Dania Beach Pursues Horizontal Wells

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Abstract

The City of Dania Beach is in need of additional water supply. Because of the potential for saltwater intrusion and the uncertainty of sea level rise, the City's current wells will likely be negatively impacted. Because the alternatives for new water supplies are limited (mostly saltwater sources), a small City like Dania Beach can be confronted by significant costs to build new water treatment facilities. As a result, the City is looking at the use of horizontal well technology to capture water that would otherwise be lost to tide. Horizontal wells have not been used in South Florida except as exfiltration trenches for drainage purposes. Downstream of salinity structures, the natural water table head diminishes. Horizontal wells could spread the cone of depression and minimize drawdowns to permit additional capture of fresh water. Modeling of the current wells, a new shallow well and the horizontal concepts demonstrated that the horizontal technology would create less drawdown than the other well facilities.

Introduction

Water supply, water quality and the Everglades's ecosystem health are intrinsically linked. Historically there were no barriers or canals to direct or control the path of water (see Figure 1). The Central and South Florida program canals permanently reduced groundwater levels along the coast (which enabled the development that exists today – see Figure 2 which shows the canals in the SFWMD and the post-drainage modification changes to Figure 1). The SFWMD is tasked with the management and protection of regional water resources, including competing interests of water quality, flood control, natural systems and water supply. SFWMD's boundaries extend from central Florida to Lake Okeechobee, and from coast to coast, from Fort Myers to Fort Pierce, south through the sprawling Everglades to the Florida Keys. The SFWMD Governing Board approved the Lower East Coast Water Supply Plan in 2000, and the Lower East Coast Water Supply Plan Update in 2005. The plan provides a strategy for assuring adequate water supplies are available to meet environmental, agricultural and population demands through 2025 by proposing 110 alternative water supply projects, including using reclaimed water and reverse osmosis to reduce the dependency on groundwater and surface water. The State of Florida, via the SFWMD, has committed billions of dollars to reversing the impacts of the drainage projects of the 1920s and 1940s by restoring natural flows and levels as a part of an agreement with the federal government called the Comprehensive Everglades Restoration Plan (CERP). Because the plan is future oriented, more immediate measures are necessary to enhance water supplies.

In early 2007 the SFWMD felt compelled to impose stricter limitations on the use of "Everglades water" if it is to protect the Everglades. To address the immediacy of the ecosystem concerns, the SFWMD Governing Board adopted the Regional Water Availability Rule. The salient features of the Regional Water Availability Rule include the following: future water demands over and above the "base condition water use" will have to be provided from alternative water sources (AWS) or offset with reuse or stormwater (also considered AWS). The "base condition water use" is defined as the five-year historical, highest twelve-month pumpage from this wellfield. Utilities needing water supplies will be required to seek sources that are not dependent upon the Everglades for recharge. This has significant implications for southeast Florida residents. First it means no new Biscayne Aquifer water, meaning the "cheap" water supplies are no longer going to be permitted for use by urban residents.

Alternative water supply options are much more exotic and expensive. For example, alternative water supply solutions include, but are not limited to:

- Acquiring water from someone who has sufficient supplies
- Aquifer storage and recovery (this is a storage and water management too and storage does not create additional water)
- Alternative water sources using saline sources (read Floridan Aquifer or seawater sources)
- Alternative water supply options that will demonstrate recharge to current wellfields (e.g., reuse with nanofiltration technology to meet the standards for 62-610, F.A.C.)

Relying on others to provide a utility with its water supply may shift risk to the supplier, the reality is that recipient utilities will be paying of the costs of alternative water supplies developed by the utilities selling them water. Hence, this option only shifts the risk, not the cost, and is therefore not really an alternative water supply.

ASR was the original "solution" for the SFWMD's restoration plan. Within the original Everglades restoration plan, $1.2 billion was proposed to be used to install 300+ ASR wells around Lake Okeechobee. ASR wells were intended to be the major solution to water storage because surface reservoirs have very high evapotranspiration. After 10 years, this measure appears to be a failure as no wells have been completed. Even a successful ASR program creates no new water, it just stores excess water from the wet season. As a result this option has fallen from favor.

Next, the Floridan aquifer brackish water supply was touted as a solution to utilities starting 5-10 years ago, but upon further review it seems clear that since the Floridan aquifer does not recharge anywhere close to south Florida (water is dated at 20,000 years old), and testing/operation of wells in the City of Hollywood showed drawdown in excess of 80 feet per well withdrawing under 1.5 MGD, production of water from the Floridan aquifer may cause deterioration in water quality for utilities who pursue this option. Several coastal communities, most notably Marco Island, have suffered from this phenomenon. Ultimately this left reuse.

