A Reservoir in Your Future: A Real-World Evaluation of a Reservoir for Supplemental Irrigation Water for the City of Cape Coral

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The City of Cape Coral (city) has a highly successful integrated water supply program that effectively utilizes fresh and brackish groundwater, treated wastewater, and large-scale stormwater harvesting to meet its water demands. The city recycles 100 percent of its treated wastewater, supplemented by stormwater withdrawals from canals to meet irrigation demands. While over 1 bil gal of storage have been added to the canal system since the implementation of the city's integrated water management program in the late 1980s, continued expansion of the utility service area has significantly increased demand on the canal system over time.

The canal system has been proven to be a reliable source of irrigation water for many years and continues to meet demands for most months of the year; however, the dry season of 2016 and 2017 proved to have a serious impact on canal system levels, which threatened the use of the system for irrigation needs and fire flow protection.

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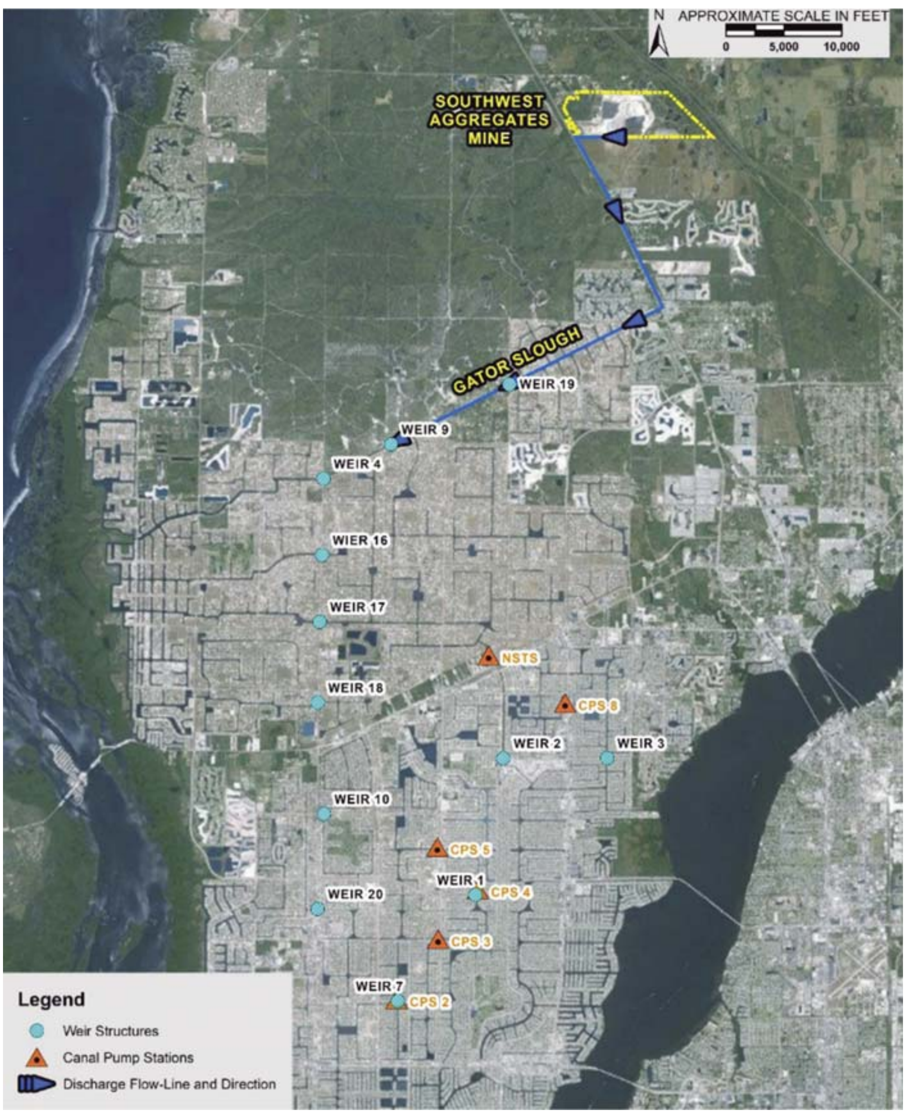

Figure 1. Regional location map.

The city is embarking on a comprehensive update to its water utility plan that will identify and prepare a capital improvement plan for additional water sources. One potential source is creating an off-line water supply reservoir at the Southwest Aggregates Mine (mine) in southern Charlotte County just east of U.S. 41. The source of water would be wet season flows that are currently stored in the Cecil Webb Wildlife Management Area (WMA). Blockages to historic flow-ways west of WMA have caused the backup of water to the extent that the southwest portion of WMA has elevated water levels and extended hydroperiods that are damaging both to wetland and upland habitats. Reconnecting a flow-way from WMA to the mine property would have substantial habitat benefits for the flooded lands on the southwest portion of WMA and potentially provide a viable source of irrigation water to the city.

