99	11.96
4M5	1.80	15.71		5.56		
G3575	5.70	7.92		-2.16	7.21	10.68
G3577			16.54			

Table A.2: 1996 Deuterium Data

Site	2/6/ 1997	3/4/ 1997	4/8/ 1997	5/5/ 1997	6/4/ 1997	7/3/ 1997	7/30/ 1997	9/10/ 1997	10/9/ 1997	11/6/ 1997	12/3/ 1997
G3551	1.02	1.04	1.04	1.54	1.22	1.04	-0.13	0.88	0.55	0.39	0.65
G3552	0.75	1.04	1.13	1.18	1.14	0.96	1.23	1.14	2.24	0.40	0.44
G3553	0.61	0.49	0.71	0.72	0.75	0.36	0.98	0.75	0.42	0.31	0.43
G3554	0.28	0.07	0.34	0.78	0.31	0.02	0.76	0.73	0.26	0.55	0.49
G3555	-0.43	-0.51	-0.57	-0.29	-0.45	-0.67	-0.02	-0.62	-2.11	-1.70	-1.09
WELL 29/30	1.02	1.25	1.07	1.28	1.50	1.40	1.52	1.41	1.40	1.15	0.86
G618				2.12	2.72	2.39	2.55	1.68	2.07	1.63	1.32
2M3			1.41	1.13	1.79	-1.82	0.39	0.87	0.38	0.88	1.31
3M4	0.91	0.87	1.36	1.03	1.81	-0.67	0.78	0.98	0.23	1.08	0.69
4M5			1.18	1.42	1.75	-0.03	0.36	1.00	0.56	1.01	0.86
G3439				0.56	0.42	-2.25	-1.84	-0.13	-0.19	0.06	0.33
G3575	0.87	1.00	0.66	0.82	0.87	-3.46	0.49	1.74	1.28	0.42	0.99
G3577							-1.07	1.36	-0.57	0.22	-0.85
G3663											-0.03
G3578							2.05	1.87	2.08	1.71	0.57
G3664											1.66
RAIN-WW								-4.70	-1.44	-0.94	-2.98
RL1											1.3

Table A.3: 1997 Oxygen-18 Data

Site	2/6/ 1997	3/4/ 1997	4/8/ 1997	5/5/ 1997	6/4/ 1997	7/3/ 1997	7/30/ 1997	9/10/ 1997	10/9/ 1997	11/6/ 1997	12/3/ 1997
G3551	14.02	12.65	15.33	7.73	8.65	8.06	1.03	-0.54	-0.63	1.54	1.67
G3552	13.39	8.95	12.02	8.02	6.74	9.42	8.20	1.16	0.06	-1.24	-0.07
G3553	9.22	4.26	9.60	1.81	2.88	3.93	6.10	1.18	3.81	9.40	1.40
G3554	6.18	7.03	4.73	2.31	2.79	1.63	8.43	1.44	-0.29	1.17	-1.96
G3555	1.36	3.78	2.50	-1.81	-2.80	-5.34	9.18	-3.68	-10.50	-7.40	-9.94
WELL 29/30	9.03	10.54	14.06	6.52	5.40	5.80	5.12	0.94	0.80	1.23	1.25
G618				13.90	15.07	15.49	17.80	7.39	14.60	9.54	4.00
2M3			8.77	11.32	10.66	-9.30	3.97	6.47	0.42	4.86	4.48
3M4	15.66	16.46	15.80	6.85	11.23	-10.97	5.16	1.60	0.16	9.02	0.05
4M5			9.23	11.40	11.42	2.60	4.61	6.90	1.32	7.44	2.34
G3439				3.38	1.02	-23.00	-11.79	-10.97	-12.26	-2.38	-7.62
G3575	15.09	10.57	13.58	5.97	4.89	-28.00	2.55	2.40	-5.77	4.98	5.71
G3577							-8.34	4.06	-3.37	-1.50	-6.63
G3663											-4.33
G3578							16.65	6.05	8.44	16.88	-1.02
G3664											3.82
RAIN-WW								-28.43	7.22	8.78	-17.11
RL1											4.14

