A Manager's Paradigm: Too Much Water *and* Limited Water Supplies

Frederick Bloetscher, Nadia Locke, Trent VanAllen, and Albert Muniz

In the future, the coastal and low-lying areas of Florida will be flush with water due to sea-level rise and increased storm intensity. Stormwater utility managers are looking for a solution to deal with increased flooding frequency. Water supply managers are looking for reliable water supply solutions. The traditional barriers, or "silos," among water, wastewater, and stormwater entities may prevent the potential for a unique solution to address both issues concurrently: infiltration galleries as stormwater control tools. Infiltration galleries will reduce groundwater levels, which make soil capacity to absorb an increase in rainfall, and flooding will decrease. The systems will run continuously, which sounds like a water supply solution.

Much work on the exact mathematics of recovery and treatment needs should be undertaken. This article presents a concept where horizontal wells are used for both flood protection and water supplies. This solution has the potential to help protect many low-lying areas and island communities from flooding damage by reduce flood risks. At the same time, it may capture water to treat for water supplies.

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Climate Change Factors

There has been significant discussion about the potential impacts of climate change on the world. Climate change is expected to

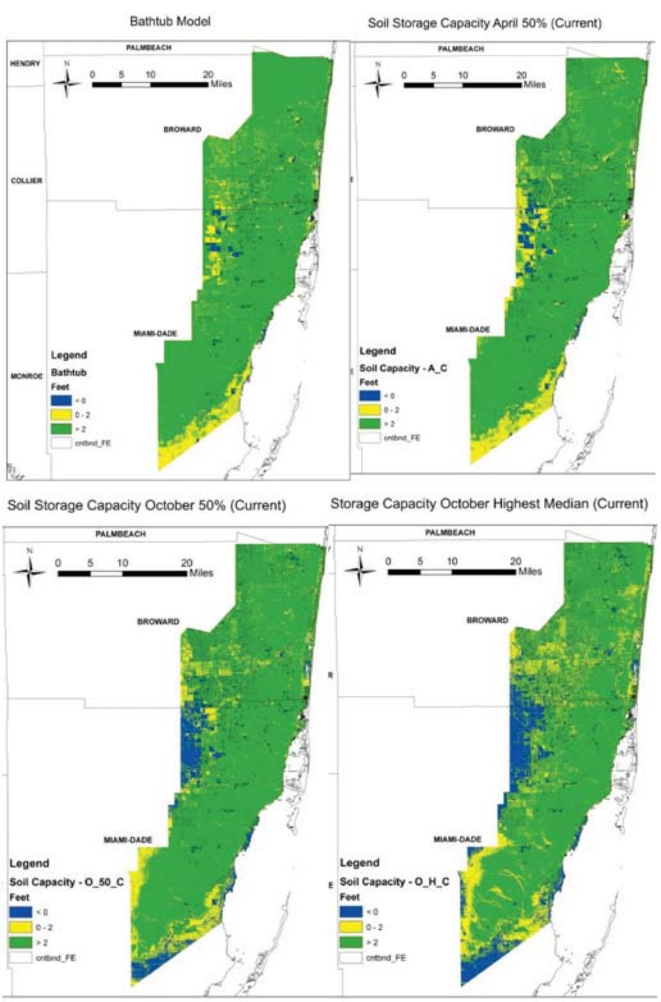

Figure 1a. This shows the results of the bathtub model (current condition), while 1b-d show soil storage capacity under the current condition.

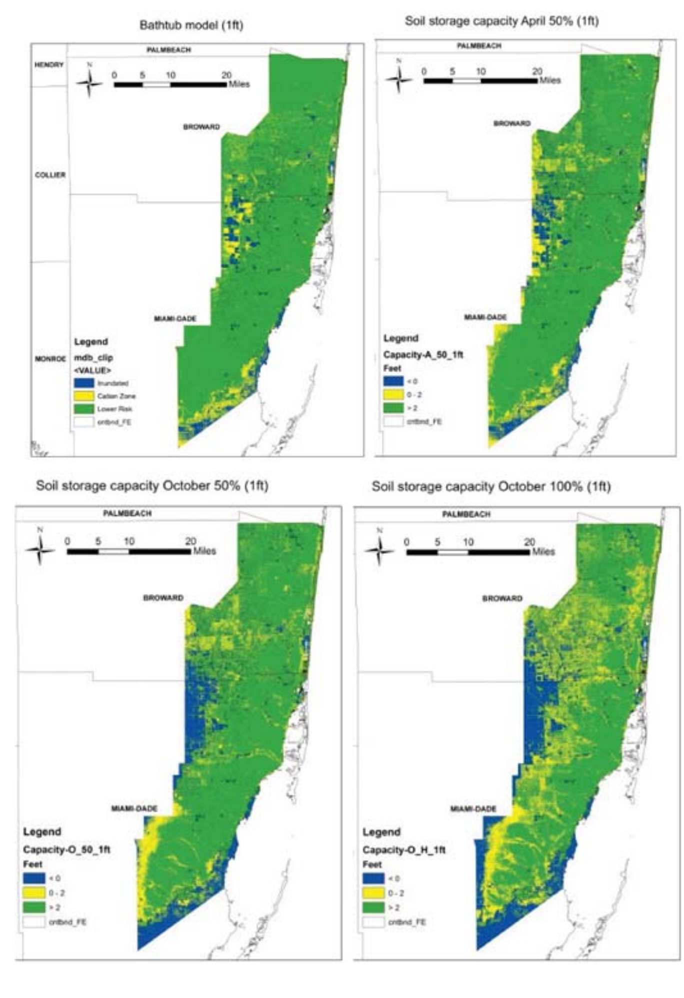

Figure 2a. This shows the bathtub results model (current condition), while 2b-d show soil storage capacity with 1-ft sea-level rise.

cause more intense rainfall events, such as more severe thunderstorms and tropical cyclones (IPCC, 2007; Karl, et al, USCCSP, & NOAA, 2009), including in Florida, which may overwhelm its current stormwater infrastructure. In addition, along the coast, the climate issue that is most likely to create significant risk is sea-level rise due to topography. Florida often is water-supply-limited as low elevation and topography limits the ability to store excess precipitation for use during the anticipated extreme dry periods. Extremes in weather phenomena and occasional flooding are not new to Florida.