Water Science Associates Inc. was contracted by the city to evaluate the feasibility of using inactive mining pits at the mine, which is a 90 percent mined-out facility, as a surface water source to supply water to the city canals. The pilot test was conducted between April 27 and July 7, 2017, during which approximately 17 mil gal per day (mgd) were pumped from the reservoir into the stormwater ditches along U.S. 41. The discharged water was routed south for approximately 3 mi to reach Gator Slough, a source canal to the city's canal system. Water-level responses to pumpage, flow rates in the ditches, and daily rainfall were monitored during the pilot test. Figure 1 shows the location of the mine site, water conveyance routing, and the canal system receiving area.

Test Plan Development

A work plan was developed to distribute among the stakeholders prior to the commencement of the pilot test. Stakeholders for this project included, among others, the city, the mine owners, the Southwest Florida Water Management District (SWFWMD), the South Florida Water Management District (SFWMD), Lee County, Charlotte County, the Florida Department of Transportation (FDOT), the Charlotte Harbor Flatwoods Initiative, and the consulting team implementing the pilot project. The work plan provided test guidelines, methods, and protocols, including pump locations and capacities; monitoring locations, depths, and sampling frequency; water routing and erosion control; and other elements of the water production and monitoring program. Project team members and roles were identified, and detailed maps and tables were prepared showing the locations, dimensions, and operational parameters for each monitoring well; pumps; and the ditch flow measurement station.

Water Delivery

Two hydraulic pumps capable of producing a combined flow of 12,000 gal per minute (gpm), or 17.3 mgd, were installed in the main reservoir lake (Figure 2). The pumps discharged into an existing ditch along the southern boundary of the mine property that connected directly to the U.S. 41 ditches (Figure 3). Rock rip-rap was placed at the pump discharge outfall and on the west bank of the ditch at the point of discharge for minimization of erosion associated with the pumped water. A temporary culvert block (air bladder) was installed immediately north of the point of discharge in the ditch to prevent northward flow of water.

Monitoring

The monitoring program consisted of measurement of water levels, precipitation, and flow rates at several locations on the mine property and in the ditches south of the mine. A total of 13 pressure transducer/dataloggers were deployed to measure and record groundwater levels in wells and surface water levels in the mine pit and in downstream ditches. Seven new monitoring wells and two existing monitoring wells were equipped with water-level recorders at the mine site. Three water-stage recording stations were installed at ditch crossing culverts along U.S. 41 and one additional monitoring station was installed in the mine pit adjacent to the point of withdrawal. All of the water-level recorders were time-synchronized and programmed to simultaneously collect water-level readings hourly. Figure 4 shows the monitoring locations.

Environmental Safeguards

A number of environmental protection protocols were established as part of the pilot testing program to ensure that there were no adverse impacts on nearby domestic well users or on the FDOT stormwater management system during the test. These included close monitoring of groundwater levels between the mine lake and an adjacent neighborhood to the north, with protocols for reducing pumping rates if groundwater level fell below a set point. Also, daily weather forecasts were monitored with protocols for pump shutdown if any significant rainfall was predicted. There were strict limitations on flows in the ditches, and daily and weekly reports were provided to FDOT and SWFWMD.

Permitting

Water Management District Permits

The mine falls under the jurisdiction of SWFWMD, but the water directed from the mine to Gator Slough enters the jurisdiction of SFWMD. The SWFWMD considered this project as a permit-by-rule under provisions specific to hydrogeologic testing purposes and requested a copy of the water delivery plan, as well as assurance that any other required permits had been obtained. No permit was required from SFWMD for water flows into its district.

Florida Department of Environmental Protection Permits

The Florida Department of Environmental Protection (FDEP) granted a waiver to allow a surface water discharge after review of the water delivery plan, and requested a notice of intent to use a multisector generic permit (MSGP) for stormwater discharge associated with industrial activity. That application was filed, and a MSGP was obtained.

Florida Department of Transportation Permit

The FDOT required an application for a general-use permit and water delivery plan. The plan described actions that would be taken to assure that the discharge did not result in the flooding of U.S. 41 or adjacent properties, including daily monitoring requirements; key individuals responsible for reporting any problems observed along U.S. 41; and actions to resolve any observed problems. An engineer's estimate of potential damages to U.S. 41 culverts was provided to FDOT, and an escrow account that covered these costs was established by the city.