The use of reclaimed water is a stated goal of the Comprehensive Plan for the State of Florida. Florida is among the leaders in reclaimed water use in the United States, with some 400 facilities using reclaimed water in a variety of uses, including the irrigation of agricultural land, golf courses, roadway medians, landscaping and residential homes and industrial uses such as cooling towers. Southwest and central Florida have been pursuing reclaimed water for over forty years because there are no other obvious disposal alternatives (lacking access to streams, ocean outfalls or injection wells), and costs because many of the wastewater treatment plants have their origin as small developer-owned systems designed to serve their development, and later deeded to local governments. South Florida does not for due to ready access to the Intra-coastal Waterway, Atlantic Ocean and injection well disposal options for the larger, regional systems created in the 1960s and 1970s as a part of the Federal 201 process. The result is that southeast Florida has had larger quantities of wastewater to dispose of for over 50 years, and centralization of treatment has made outfalls and injection wells economically justifiable (Englehardt *et al*, 2001, Bloetscher *et a*l, 2005).

In addition, sea level rise may reduce the usefulness of reuse. The water levels in the Biscayne Aquifer fluctuate in response to rainfall, drainage and withdrawal for irrigation and potable use. The canals drain the aquifer to permit development. If sea level rises, the water table aquifer will increase as well, lowering the amount of soil storage capacity. Adding reuse irrigation would exacerbate the situation.

Dania Beach's Situation

The City of Dania Beach, being a coastal community, has historically had difficulties with its raw water supply wells. The City's initial wells were installed near the current water plant along the Florida East Coast railroad. Use of these wells has been discontinued due to high levels of chlorides in the water, and formally abandoned in 2007. In 1976, two new wells were installed on the west side of the City near Ravenswood Road west. These wells are currently in use (referenced as Wells G and H). These wells are restricted due to saltwater intrusion although it appears that the chloride content of the raw water is diminishing slightly with time and responds to rainfall. The City has been testing for salt water intrusion for the past ten years on a monthly basis in both the production wells and adjacent monitoring wells. The wells were rehabilitated in 2003 (H) and 2005 (G), which reduced capacity a minor amount in each. The City's hydro-geological consultant suggested that the City might be able to recapture firm capacity by drilling a third well southwest of the existing wells on Stirling Road. Investigation was initiated during the 2007 budget year, but a layer of connate water to the west is being mapped prior to finding a new well location.

While the City's water use permit allows for the majority of withdrawals from the City's wells, additional supplies are available from Broward County's Brian Piccolo Park wellfield and from Well 6 in the old Broward County 3A wellfield. The concept was that since the SFWMD would not approve additional water supplies for eastern utilities due to concerns about saltwater intrusion, a regional wellfield would provide the long-term permanent solution. The Broward County raw water agreement was executed in June 1990 between the City of Dania Beach and the County. Broward County used Certificates of Participation (CoPs), paid off via General Fund revenues, to construct the regional 21 MGD wellfield. The wellfield came on line in 1994 with an installed capacity of 21 MGD. The SFWMD permitted the wellfield at 14.9 MGD average daily flow and 21 MGD maximum daily flow. The City's agreement with Broward County permits it to withdraw up to 1.1 MGD of raw water from the southern regional wellfield (Brian Piccolo Park wellfield). The intent has been for the wellfield to be incrementally increased in flow until fully allocated. The City has planned on the BPP supply as its long-term raw water solution as per direction of the SFWMD.

In addition to the prior goals set by the City, the City is pursuing another option for water supply options:

- Investigate additional well locations in the City's current wellfield. This will require drilling of test wells, additional monitoring wells (completed 2007) and modeling of proposed locations to determine if additional raw water is available in Dania Beach.
- Participate with the Broward County efforts to recharge the County wellfield on a utilization basis. This may include additional wells, storm water recharge or reuse recharge.

Potential Solution

The City's hydrogeological consultant suggested that the City might be able to recapture firm capacity by drilling a third well southwest of the existing wells on Stirling Road. The resulting investigation may provide additional supplies for the City. The City's current water use permit allows for 1.8 MGD to be withdrawn from the City's two wells. The SFWMD indicates that under their Water Resource Availability Rule approved in 2007, this amount may be reduced to 1.8 MGD, which is the highest 12 month withdrawal period between 2000 and 2005. Between the City's 1.8 MGD and the 1.1 MGD in the County contract, the withdrawal amount is adequate to meet the City's current and short-term average daily demands through 2019 Based on permit discussions, the City will attempt to skim additional water from its coastal wellfield to regain lost capacity (0.2 MGD) which will solve the water supply issues through 2030 (see Table 1). The City is among the limited number of utilities that is positioned to take advantage of direct rainfall harvesting. The City is located east of the salinity structures and as a result all shallow groundwater is rainfall. The canal system is very effective at draining the sands above the Biscayne aquifer effectively.