The challenge for water managers in the state, especially in southeast Florida, is to control the groundwater table, because control of the water table is essential to prevent flooding of the low terrain. The highly engineered stormwater drainage system of canals and control structures has effectively enabled management of water tables and saltwater intrusion. The advent of sea-level rise will present new challenges, because the water table is currently maintained at the highest possible levels to counter saltwater intrusion, while limiting flood risk in southeast Florida's low-lying terrain and providing for water supplies (Bloetscher, 2008). However as the sea rises, flooding is more likely to occur, disrupting the balance struck between flood risk and water supply availability. But, flooding is more likely to occur as sea levels rise.

Currently, during periods of excessive rainfall or in anticipation of major rainstorms or hurricane landfall, levels in the canals and the water table are lowered to increase stormwater storage capacity in the soil. The effect of sea-level rise on groundwater and surface water flow through the canals to the ocean is estimated as follows: Assuming that the current average differential head is 2 ft at the coastal flood control structures, sea-level rise of 0.5 ft would reduce the hydraulic head differential by about 25 percent; 1 ft of sea-level rise would reduce the head differential by about 50 percent. According to Darcy's Law, flow through an aquifer is proportional to the pressure or head differential. Groundwater flow would be reduced and surface water discharge through the canals and structures would have to make up the difference. Sea-level rise of 1 ft would result in about a 5 percent increase in the canal discharge rates from 53.9 to 56.5 bil gal per year per 100 sq mi (Heimlich, 2009). As sea level approaches the level of the water table, groundwater seepage would approach zero and could even reverse when the sea level rises above the water table (Todd & Mays, 2008). This will increase the burden on the canals and coastal control structures. At the same time, the capacity of the coastal control structures will be reduced by sea-level rise.

Current hydrologic modeling of the effect of sea-level rise to date has assumed that the water table would be held constant at current levels to protect current development by active management of the flood control system. This strategy may encourage significant migration of saltwater inland. Furthermore, most flood risk

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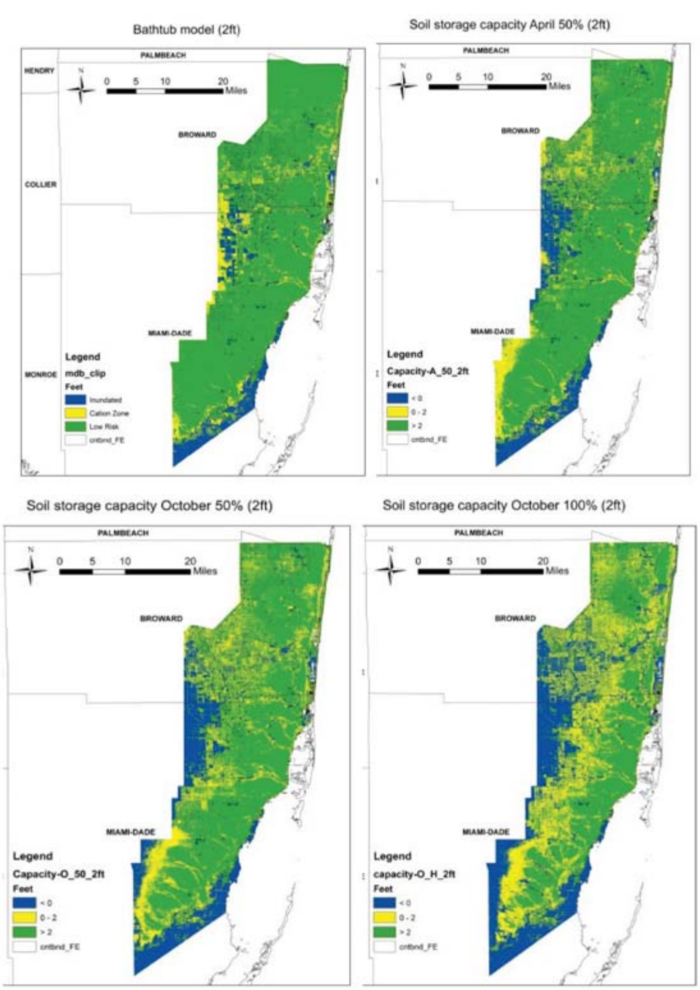

Figure3a. This shows the bathtub results model (current condition), while 3b-d show soil storage capacity with 2-ft sea-level rise.

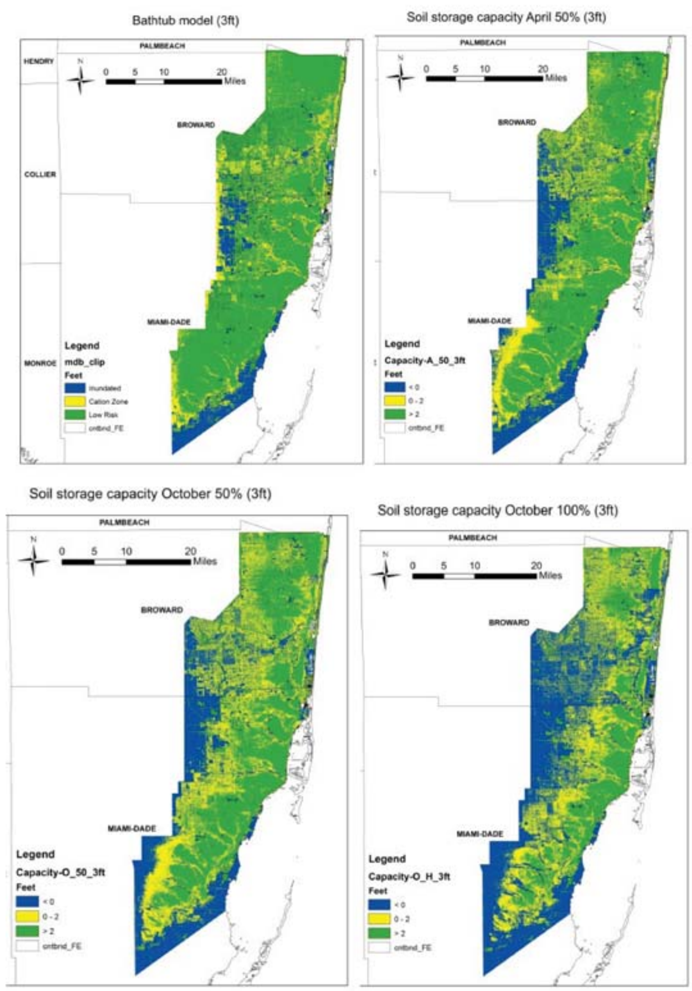

Figure 4. This shows the 3-ft sea-level rise vulnerability using soil storage capacity.