Data Collection and Analysis

Pumping Rates

During the period of the test pumping, the combined flow from the two pumps ranged between 6.4 and 21.2 mgd, with a mean value of 15.5 mgd. Figure 5 presents flow rates during the test period, along with recorded rainfall. The graph indicates a cautious start-up with rapidly increasing pumping levels that were able to confirm that the system was operating within designed and permitted parameters. The reduction in the pumping rate on May 24 and 25 was in direct response to the established environmental safeguards for a significant forecasted rainfall amount of more than 3 in. predicted on May 24; however, none of the rainfall events during the pilot test caused any significant

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Figure 2. Pumps at the Southwest Aggregates withdrawal lake.

Figure 3. View of the south ditch of the Southwest Aggregates site at the point of discharge.

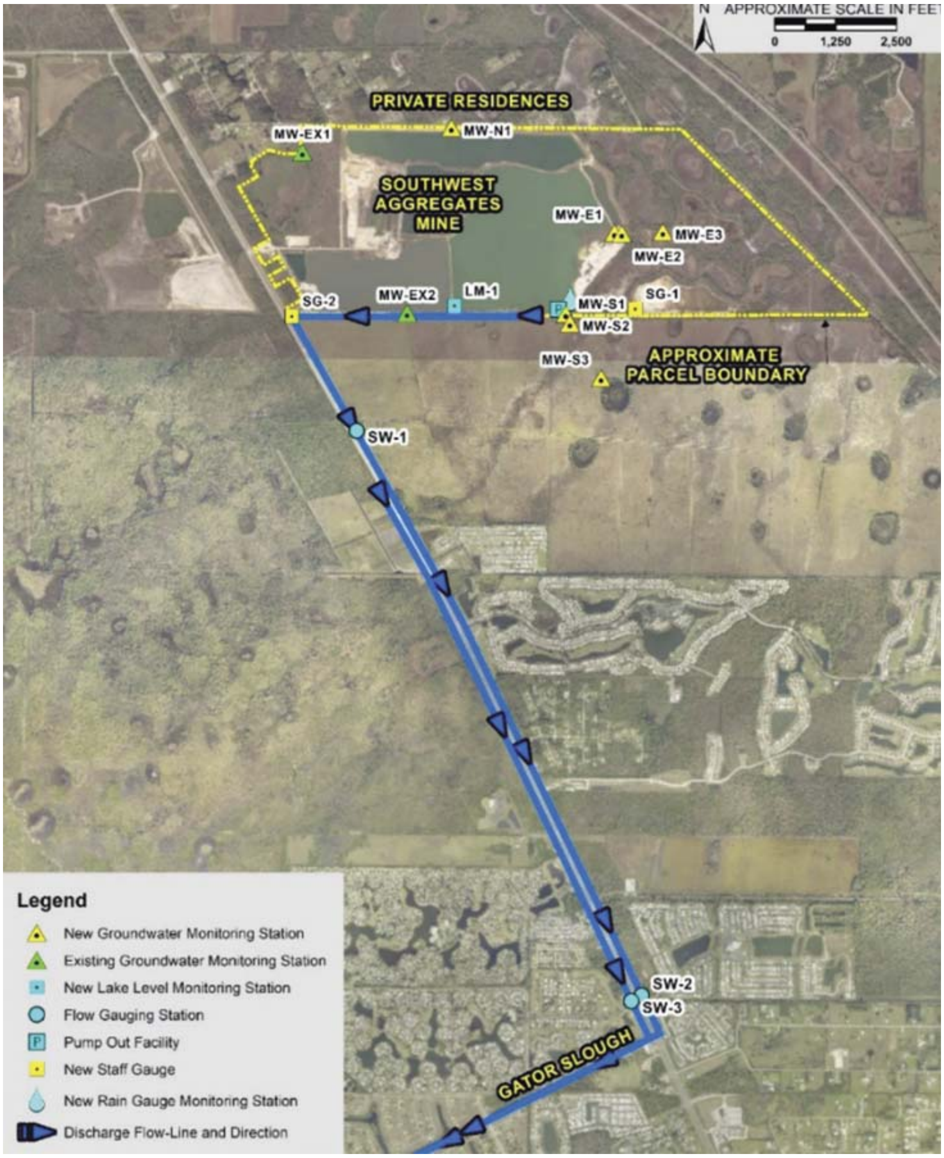

Figure 4. Map showing monitoring station locations.