Table A.4: 1997 Deuterium Data

Site	1/6/1998	2/10/1998	3/3/1998	4/7/1998	5/5/1998	6/1/1998	7/6/1998	8/3/1998	9/1/1998	9/24/1998	10/6/1998	11/10/1998	12/10/1998
G3551	0.64	1.37	0.24	0.83	1.07	1.44	1.64	1.78	2.70		1.83	1.31	0.88
G3552	0.50	1.33	0.86	-0.06	0.21	1.22	1.02	1.27	0.72		1.08	1.55	1.39
G3661	1.14	1.03	0.68	0.99	1.53	1.38	1.27	0.93	1.65		1.23	1.56	1.32
G3553	0.76	1.11	0.81	0.38	0.70	1.07	1.30	0.78	0.61		1.09	1.18	1.27
G3554	0.72	0.65	0.77	0.29	0.64	1.02	0.50	0.41	0.41		0.61	1.03	0.57
G3662	1.91	1.15	0.89	1.52	1.20	0.81	0.98	0.66	0.95		1.04	1.38	1.30
G3555	-1.20	-0.68	-0.61	-0.31	0.00	0.41	0.30	-0.17	-0.13		-0.31	0.10	-0.84
WELL 29/30	2.06	1.27	0.85	1.59	1.14	1.43	1.24	0.98	0.78		1.63	1.56	1.61
G618	1.55	1.17	1.47	1.52	2.29	3.43	3.04	2.42	2.74		2.43	2.00	2.16
2M3	0.81	1.15	0.69	1.26	2.05	2.97	1.84	1.83	1.56		0.08	0.83	1.18
3M4	0.68	0.99	0.68	0.97	2.03	2.53	1.60	2.09	2.02		0.37	1.22	1.28
4M5	0.97	0.94	0.58	1.08	1.84	2.73	1.43	1.74	1.77		0.82	0.89	1.16
G3439	0.37	0.54	-0.96		0.32	0.44	0.01		1.27		-1.05	0.02	0.34
G3575	0.71	0.75	0.65	1.81	3.08	4.17	3.28	1.69	1.78		0.16	0.57	1.61
G3660						0.69	1.40	0.97	1.61		1.86	1.59	1.44
G3577	0.36	1.36	1.40	1.49	3.39	3.77	3.55	1.86	2.04		0.53	0.86	1.09
G3663	0.06	0.84	0.99	0.13	0.28	0.21	1.25	0.31	0.22		-0.07	0.22	0.25
G3578	1.82	1.81	1.13	1.57	2.74	2.91	2.25	1.91	1.88		1.38	2.07	2.09
G3664	1.87	1.71	1.86	1.84	1.83	1.84	2.11	1.35	2.09		1.94	1.92	1.95
RAIN-WW	-4.41	-2.76	-0.29	-2.92	-1.71	-2.05	-1.77	-2.30	-1.38	-4.54	-2.99	-2.10	-0.56
RAIN-G618						-2.39	-1.53	-3.43	-1.30	-3.90	-3.72	-2.99	-1.27
S3575									2.22		0.96	0.59	1.43
S3577							4.08	4.11	2.77		0.67	-0.18	1.52
S3578							2.66	2.72	2.42		0.77	0.35	1.25
RL1	1.22	1.05	0.85	1.01	1.4	1.36	1.93	1.53	1.56		2.06	2.02	1.95
RL3	1.06	1.25	1.49	1.08	1.3	1.49	1.6	1.66	1.22		1.99	1.65	1.47

Table A.5: 1998 Oxygen-18 Data

Site	1/6/1998	2/10/1998	3/3/1998	4/7/1998	5/5/1998	6/1/1998	7/6/1998	8/3/1998	9/1/1998	9/24/1998	10/6/1998	11/10/1998	12/10/1998
G3551	6.42	0.36	-0.43	2.67	4.65	5.35	11.41	15.94	13.22		19.38	6.57	4.14
G3552	12.62	1.60	1.25	-0.99	4.68	3.08	3.46	7.88	-2.17		7.46	10.11	10.15
G3661	5.26	-2.45	-4.84	0.36	5.98	1.69	1.61	6.57	5.37		9.72	10.78	14.42
G3553	8.86	0.48	-0.54	-1.49	1.49	0.22	4.36	8.60	-0.83		7.19	8.12	5.21
G3554	1.40	0.58	2.14	0.17	-1.49	2.06	2.91	3.70	1.34		2.73	4.91	5.20
G3662	7.53	9.67	-0.66	-2.61	3.06	0.74	3.21	9.98	1.33		9.85	14.91	14.55
G3555	-6.41	-9.35	-5.13	-7.33	3.81	-5.80	-3.96	2.12	-8.51		8.08	-1.08	-0.29
WELL 29/30	5.91	1.71	3.63	-1.40	4.99	2.88	7.03	4.77	5.52		19.61	14.11	13.67
G618	13.20	3.02	5.83	8.21	4.84	13.94	13.61	21.00	21.38		20.63	19.27	16.83
2M3	4.46	0.37	1.83	5.59	9.09	11.79	13.70	10.40	8.51		-2.24	6.15	8.63
3M4	12.61	-1.34	2.86	4.63	7.62	12.89	11.90	13.26	11.36		8.82	8.89	4.66
4M5	2.63	0.15	3.37	4.62	0.57	10.73	8.41	6.08	7.25		-1.95	4.27	6.60
G3439	2.99	-4.54	-2.14		13.61	-1.51	1.40		6.82		-2.59	-0.19	-1.15
G3575	4.47	1.69	5.94	-3.53	14.96	14.73	12.97	9.80	10.46		-0.34	5.13	12.51
G3660						2.75	10.66	6.36	6.46		10.26	7.23	4.95
G3577	4.76	5.70	9.46	9.61	6.25	17.39	18.95	9.07	11.84		-1.05	5.77	11.88
G3663	4.65	-0.35	-2.31	0.70	10.91	-1.25	0.74	2.43	2.90		2.19	0.82	5.23
G3578	7.63	5.37	6.71	8.44	5.36	11.74	12.61	13.19	10.23		15.14	17.21	13.50
G3664	20.77	2.08	5.19	8.09	6.98	7.94	12.16	9.24	5.34		15.65	7.81	8.37
RAIN-WW	-20.79	-9.54	4.09	-11.69	0.78	-16.35	-3.97	-14.70	-2.78	-32.93	-15.31	-13.05	-5.65
RAIN-G618						-13.71	0.52	-17.20	-4.87	-18.56	-26.86	-9.91	4.89
S3575									13.57		9.21	2.65	11.43
S3577							16.03	16.96	19.88		1.83	-0.24	14.22
S3578							9.82	7.10	13.30		8.39	5.89	14.97
RL1	4.85	5.35	5.95	6.16	8.68	6.64	8.48	10.96	9.51		9.44	6.25	9.17
RL3	3.46	3.27	3.99	3.72	5.84	6.24	7.58	6.70	8.75		7.68	6.8	8.54

Table A.6: 1998 Deuterium Data