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models assume that the aquifer is flat (bathtub model), and/or exists at mean sea level (as opposed to mean high tide), neither of which is true. To address these shortcomings, the bathtub model must be adjusted for the groundwater surface to determine the potential vulnerability of infrastructure and land areas due to sea-level rise. The protocol was applied to Miami-Dade and Broward counties because of their high level of preconceived vulnerability due to having a low-elevation ground surface. Analysis on Miami Beach indicated mean high tide was the appropriate planning water level.

Methodology

A map of vulnerable areas using the bathtub approach is shown in Figure 1a. The results reflecting the groundwater surface elevation methodology is shown in Figures 1b-d. When comparing the results of the bathtub model to the groundwater-enhanced model, no significant difference is noticed for the model in the month of April. The results make sense in that, when the water table is low, the effects of the groundwater surface do not exhibit an influence on infrastructure vulnerability. When viewing the current time period maps in Figure 1, the influence of the groundwater table between the different seasonal groundwater surface elevations can be seen.

The results for the 1-ft-influenced bathtub were created by changing the symbology within ArcGIS. The results of the 1-ft-bathtub model reflect less vulnerability than either of the current condition models showed for the high-level month of October. One ft of sea-level rise using the soil storage capacity method is shown in Figure 1 a-d; Figure 2 shows the bathtub model with 2-ft rise results. The results for the adjusted bathtub model show greater vulnerability compared to the bathtub model as shown in Figure 1, notably in the southwestern region. Finally, Figure 4a reflects the 3-ft rise expected around 2100.

Modeling performed at Florida Atlantic University indicates that the groundwater table is not flat, and that western areas may flood more quickly than current projections. Rising water tables will lead to greater risk of flooding. The results for the adjusted bathtub further increase the amount of vulnerability given the 3 ft of sea-level rise, as shown in Figure 4 b-d. The comparison results of the bathtub model verses using the soil storage capacity indicate high areas of unrealized vulnerability. The results, considering the October 50th-percentile groundwater table surface elevation, produced different results, indicating vulnerability in the western region, as shown in Figure 5. In particular, the western portion of the study region has a higher predicted vulnerability to sea-level rise than the bathtub model predicts. The results further illustrate that sea-level rise vulnerability is not just a coastal feature for the study region in that the inundation is shown to move from inland areas towards the eastern coast of Florida.

The results indicate that the inclusion of the groundwater table into the calculations of vulnerable infrastructure due to sea-level rise will have a significant impact on the results. A summation of potential inundation for the different models is given in Table 1. The area calculations were created by multiplying the number of cells inundated by the area of the cells to determine the inundation areas; adjusting the model for groundwater conditions creates a different result. A table of the results in terms of percent increase between the base bathtub model prediction and each of the different groundwater applied methods are given in Table 2 (Romah and Bloetscher 2013).

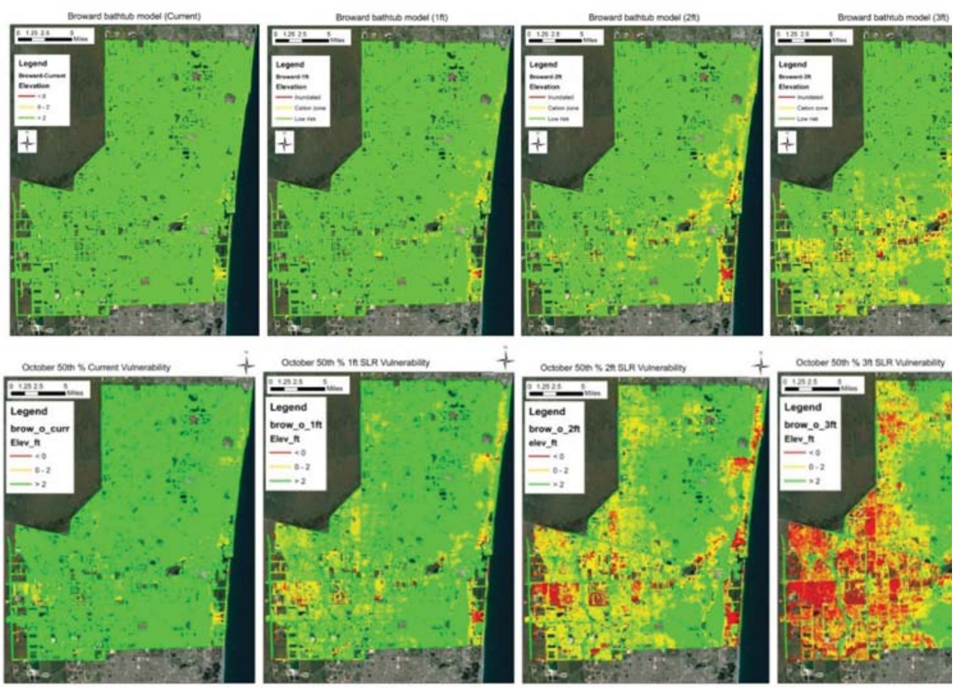

Figure 5. Broward County all-roads bathtub and groundwater-adjusted model results.