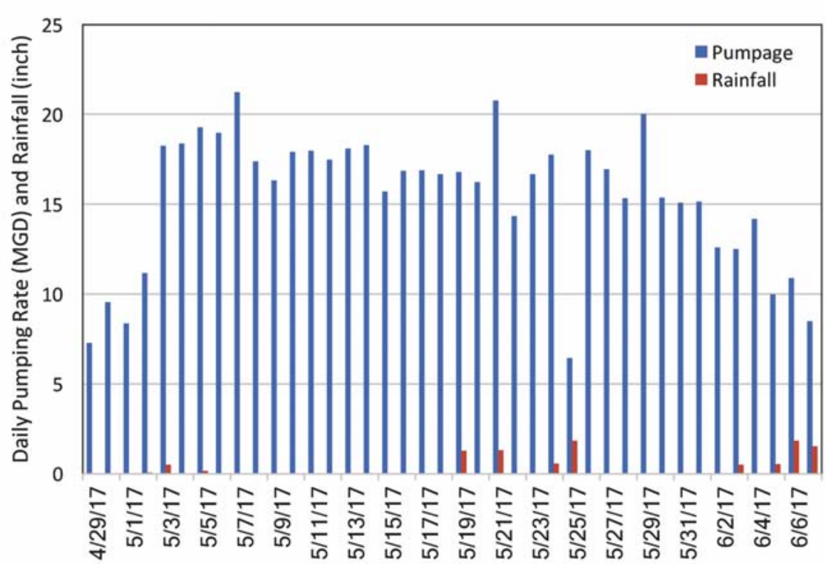

Figure 5. Reported pumping rates for the two pumps utilized for the Southwest Aggregates pumping test.

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increases in area water levels or stormwater flows, so the pumping was re-engaged at the full rate on the morning of May 25. Pumping was terminated on June 8 due to significant rains the prior week and additional heavy rainfall in the forecast.

Surface and Groundwater Response

Figures 6 and 7 show groundwater and surface water level responses before, during, and after the pilot test. Figure 6 shows lake-level and groundwater-level responses along a southern transect from the mine; Figure 7 shows lake-level and groundwater-level responses along an eastern transect from the mine. Both figures show notable declines in water level in the mine in response to the pilot-test pumping and decreasing groundwater-level impacts with increasing distance from the mine. The data also show more pronounced influence from rainfall events in the wells most distant from the mine lake.

While most of the data sets show reasonably anticipated responses from the pilot testing procedures, there were a few anomalies created by working in an active mining site. For example, Figure 7 shows measured water levels for monitoring well MW-N1, which is at the north side of the mine property. There was a sharp decline in water levels of 1.2 ft at MW-N1 on May 19, which was due to mining staff opening a small gap between the north lake and the withdrawal lake. The water level in the withdrawal lake rose approximately 0.5 ft as a result of the inflow from the north lake.

The majority of wells installed in the east and south transects from the mine perimeter provided highly valuable data for determination of potential impacts due to pumping from the mine and for determination of aquifer hydraulic coefficients for the groundwater system surrounding the mine. During the course of the pilot test, water levels declined in the lake by approximately 6 ft, declined in the groundwater system by 2 to 3 ft in close proximity to the lake, and showed essentially no declines beyond a distance of about 1,500 ft from the mine.

Water levels were monitored after pumping ceased to evaluate recovery. Water levels in the wells furthest away from the withdrawal lake (MW-S3 and MW-E3) increased to levels higher than existed prior to the pumping test due to significant rainfall in late May and early June. Water levels at MW-S2 and MW-E2 (200 to 300 ft away from the mine) returned to prepumping levels within a few days after cessation of pumping, again primarily due to rainfall. Water levels in the wells closest to the mine and the mine itself remained below prepumping levels due to the low water level in the withdrawal lake through the month of June.

Groundwater Hydraulics

Data collected during the pilot test provide a unique opportunity to define selected groundwater hydraulics, which may be used during more detailed reservoir design analysis. During the pilot test, approximately 15.5 mgd was pumped out of the withdrawal lake on a daily basis for 41 days. The water withdrawn from the mine includes typical water budget inflow components of groundwater baseflow, rainfall, and surface water inflow. Water losses to the lake include evaporation, surface water runoff, and the water pumping from the mine lake. For the testing period, the primary inflow contributor is groundwater and the primary outflow is the test pumping. The key hydraulic coefficient that determines groundwater flow characteristics is hydraulic conductivity (K), which determines the ease at which water flows through the aquifer matrix. Soil borings onsite have indicated that the aquifer connected to the withdrawal lake is an unconfined aquifer that is approximately 30 ft thick, comprised primarily of fine sand and silt, with some shell and limestone lenses.