As the City reads the Regional Water Availability Rule, the intent is to reduce demands on the Everglades recharge area for the Biscayne aquifer and to reduce saltwater intrusion, so harvesting direct rainfall that would otherwise be lost to tide would qualify as long as it does not encourage saltwater intrusion. The solution the City is investigating is a horizontal well. A horizontal well configuration includes a central concrete caisson - typically 16 feet in diameter - excavated to a target depth at which well screens project laterally outward in a radial pattern. In a practice referred to as riverbank filtration, the wells are designed to induce infiltration from a nearby surface water source, combining the desirable features of groundwater and surface water supplies.

The City has had discussions about a horizontal well. The benefit of a horizontal well is that is can skim water off of the sands above the Biscayne aquifer, while creating minimal drawdown that will prevent saltwater intrusion and upconing (which is an issue for the City), and shallow enough that the Biscayne Aquifer/ Everglades is not affected. Compare Figures 3a and 3b and the potential drawdown. A horizontal well has over 10 times the screening that a vertical well has, which directly translates to lower drawdowns, and for Dania Beach, less potential for upconing.

Horizontal wells have screened sections that can be positioned parallel to the static water table. There are several advantages to horizontal wells: more even flow to the well screen, more uniform proximity to the formation, larger contact area with the aquifer, and longer well screens which permit horizontal wells to have a larger contact zone to the aquifer (Zhan, 2002). However, until recently, the construction techniques have been more difficult that vertical wells. The advent of deep trenching tools and development of screening/gravel back units has significantly easier construction, and a reduced cost. The operational stability of horizontal wells has improved as a result.

In most cases, a horizontal well will be in a sand or alluvial formation, not a rock formation. As a result there is significant potential for migration of solids to the well and no ability to clean the well. A horizontal well needs to have a low entrance velocity and as a result the infiltration rate is best matched with pumping rate in the caisson. Matching flow rates can be done through field testing, and confirmed during modeling.

Analytical solutions for the drawdown from a vertical well (in two dimensions) is a readily understood equations dependent on Darcy's Law. Likewise, numerical solutions for groundwater flow were developed over 30 years ago, with MODFLOW being the most common base modeling efforts. However the solution for horizontal wells is more challenging. Hantush and Papadopolus (1962) suggested an analytical solution in their collector well paper. This solution assumed an aquifer of uniform hydraulic properties, a small radius of collector wells when compared to the aquifer thickness, and a small caisson diameter when compared to the length of the collector lateral. They developed a series of equations to solve for yield:

$$s = \sum_{i=1}^{N} \frac{Q_i}{l_i} f_1(r, \theta, z, t; \ldots; r_i, \theta_i, z_i, t_i)$$

Which they solved for long periods of time in a confined aquifer to obtain:

$$s_i = \frac{Q_i}{4kb\pi l_i}\left\{\alpha W\left(\frac{\alpha^2+\beta^2}{4\nu' t}\right) - \beta W\left(\frac{\delta^2+\beta^2}{4\nu' t}\right) + 2l_i - 2\beta\left(\tan^{-1}\frac{\alpha}{\beta} - \tan^{-1}\frac{\delta}{\beta}\right) + \frac{4b}{\pi}\sum_{1}^{\infty}\frac{1}{n}\left[L\left(\frac{n\pi\alpha}{b}, \frac{n\pi\beta}{b}\right) - L\left(\frac{n\pi\delta}{b}, \frac{n\pi\beta}{b}\right)\right]\cos\frac{n\pi_z i}{b}\cos\frac{n\pi z}{b}\right\}$$

where

$$\alpha = r\cos(\theta - \theta_i) - r$$

$$\beta = r\sin(\theta - \theta_i)$$

$$\delta = r\cos(\theta - \theta_i)$$

$$l'' = r_c + l_i$$

$$\nu' = \frac{Kb}{Sy}$$

$$L(u +/- w) = \int_0^u K_o\left(\sqrt{w^2 + y^2}\right)dy$$

They solved this equation for a short periods of time in an artesian aquifer to obtain:

$$s_i = \frac{Q_i}{4T\pi l_i}\left\{\begin{aligned}&\frac{\alpha}{l_i}W\left(\frac{\alpha^2+\beta^2}{4\nu' t}\right)-\frac{\beta}{l_i}W\left(\frac{\delta^2+\beta^2}{4\nu' t}\right)+2l_i-2\beta\left(\tan^{-1}\frac{\alpha}{\beta}-\tan^{-1}\frac{\delta}{\beta}\right)+\frac{\frac{2}{l_i}}{\sqrt{4\nu t}}\left[L_0\left(\frac{\alpha}{\sqrt{4\nu t}},\frac{\beta}{\sqrt{4\nu t}}\right)-L_0\left(\frac{\delta}{\sqrt{4\nu t}},\frac{\beta}{\sqrt{4\nu t}}\right)\right]\exp\left(\frac{-\beta^2}{\sqrt{4\nu t}}\right)\\&+\frac{\frac{2}{l_i}}{\sqrt{4\nu t}}\sum_{1}^{\infty}\left[F\left(\frac{\alpha}{\sqrt{4\nu t}},\frac{\beta}{\sqrt{4\nu t}},\frac{\frac{n\pi}{b}}{\sqrt{4\nu t}}\right)-F\left(\frac{\delta}{\sqrt{4\nu t}},\frac{\beta}{\sqrt{4\nu t}},\frac{\frac{n\pi}{b}}{\sqrt{4\nu t}}\right)\right]\cos\frac{n\pi z}{b}\cos\frac{n\pi_1 z}{b}\ldots\end{aligned}\right\}$$