Miami Beach Application

Florida Atlantic University partnered with E Sciences Inc. to monitor existing mon-

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Table 1. Inundation results prediction

Inundation results (sq. mi.)				
Model	Current	11ft	22ft	33ft
Bathtub	37	88	133	172
April 50th percentile	70	123	180	239
Oct. 50th percentile	128	180	236	315
Oct. 100th percentile	177	244	337	483

Table 2. Bathtub model increases percent increase from bathtub model

Percent increase from bathtub model				
Model	Current	11ft	22ft	3ft
April 50th percentile	36	338	441	40
Oct. 50th percentile	78	883	992	85
Oct. 100th percentile	154	2233	1182	138

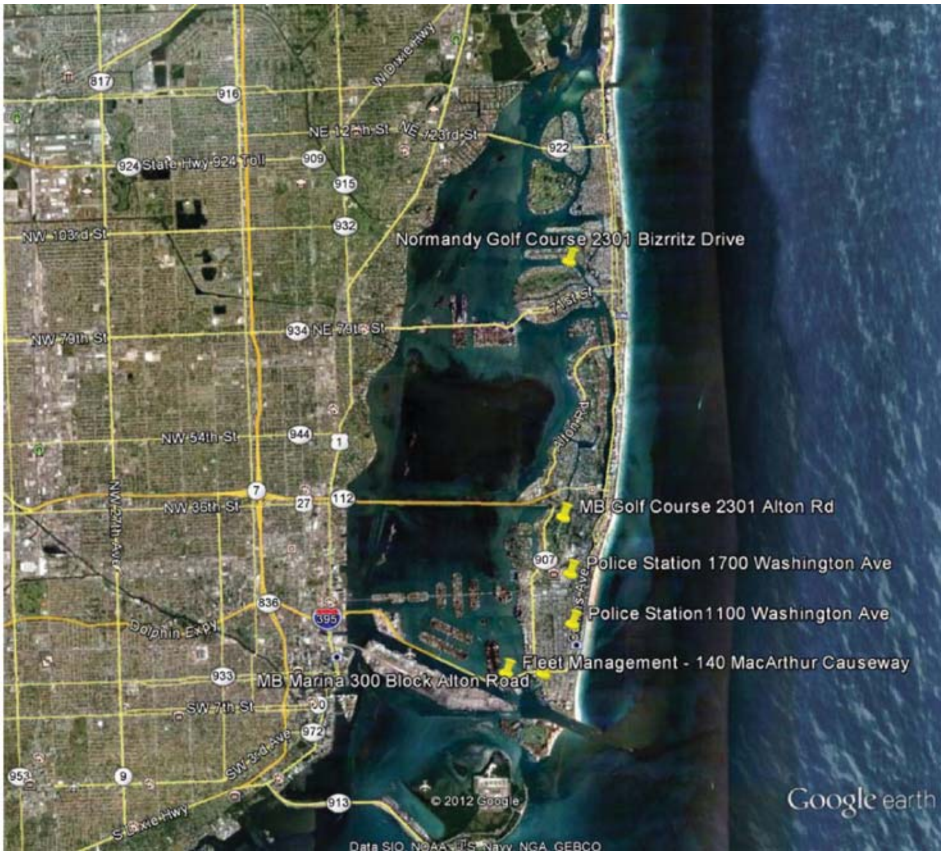

Figure 6. Locations of monitoring wells.

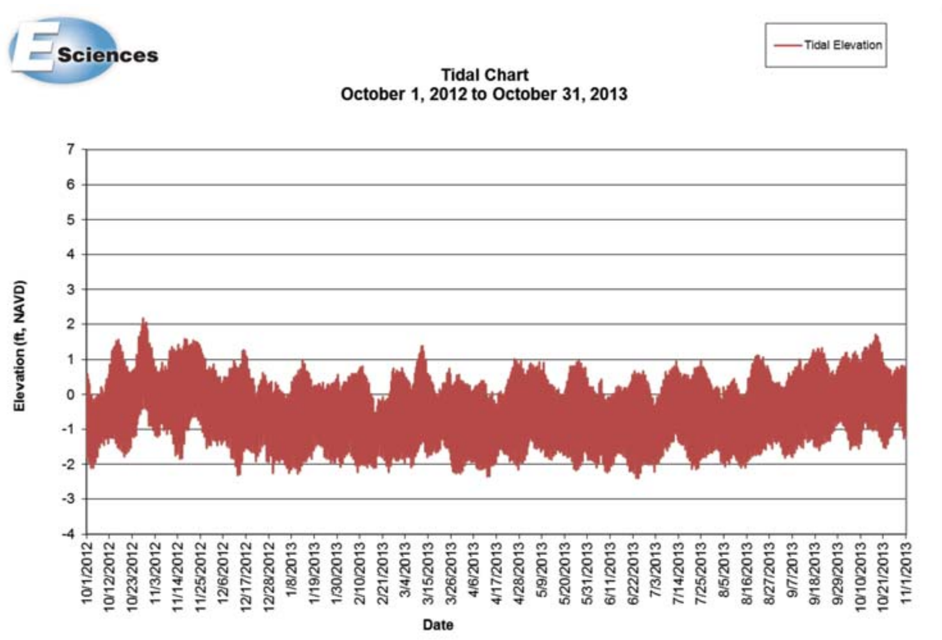

Figure 7. Tides from Oct. 1, 2012 to Oct. 31, 2013. Note the highest three-day total is 2 ft. Normal low-water table tide three-day events are above 1 ft.

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itoring well stations throughout the City of Miami Beach. Six existing well locations were selected to conduct continuous groundwater elevation monitoring, as shown in Figure 6. An attempt was made to select appropriate locations based upon the proximity of wells to the coast, to each other, and spatially, and the hydrogeologic/hydrologic characteristics of their locations. Data loggers that collect water depth were placed in each of the monitoring stations in October 2012; salinity was also measured at two of the stations. Rainfall data was provided by the City. The data was collected for a period of 12 months (October 2012 through October 2013). The results of the data have been compared with data collected and reported by the South Florida Water Management District (SFWMD), National Oceanic and Atmospheric Administration (NOAA), and other agencies. The data was downloaded monthly.