Numerous equations have been derived to estimate the K of unconfined aquifers using various forms of aquifer performance testing (APT). The most common form of APT typically involves a single pumping well and one or more monitoring wells, which cannot be used in this test. Two different mathematical approaches that are appropriate for evaluation of the hydraulics of the shallow aquifer system around the mining lake were used. These included a method developed by Guo (1997), which allows prediction of groundwater drawdown adjacent to a dewatered lake and the use of parameter estimating tools (PEST) in an analytic groundwater model that accurately simulates the lake and groundwater drawdowns resulting from the lake pumping (Doherty, 2007); each of these approaches are discussed in detail. Guo's method provides a mathematical approximation of groundwater-level changes over time and distance in a semi-infinite water table aquifer in response to a drop of water level in a lake. Guo's method reduced the nonlinear Boussinesq equation into a relatively simplified ordinary differential equation.

A review of data presented in Figures 6 and 7 indicate that the testing period between April 28 (near the beginning of the test) and May 19 was not significantly influenced by rainfall and that a steady decline in water levels due to pumpage was observed during this period. Significant fluctuation in water-level data due to rainfall events were noted subsequent to May 19, hence data collected after May 19 were considered less reliable for estimation of hydraulic coefficients and were not used for the analysis.

The water levels observed in Wells MW-E1, MW-E2, MW-S1, MW-S2, and the lake as observed on May 19 were selected for analysis. These

Continued on page 28

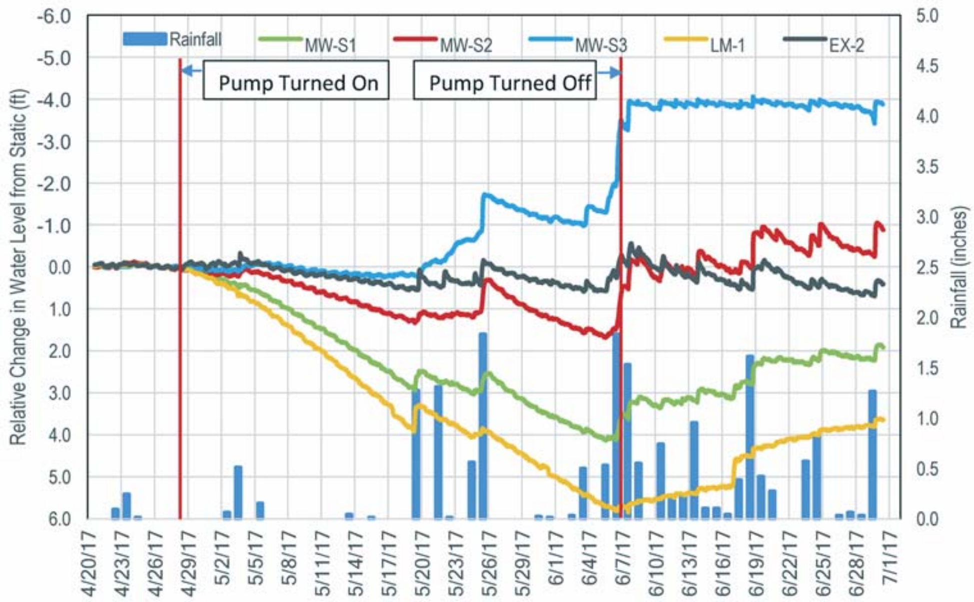

Figure 6. Relative water-level data for the withdrawal lake and wells south of the withdrawal lake.