where

$$\alpha = r\cos(\theta-\theta_i)-r$$

$$\beta = r\sin(\theta-\theta_i)$$

$$\delta = r\cos(\theta-\theta_i)$$

$$\nu' = \frac{K}{S}$$

$$L(u+/-w) = \int_0^u \frac{\beta^2 e^{-\beta^2}}{w^w+\beta^2}d\beta$$

$$F(u+/-w) = \int_0^u W\left(x^2+\beta^2, y\sqrt{x^2+\beta^2}\right)d\beta$$

Numerically the solution to a horizontal well has proved more difficult. Zhan (2002) attempted to solve this problem analytically. The initial method to solve the problem numerically was to put in a series of small wells in the water table aquifer zone, where it was assumed that the drawdown of the wells was smaller than the saturated thickness of the aquifer. The assumption is not very restrictive because this situation is the norm. He solved:

$$S\frac{\partial h}{\partial t} = K_x\frac{\partial^2 h}{\partial x^2}+K_y\frac{\partial^2 h}{\partial y^2}+K_z\frac{\partial^2 h}{\partial z^2}-Q\delta(x-x_0)\delta(y-y_0)\delta(z-z_0)$$

using a point sink solution in the LaPlace domain (Zhan, 1999; Zhan and Zlotnik, 2002; Kompani-Zare *et al*, 2005) to achieve:

$$\nabla^2 \bar{s}_D - \Psi^2 \bar{s}_D = \frac{4\pi \overline{q_{fD}}(p)}{p} \delta(x_D - x_{0D}) \delta(y_D - y_{0D}) \delta(z_D - z_{0D})$$

where

$$\Psi = \sqrt{\phi\sqrt{\gamma p}\coth(d_{CD}\sqrt{\gamma p}) + \mu\left\{\sqrt{\frac{p}{\omega}}\coth\left(\sqrt{\frac{p}{\omega}} r_{mD}\right) - \frac{1}{r_{mD}}\right\} + p}$$

where:

$s_D = drawdown$

$\overline{q_{fD}} =$ *pumping rate in the LaPlace domain*

$x_D, x_{0D}, y_D, y_{0D}, z_D, z_{0D} = x, y, z$ dim*ensions*

$\gamma =$ *Angle of inclination*

$p =$ *LaPlace transform*

$\phi =$ *inclination or tilt*

$r_{mD} =$ *well diameter*

As a result, there are two ways to attack the modeling. One is as a drain, the other as a series of wells inserted into a computer model designed to represent groundwater flow.

The underlying basis for the groundwater modeling was MODFLOW. MODFLOW is a three-dimensional finite-difference groundwater flow model created by United States Geological Survey (USGS) and is the most widely-used groundwater model in the world. MODFLOW is used to simulate systems for a variety of purposes including as water supply, contaminant remediation, and mine dewatering. MODFLOW uses block-center finite difference approximation to analyze groundwater flow rate and volume balance for each block and simulate three-dimensional results. Layers can be simulated as confined, unconfined, or a combination of both. Flows from external stresses such as flow to wells, recharge, evapotranspiration, flow to drains, and flow through riverbeds can be simulated in MODFLOW. MODFLOW can also withdrawal effects on the aquifer, canals, ocean, and recharge within the aquifer system. A coupled program is MODPATH which is utilized to trace particles, which can be placed within the aquifer and allowed to migrate with the flow regime depicted in the MODFLOW model. This module of the program illustrates the movement of water in various locations of the aquifer.

SEAWAT is a generic MODFLOW-based computer program designed to simulate three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport (Langevin, 2009). SEAWAT is used to simulate systems for a variety of purposes such as saltwater intrusion or brine migration. SEAWAT uses the structure of MODFLOW and many of the commonly used pre and post-processors can be used to create SEAWAT datasets and visualize results. The MODFLOW concepts of "packages" and "processes" are retained in SEAWAT, which allows the program to work with many of the MODFLOW-related software programs (Langevin, 2009).