Figure 7 shows the sea level over the course of the investigation collected from NOAA. The sea level rises and falls every six hours, but also rises and falls given the proximity of the moon to the Earth. In the spring, the moon is farther away and provides a smaller pull on the tides; the reverse is true in the fall, resulting in a high, high tide. Coinciding with the end of the wet season makes the situation worse. The graph shows that the three-day average high, high tide for Miami Beach was 2 ft. What this suggests is that any portion of the island that is less than 2 ft, North American Vertical Datum 88 (NAV88), or 2ft above average sea level, will be inundated.

Figures 8-12 show the results of the six monitoring sites. The figures indicate that the groundwater levels at five of the six sites varied with the tides:

- The Miami Beach Police Station site shows that the groundwater level basically matched the high tide, but fluctuated 0.5 ft downward as tides went out (Figure 8).
- The irrigated Normandy Beach Golf Course site shows that, for the first six months, the groundwater level fluctuated between 0.5 and 1 ft with tides, but while irrigating, remained 0.5 feet above high tide. In October, the end of the rainy season, the tides and groundwater levels matched (Figure 9).
- The Miami Beach Marina site shows that the groundwater level fluctuated 0.3 ft with the tidal cycle, with the peaks at or within 0.5 ft of high tide (Figure 10).
- The Miami Beach Golf Club site was also irrigated. Groundwater levels remained at or above high tide for the majority of the

time. The tidal fluctuations were 0.1 ft, meaning the soils are far less transmissive than some other sites (Figure 11).

- From November 2012 to March 2013, the convention center site groundwater levels varied at about 0.5 times the tidal amount, the most for any site. However, the high groundwater levels fluctuated with tides, but were about 1 ft above the tidal elevations (Figure 12).

Because the groundwater varies with tides, rainfall exacerbates the tidal influent. During the wet season, the groundwater levels are higher than the dry season, while the levels come together when rainfall is absent. Hence, stormwater flooding is exacerbated in the wet season, so predicting where water flooding will occur can be determined by looking at the light detection and ranging (LiDAR) topography and groundwater levels on Miami Beach. Salinity at Miami Beach showed somewhat of an inverse relationship with groundwater, but the results are less clear than might be expected (Figure 13).

In conjunction with water levels, a goal was to develop a means to help identify areas of potential short- and long-term flooding. To accomplish this task, a geographic information system (GIS) layer was created for topography and surface-water levels from high-quality LiDAR data. Previous approaches to modeling inundation from simulated sea-level rise have been limited by coarse-resolution elevation datasets (surveys, field spot elevations, and U.S. Geological Survey maps). However, the geospatial data user community has recognized the usefulness of LiDAR as a means to provide the highly detailed and accurate topographic data needed for sea-level-rise projections, which has increased interest in developing a national LiDAR database. Low-resolution LiDAR is available in many areas, but the coarse vertical definition (+/- 2 ft) is not useful for coastal areas where inches matter.

High-resolution elevation data are needed for investigating the influence of topographic complexity on landscape processes, including drainage canals and levees. Due to the narrow and compact organization of drainage channels, such improvements may be detectable in raster elevation datasets at less than high resolution. However, while higher-resolution elevation data represent a significant advance for modeling sea-level rise impacts, there can be a large variability in inundation estimates (Romah, 2012).

The LiDAR data format used was the American Standard Code for Information In-

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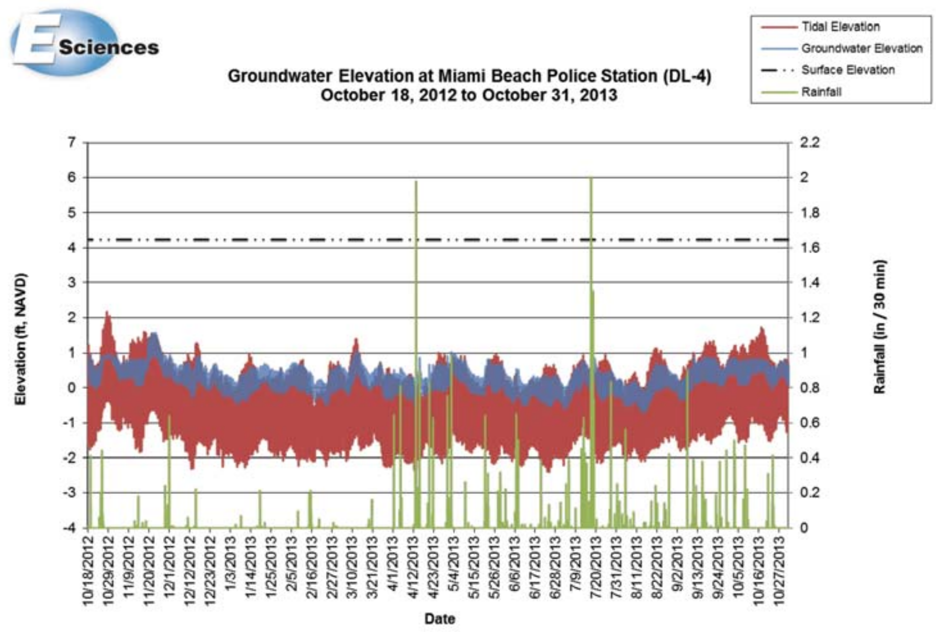

Figure 8. The Miami Beach Police Station site shows that the groundwater level basically matched the high tide, but fluctuated 0.5 ft downward as tides went out.