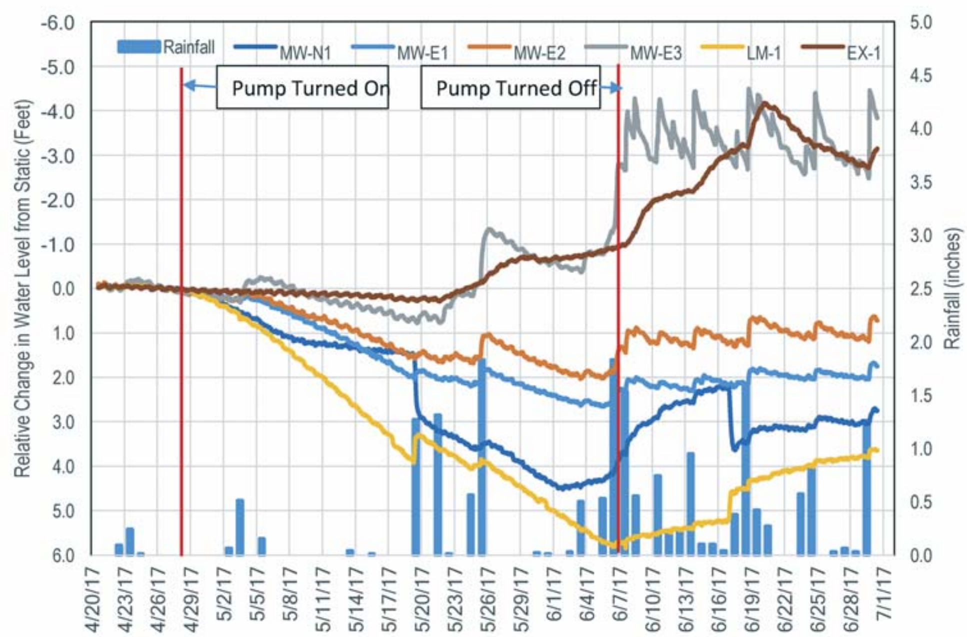

Figure 7. Relative water-level data for the withdrawal lake and wells east and north of the lake.

Table 1. Summary of Results Using Guo's Method.

Well ID	Distance from Lake (ft)	Water Level in Well (ft)	Initial Lake Level (ft)	Pumping Lake Level (ft)	Estimated Hydraulic Conductivity (ft/d)
MW-E1	380	19.57	22.11	18.21	**27**
MW-E2	512	19.88	22.11	18.21	**21**
MW-S1	110	18.64	22.11	18.21	**48**
MW-S2	309	19.24	22.11	18.21	**43**
				Average	**35**

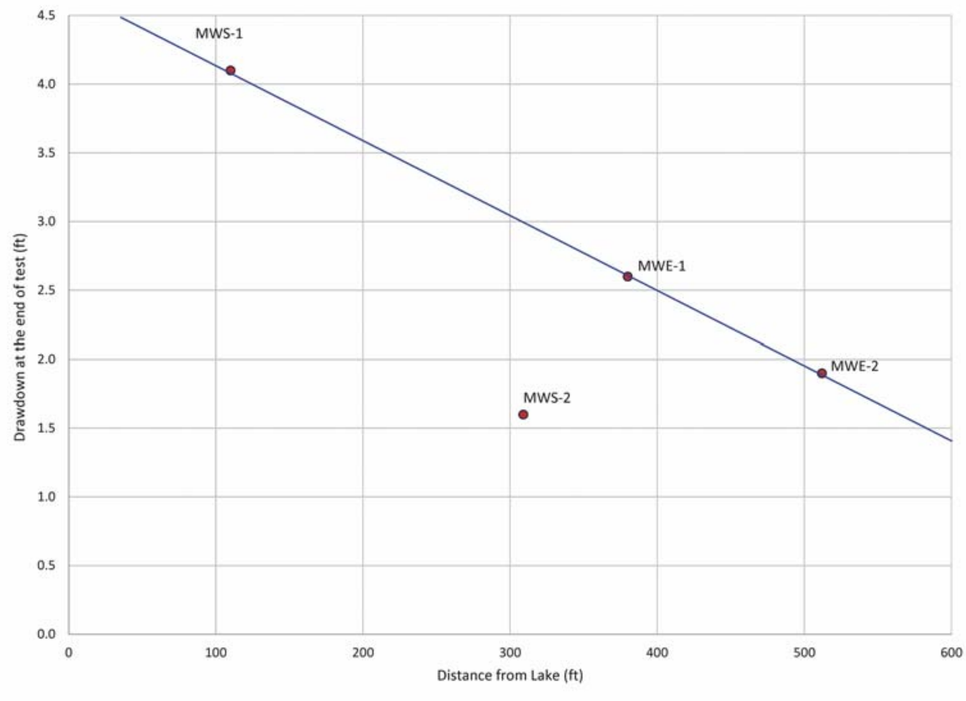

Figure 8. Drawdown versus distance from the withdrawal lake for selected wells.

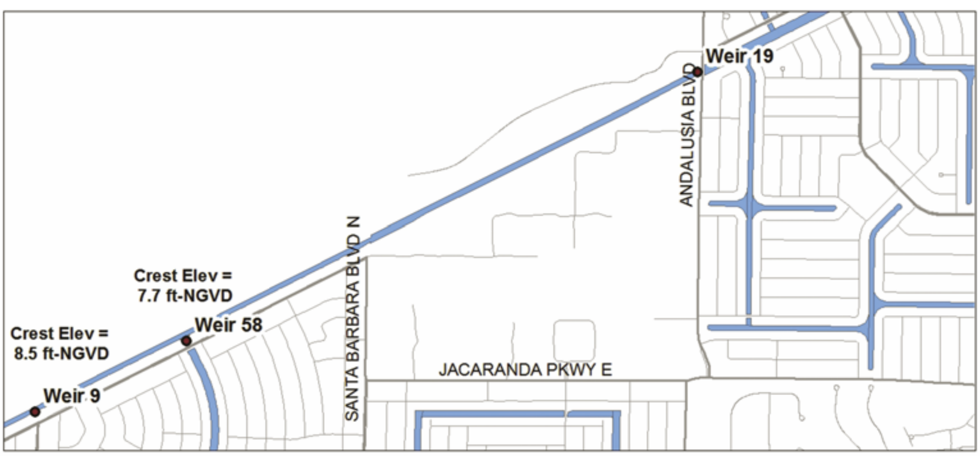

Figure 9. Map of Weir 9, 19, and 58 in Gator Slough.