The pre-processing software that was used was Groundwater Vistas (GV), a sophisticated windows graphical user interface for 3-D groundwater flow and transport modeling that incorporates MODFLOW MODPATH (both steady-state and transient versions), MT3DMS, MODFLOWT, MODFLOWSURFACT, MODFLOW2000, GFLOW, RT3D, PATH3D, SEAWAT and PEST. The modeling software should be able to represent the withdrawal effects on the wells, canals, ocean, and recharge within this aquifer system. It should be noted that the drain function in the MNW subroutine does not work in Groundwater Vistas so the horizontal well was modeled by using 3 x 3 ft grid cells and a 2 ft diameter well

Three scenarios were modeled so results from both simulations can be compared between the 2 vertical well options and horizontal well. All settings include 1.5 million gallons per day (MGD) withdrawal from the wellfield, the allowable withdrawal rate for the City of Dania Beach. The first scenario is the existing scenario. Once the hydraulic parameters are input into the model, MODFLOW was used to run the simulation of 2 years under normal conditions using data downloaded from the South Florida Water Management District website for rainfall, and 90 days with no recharge following that simulation. The maximum withdrawal flow rate, well radii, and grid locations for the vertical well is listed in Table 2.

The first scenario models 24 stress periods where each stress period represents a month of the year beginning January 2006 and stress period 13 corresponds to January 2007. Rainfall is considered as the only source of recharge for scenario two. A rainfall curve was made from the 2006 and 2007 rainfall amounts obtained from DBHYDRO. DBHYDRO is a data collection website for all drainage structures that are regulated by South Florida Water Management District (SFWMD). The 2 DBHYDRO stations in the vicinity of the project site are stations *S13_R* and *FtLaud*. The S13_R station is closest to the Dania Beach wellfield, therefore the rainfall information for this station was used in this analysis. After the rainfall simulation, the program considers one stress period of 90 consecutive production days with no recharge to simulate the worst condition, occurring after the first scenario.

The parameters of the vertical well are included in Table 3. The steady state models might indicate that the canals are the recharge source, meaning that there is the potential to draw saltwater into the aquifer adjacent to the canals. Figure 4 shows the horizontal well, which has higher heads, an expectation of the horizontal well configuration.

Figures 5 to 7 show the drawdowns for each of the scenarios. The conclusions for each are.

- Current well (63-66 ft) to 0.8 ft
- Shallow well (45-65 ft) to -2.4 ft
- Horizontal Configuration (25-27 ft series of 55 wells) too 1.4 ft

The horizontal well is a potential solution for the southeast Broward County region. Without Lakes, the drawdowns are much greater. The results are that the City could use the horizontal wells to address its long-term water supply needs (see Table 4).

Conclusion

This paper evaluates at the effects of a horizontal well on the fresh/salt water interface near the City of Dania Beach's wellfields. One specific element analyzed is how to capture water from the canals that would otherwise be lost to tide and the ocean. Horizontal wells offer and opportunity to capture water with minimal impacts. This project will look at/examine the use of a horizontal well for municipal water supply of the City of Dania Beach. The primary tasks included in the scope are as follows:

1) Use of Groundwater Vistas (GV) software to model the existing vertical well in two scenarios of 90 days with no recharge and 2 years under normal conditions.
2) Use of GV software to model a horizontal well in two scenarios of 90 days with no recharge and 2 years under normal conditions.

Additional scenarios were run to determine the effects of changing the hydraulic conductivity. Preliminary modeling indicates that the horizontal well concept has viability. The City plans to complete the horizontal well investigation and modeling by 2011, which will provide sufficient time to evaluate the ultimate potential capacity of such a system. The protocol for this investigating. Horizontal wells are presented below:

1. Drilling one of more wells to 40 feet for the purposes of identifying the characteristics of the sand and other formation materials in the range of -30- to -40 ft below land surface where the horizontal well is intended to be placed. This activity is required to determine the potential for further development
2. Construct a test trench.
3. Determine appropriate infiltration and pumping rate via field tests.
4. Remodel the system based on field data
5. Permitting a horizontal well system.
6. Final design and construction of a horizontal well.
7. Address the Groundwater Under Direct Influence Of (GWUDI) surface water issue that is likely to arise due to the shallow nature of the horizontal well. A program must be designed for ongoing testing to comply with the GUWDI rules, while also testing to demonstrate the lack of influence which would result in reduced monitoring requirements.

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Table 1

Projected Demands to 2030
Expected Water Supply Scenario

Year	Population City Service Area only	Raw Water ADF (City Wells)	Raw Water ADF (County)	Total Water Supplies	Total ADF	Water Lost in Treatment	Net Difference	Additional BPP Raw Water	Net
2008*	16317	1.8	1.1	2.9	2.4	0.02	0.48	0.6	1.08
2010	16568	1.8	1.1	2.9	2.4	0.02	0.48	0.6	1.08
2015	20054	1.8	1.1	2.9	2.7	0.1	0.1	0.6	0.7
2020	22869	1.8	1.1	2.9	3.1	0.1	-0.3	0.6	0.3
2025	24192	1.8	1.1	2.9	3.4	0.1	-0.6	0.6	0
2030	24801	1.8	1.1	2.9	3.5	0.1	-0.7	0.6	-0.1

*Note Actual 2008 and 2009 flows were 2.2 MGD

Table 2 - Vertical Well parameters.