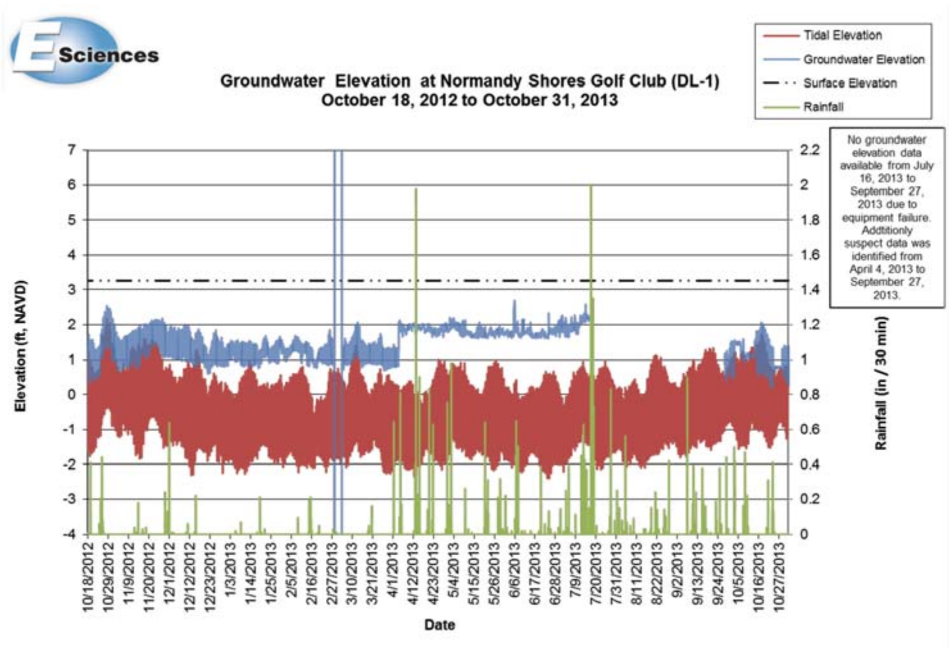

Figure 9. The Normandy Shores Golf Course site is artificially irrigated. This site shows that for the first six months of monitoring, the groundwater level fluctuated between 0.5 and 1 ft with tides, but while irrigating, remained 0.5 ft above high tide. In October, the end of the rainy season, the tides and groundwater levels correspond.

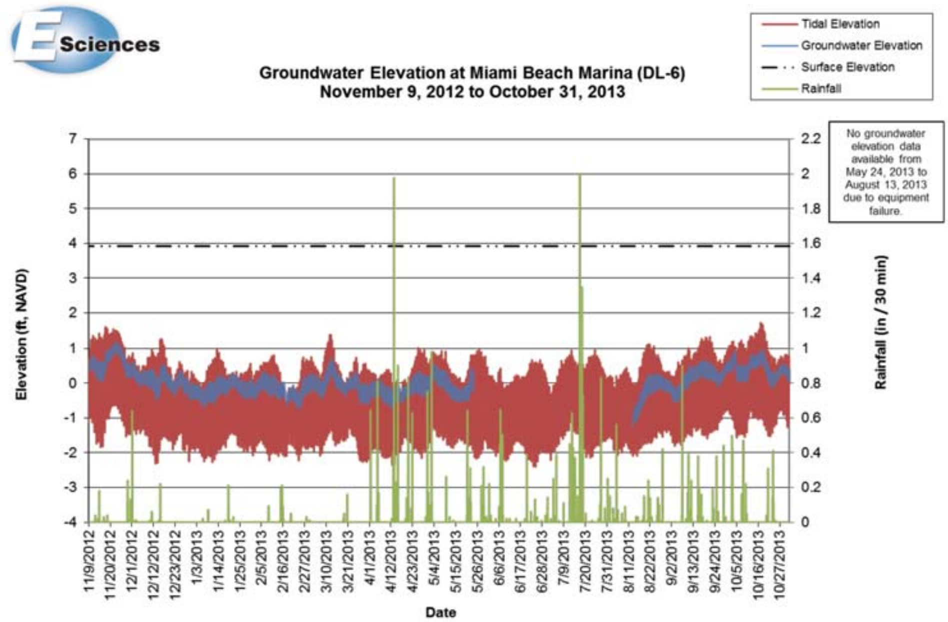

Figure 10. The Miami Beach Marina site shows that the groundwater level fluctuated 0.3 ft with the tidal cycle, with the peaks at or within 0.5 ft of high tide.

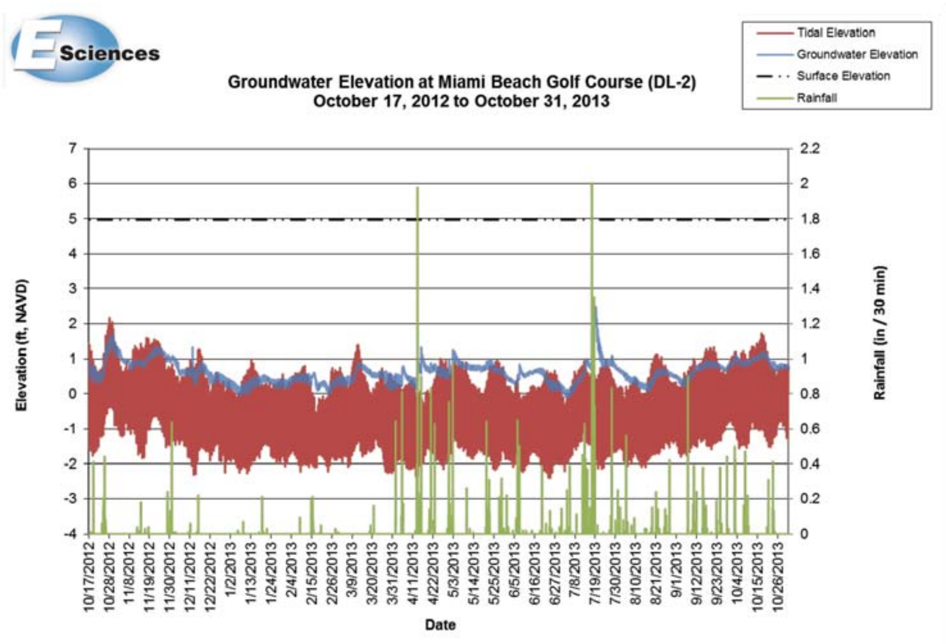

Figure 11. The Miami Beach Golf Club site was also irrigated. Groundwater levels remained at or above high tide for the majority of the time. The tidal fluctuations were 0.1 ft, meaning the soils are far less transmissive than some other sites.

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terchange (ASCII). This data format is easily handled by ArcGIS software. The ASCII format is comprised of the raw LAS LiDAR datatype format, translated into a geographically referenced X, Y, and Z global coordinate plane system. Of the different topographical data repository sources, NOAA offered the data natively in ASCII format, and it has LIDAR that allow use of 3 x 3-ft LiDAR pixels with 7 in. of vertical accuracy for the City.