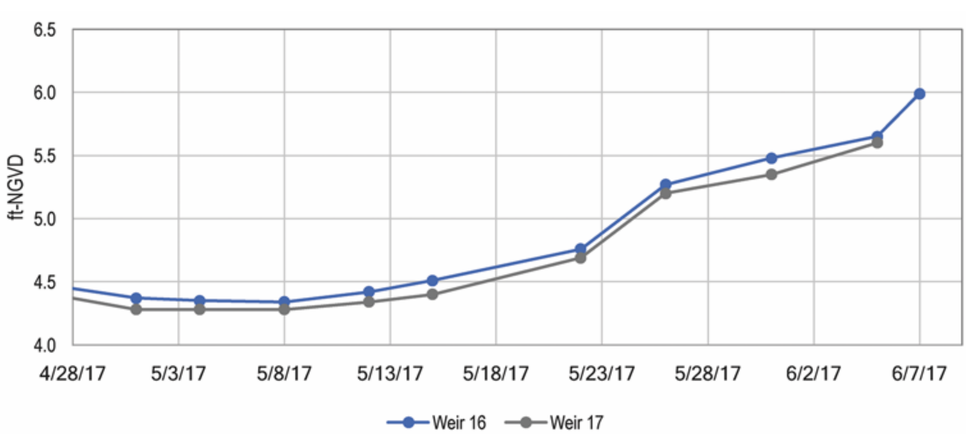

Figure 10. Measured water levels (ft – National Geodetic Vertical Datum [NGVD]) in Basin 4.

Continued from page 27

wells were selected as having significant and consistent drawdown signatures. Based on lithologic analysis of the surrounding groundwater system, a specific yield of 0.1 and a saturated thickness of 30 ft were assumed for the initial calculations. Using an iterative approach, the K that best matched the drawdown patterns in the aquifer was determined using Guo's equation.

Results indicate that the K of the aquifer ranged between 21 and 48 ft/day, with an average value of 35 ft/day. Table 1 shows a summary of the results.

A numeric groundwater flow model was developed to simulate the water-level responses to pumpage observed during the period from April 28 and May 19. The model was developed using MODFLOW (Harbaugh et.al, 2000), with Groundwater Vistas as the graphical user interface, and calibrated using PEST (Doherty, 2007). The modeling approach provided for incorporation of all the known test parameters and site features into a conceptual model (pumpage, aquifer thickness, distance to wells, rainfall, surface water bodies, etc.), with the use of PEST to select the hydraulic parameters that yield the best calibration to the observed water levels. The water levels observed in Wells MW-E1 and MW-E2 (east transect) and MW-S1 and MW-S2 (south transect) were used for calibration. These wells were selected because there are no surface water bodies between these wells and the withdrawal lake, so the water-level changes in these wells are the best reflection of aquifer characteristics of the strata that lie between the lake and the wells. It was also noted that the more distant Wells E-3 and S-3 were outside the influence of pumpage. The model simulated a 20-day period from April 29 to May 18 using daily stress periods.

The three parameters that were calibrated in the model are: K, specific yield (SY) and evapotranspiration rate (ET). During calibration, K values were allowed to fluctuate between 1 ft/day and 200 ft/day, SY was allowed to fluctuate between 0.05 and 0.2, and ET was allowed to fluctuate between 0.001 and 0.02 ft/day. The model was run numerous times with various permutations and combinations of these parameters. The hydraulic coefficients that best matched or otherwise minimized the difference in simulated drawdown and field measured drawdown were selected by the model. The hydraulic coefficients that yielded the best calibration are K of 32 ft/day, SY of 0.18, and ET of 0.0037 ft/day.

The value for K determined through model calibration closely matches the average K value developed from the Guo method. Final calibration statistics for the model calibration approach also demonstrate that the model-predicted drawdown agrees closely with the observed drawdown. The normalized root means squared

(NRMS) for the calibration is about 3.4 percent, which is an indication of very good calibration.

Based on the analytic and numeric modeling analyses presented, the K of the shallow unconfined aquifer is estimated to be about 35 ft/day, with a specific yield of 0.18. These values provide a reasonable basis for future reservoir and conveyance design analysis. Note that the methods used for analyses are mathematical approximations of complex physical conditions and have some inherent limitations based on assumed homogeneity.