# of Well	Layer	Row	Column	Flow Rate (cf/day)	Radius (ft)
G	9	62	62	-207,000	0.5
G2	7, 8	62	62	-207,000	0.5
H	9	--	--	0	0.5

Table 3 - Horizontal Well parameters.

# of Well	Layer	Row	Column	Flow Rate (cf/day)	Radius (ft)
I	4	63-108	62	-207,000 total	1.0

Table 4 – Revised Water Use Projections

Year	Population	Raw Water ADF (City)	New Water-Horiz Well (ADF)	Raw Water ADF (County)	Water Lost in Trmt	Total ADF	Net Difference
2008	16317	1.8	0	1.1	0.02	2.4	0.48
2010	16568	1.8	0	1.1	0.02	2.4	0.48
2015	20054	1.8	0.2	1.1	0.15	2.8	0.15
2020	22869	1.8	1.2	1.1	0.15	3.2	0.75
2025	24192	1.8	1.2	1.1	0.2	3.4	0.5
2028	24601	1.8	1.2	1.1	0.2	3.5	0.4

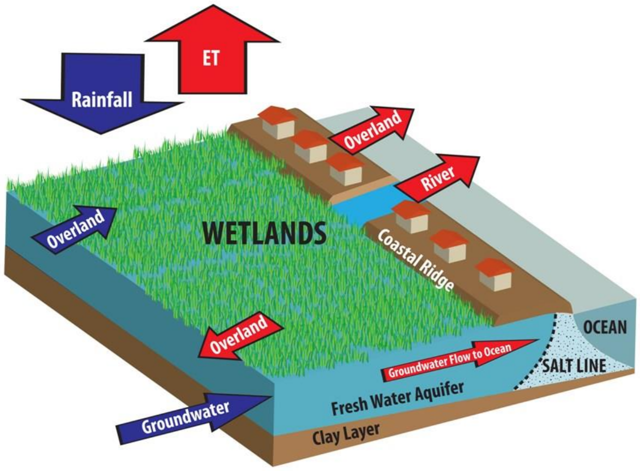


Figure 1 – Pre-drainage/Historical Drainage pattern

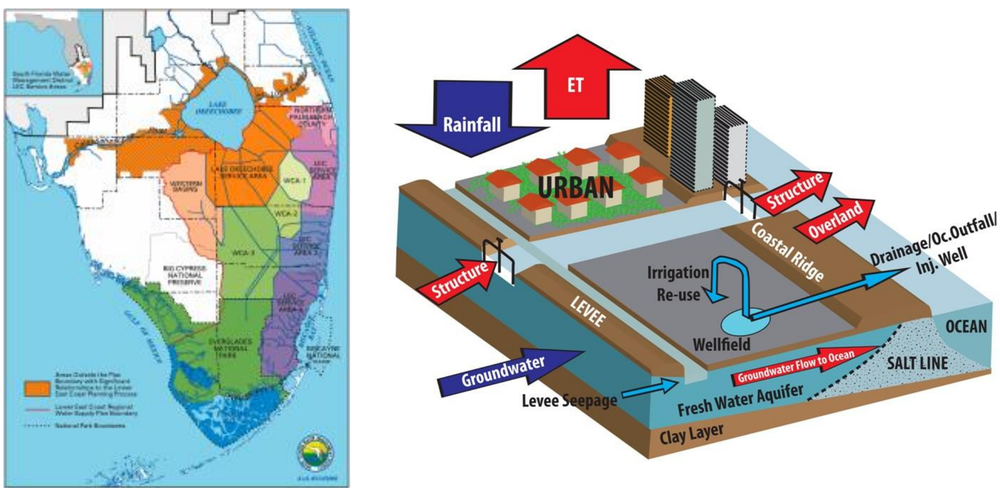
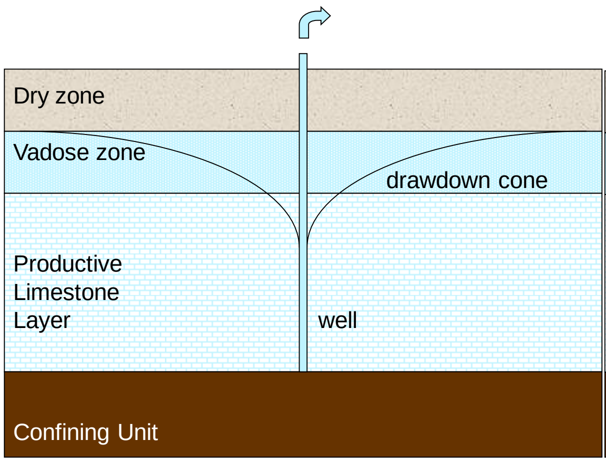


Figure 2 – South Florida Water Management District LEC service area and post-drainage/Historical Drainage pattern (SFWMD web-site)