Using the NOAA data, a digital elevation model (DEM) sensitivity analysis was conducted to determine the optimal-size resolution for use on the project. Though the native 3-ft resolution would bring the best results, the high resolution created issues in data management in calculating model results and rendering the data results. The DEM data points were resampled from the native 3-ft resolution into different cell-size resolution using different resampling techniques in the ArcGIS resample toolset. The three methods of resampling considered were using nearest-neighbor, bilinear, and cubic methods. The nearest-neighbor method works by determining an average value using a rectangular neighborhood grid (Romah and Bloetscher 2013). Mapping the City with LiDAR and topographic maps verified that the mapping could identify flooding areas (see Figure 14).

Meeting the Stormwater Challenge

The challenge in low-lying areas with increasing rainfall intensity and sea-level rise will be too much water, not too little. The balance between water supply and flood protection will be adjusted by a natural force that pays little mind to human demands. The production and delivery of drinking water, protection from flood waters, and the treatment of wastewater are recognized as vital functions of society. As a result, it falls on governments, leaders, and water industry managers to develop long-term strategies to sustain long-term economic viability and public health, despite competing interests. Securing reliable water supplies for future generations and protecting land from flooding areas are important factors in the face of changes in climatic patterns.

However, water supplies can become more reliable and sustainable through a comprehensive approach to water planning, which includes using alternative water sources and planning future infrastructure needs with long-term trends in mind. In keeping with these categories of protection and adaptation, as defined by Deyle et al (2007), the question is whether infrastructure can serve multiple

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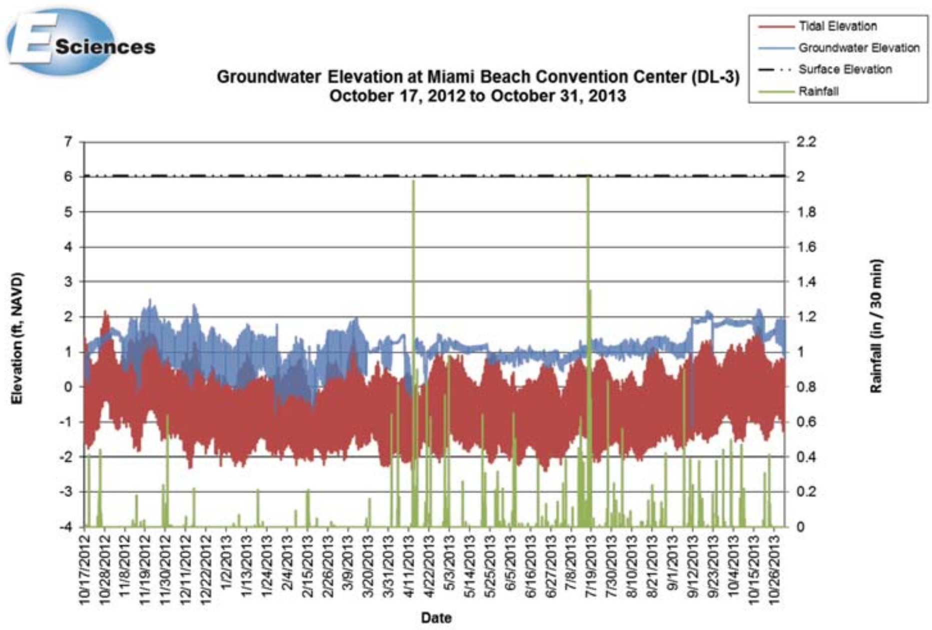

Figure 12. From November 2012 to March 2013, the convention center site groundwater levels varied at about 0.5 times the tidal amount, the most for any site. However, the high groundwater levels fluctuated with tides, but were about 1 ft above the tidal elevations.

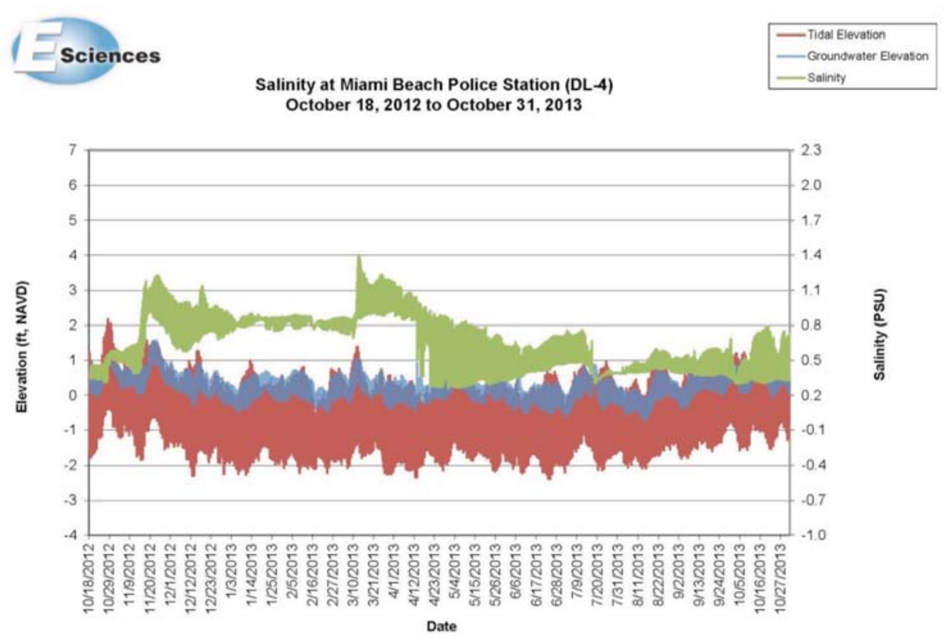

Figure 13. Salinity at Miami Beach showed somewhat of an inverse relationship with groundwater, but the results are less clear than might be expected.

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purposes; from a stormwater/water supply perspective, the answer can be yes. Because of the potential for saltwater intrusion and the uncertainty of sea-level rise, coastal water supply wells will likely be threatened further. Because the alternatives for new water supplies are limited (mostly saltwater sources), a small utility can be confronted by significant costs to build new water treatment facilities. However, many of those same communities will be dealing with increased flooding frequency because groundwater levels have consumed the soil storage capacity. Most of these communities are familiar with exfiltration trenches for drainage purposes, but as groundwater levels rise, these will cease to exfiltrate; they will infiltrate.

The use of horizontal well technology to reduce groundwater levels along streets and in neighborhoods would appear to be a solution to stormwater that could be a potential water supply option. Horizontal wells are used in conjunction with riverbank filtration and on island communities where water is limited. Horizontal wells have not been used in Florida because vertical wells have always been so productive. Horizontal wells could spread the cone of depression and minimize drawdowns to permit additional skimming of fresh water just below the surface where it can also increase soil capacity. Since these systems will run continuously, they make perfect water supplies.

Vertical well modeling and mathematics are related to the thickness, head, and transmissivity of the aquifer. The thickness is not relevant to a horizontal well and the head is constant over the entire well screen. Horizontal wells must be screened, but can be much shallower than vertical wells as a result. Larger contact with the aquifer is also provided with a horizontal well. Figure 15 shows how vertical wells capture water. The horizontal well withdraws uniformly from the groundwater surface, and as a result, the pumpage/capture can be matched to the seepage rate. No preferential flow paths result.

The production form, a horizontal well, is related to screen length, grain size of the sand, transmissivity of the sand, head, open space in the screen, and other factors. A test program would need to be pursued to determine the wells specific capacity. Once these values are known, the length of a horizontal well is easily calculated and long-term development of additional horizontal wells is easily accomplished.

Theory Behind Horizontal Wells

Much of south Florida is familiar with exfiltration trenches for stormwater, but hori-

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Equation 1. Equations to solve for yield.

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

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

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

where

$$\alpha = r\cos(\theta - \theta_i) - r$$
$$\beta = r\sin(\theta - \theta_i)$$
$$\delta = r\cos(\theta - \theta_i)$$
$$l'' = r_c + l_i$$
$$v' = \frac{Kb}{Sy}$$
$$L(u +/- w) = \int_0^u K_o\left(\sqrt{w^2 + y^2}\right)dy$$

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

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

where

$$\alpha = r\cos(\theta - \theta_i) - r$$
$$\beta = r\sin(\theta - \theta_i)$$
$$\delta = r\cos(\theta - \theta_i)$$
$$v' = \frac{K}{S}$$
$$L(u +/- w) = \int_0^u \frac{\beta^2 e^{-\beta^2}}{w^w + \beta^2} d\beta$$
$$F(u +/- w) = \int_0^u W\left(x^2 + \beta^2, y\sqrt{x^2 + \beta^2}\right) d\beta$$

Numerically, the solution to a horizontal well has proved more difficult. Zhan and Zlotnik (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, a situation that is not the norm. Zhan and Zlotnik (2002) solved Darcy:

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

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 dimensions*

γ = *Angle of inclination*

p = *LaPlace transform*

ϕ = *inclination or tilt*

r_{mD} = *well diameter*

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zontal wells employ the reverse concept. As opposed to exfiltrating water, horizontal wells have screened sections that can be positioned parallel to the static water table to permit the groundwater to infiltrate into the pipe. There are several advantages to horizontal wells: more even flow to the well screen; more uniform proximity to the formation; and longer well screens, which permit horizontal wells to have a larger contact zone to the aquifer (Zhan, 2002).

Analytical solutions for the drawdown from a vertical well (in two dimensions) are readily understood equations, dependent on Darcy's Law. Likewise, numerical solutions for groundwater flow were developed nearly 40 years ago, with a modular flow model (MODFLOW) being the most common base model. 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 (Equation 1).

Conclusions

The hydrologic cycle is well understood in most areas, but it is currently changing. At the same time, rainfall intensity is changing, despite the fact that precipitation patterns vary naturally from year to year, and over decades. There is strong evidence that global climate change is having an impact upon the world's water resources, which may exacerbate current trends. As a result, flooding from intense rains will increase with time, especially in urban areas with altered surface conditions.

Stormwater utility managers are seeking a solution to manage increased flooding frequency observed by residents. Water supply utility managers are looking for reliable water supply solutions. The traditional barrier between utilities may prevent the potential for a unique solution to address both issues concurrently: infiltration galleries as stormwater control tools. Infiltration galleries will reduce groundwater levels, which increases a soil's capacity to absorb increased rainfall, and flooding will decrease. The systems will run continuously, creating a water supply solution. Much work on the exact mathematics of recovery and treatment needs should be undertaken. A proposed protocol was included here and this solution has the potential to help many low-lying areas and island communities extend the life of their communities from flood damage by reducing flood risks. At the same time, they may capture water to treat for water supply.

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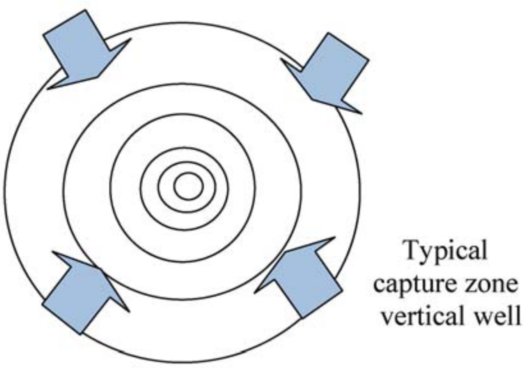

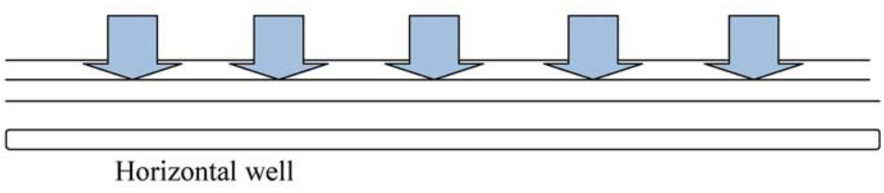

Figure 15. Horizontal versus vertical well flow path.