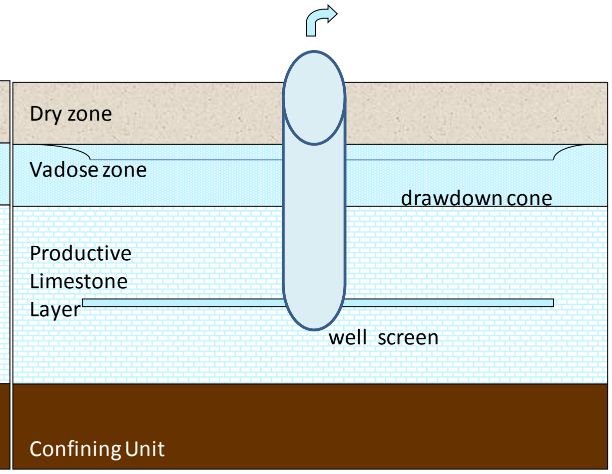


Figure 3a – Normal drawdown for vertical well

Figure 3b – much smaller drawdown with horizontal wells

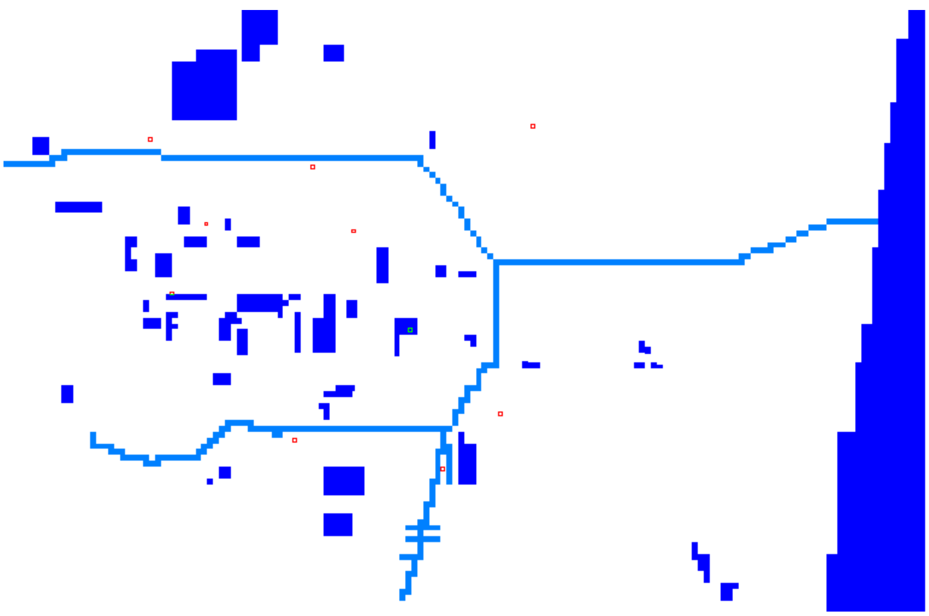


Figure 4 – Plan view of the model showing the C-10 Canal, lakes, and Atlantic Ocean.

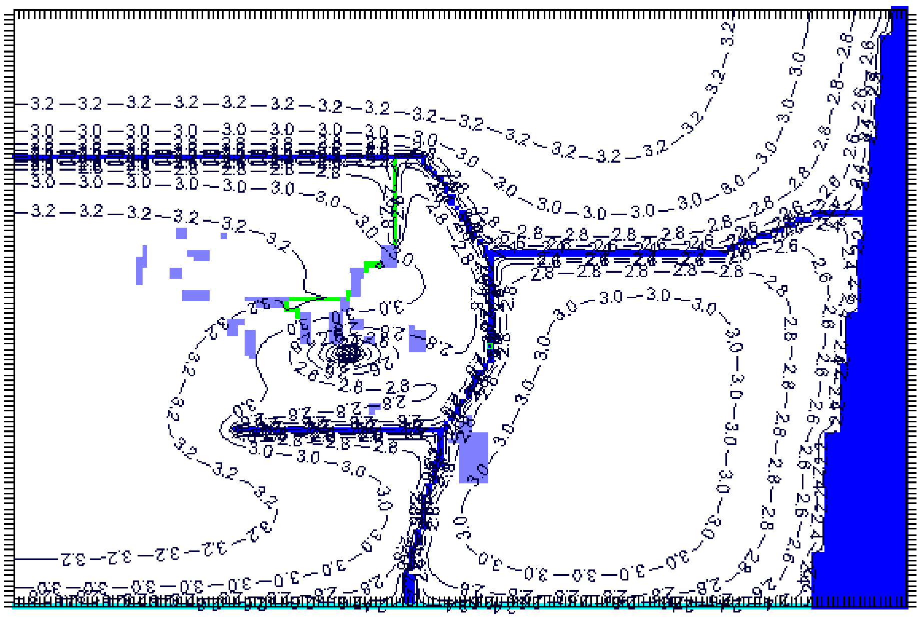


Figure 5 – Current well, with no recharge 120 days coming off the December 2007 2 year period of rainfall days. Note that the canals continue to be the major force is withdrawals of water – HC = 100 cf/d.

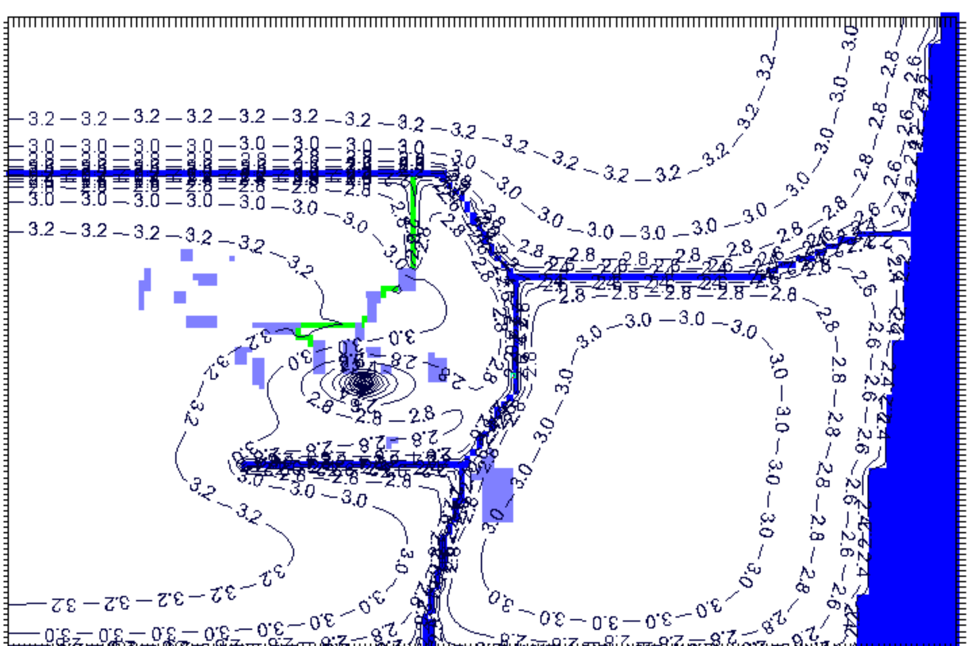


Figure 6 – New shallow well with no recharge 120 days coming off the December 2007 2 year period of rainfall days. Note that the canals continue to be the major force is withdrawals of water – HC = 100 cf/d.

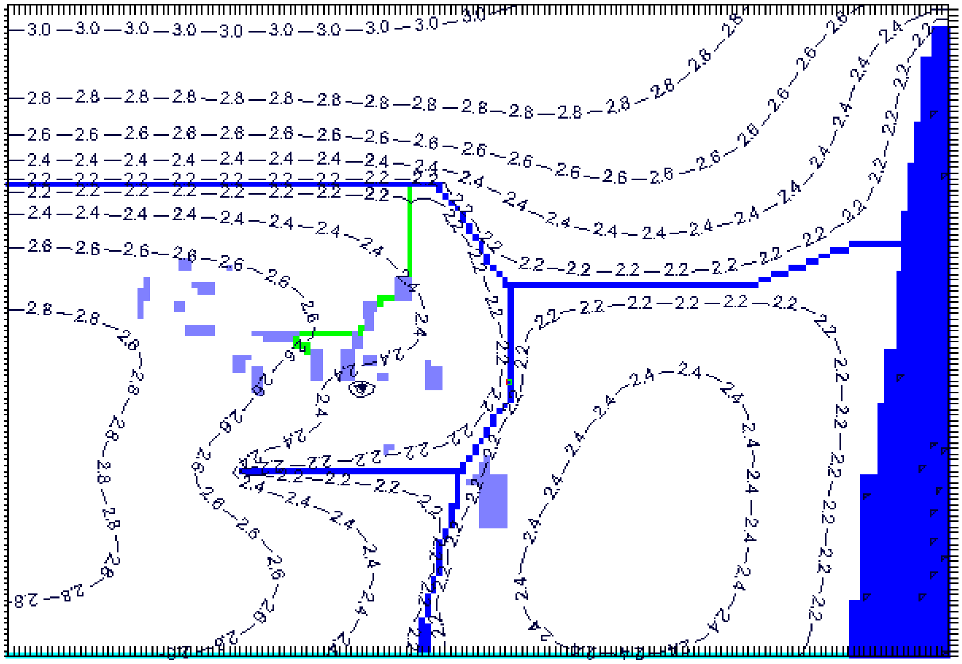


Figure 7 – Proposed horizontal well, with no recharge 120 days coming off the December 2007 2 year period of rainfall days. Note that the canals continue to be the major force is withdrawals of water – HC = 100 cf/d.