Hydraulic Barrier Concept

It's common for large water storage or dewatering projects to install hydraulic buffers to minimize and contain potential impacts within a relatively small area. The hydraulic buffers are usually recharge trenches or temporary retention cells installed between areas where water is actively being raised or lowered, and potentially sensitive surrounding areas like wetlands and other natural systems. An appropriately designed and constructed hydraulic buffer therefore should minimize or eliminate impacts from the operation of a reservoir to the surrounding area.

During this study, water conveyance to U.S. 41 and some backflow into an adjacent conveyance ditch south of the withdrawal lake created an opportunity to evaluate the potential effects of a hydraulic barrier along the southern boundary of the mine lake. The water levels observed in the eastern transect of the monitoring wells were compared with the southern transect of the monitoring wells. The hydraulic barrier effect occurred along the southern border of the mine property between monitoring wells MW-S1 and MW-S2. A plot of drawdowns at the end of the primary testing period in early June to the distance of the monitoring well from the mine lake indicate a good relationship between drawdown and distance from the lake for monitoring wells MWS-1, MW-E1, and MW-E2 (Figure 8); however, monitoring well MW-S2 located south of the hydraulic barrier shows distinctly less drawdown, indicating that the hydraulic barrier created by the filled ditch is providing some mitigation of drawdown impacts from the lake pumping. The farm ditch is relatively shallow, penetrating only a few feet into the surficial aquifer at the site, but the test results suggest that a properly designed, constructed, and operated hydraulic barrier at this site could provide an effective separation of water-level fluctuations inside the reservoir from the surrounding hydrological and ecological systems.

Open Conveyance Efficiency

The flow monitoring at stations SW-1, SW-2, and SW-3 provided valuable information regarding the ability to deliver water from the mine to the city by way of the open channel flow along U.S. 41. Flow monitoring on nine separate dates indicated that the percent yield of flow measured at upstream station SW-1 ranged from 45 to over 100 percent due to a number of factors. The primary loss was likely seepage from the ditches to the underlying groundwater system. Flow monitoring on one of the dates indicated that there was no seepage; however, the pumps from the mine were turned off for a portion of the day, therefore a comparison of SW-1 to the combined flow at SW-2 and SW-3 is not valid for that monitoring event. The higher yield experienced was in late May after three weeks of pumping.

Over the entire test period, and because the pilot project was conducted during a drought period, seepage losses accounted for about 35 percent of the pumped flows, and the net yield to Gator Slough was 65 percent.

Canal Response

An analysis was conducted to assess the ef-

Continued on page 30

Continued from page 29

fect of the test on city canal levels. Water was pumped from the mining pit for a period of 41 days, and water levels increased in Basin 4 in the city canal system. Water levels in Gator Slough are controlled at Weir 19, and the main inflow structure that diverts flows from Gator Slough into the city canals is Structure 58, as shown in Figure 9.

Figure 10 presents measured water levels at Weir 16 and 17 (Basin 4) for the same period. Since the beginning of pumping on April 28 to the end of pumping on June 7, water levels increased by about 2 ft at Weir 19 and by 1 ft at Weir 58, and water levels in Basin 4 (Weirs 16 and 17) increased by about 1.5 ft due to the pumping. Additional water-level increases are likely due to rainfall within the city. Overall, the pumping project provided significant additional water to the city during a critical drought period. As discussed, the yield to the city during the first half of May was similar to the yield from the ditches into Gator Slough, suggesting that the water distributed from the mine adequately entered the city's system.

Discussion

Successful construction and operation of a reservoir requires the ability to:

1. Load the reservoir with water during periods of high water supply without adverse impacts to the source of water supply or to the area surrounding the reservoir.
2. Maintain water in the reservoir until needed in the dry season without excessive losses to the groundwater system or to evaporation.
3. Withdraw water from the reservoir during periods of low water supply without adverse impacts to the surrounding groundwater system or local ecology.

Reservoirs have not typically been used in southwest Florida due to the integral relationship and hydraulic connection between surface water and groundwater, creating substantial losses of water to groundwater seepage during storage and a strong potential for impacts to environmentally sensitive wetland areas or existing legal water users during pumping. Regional watershed conditions adjacent to the mine and the apparent low K of the surrounding shallow groundwater system suggest that an effective reservoir system could be developed at the mine site.

The pilot testing results indicate a relatively low K for the shallow groundwater system surrounding the mine. Low K is typically not desirable in developing a water supply system; however, in the case of developing a reservoir, the low yield character of the shallow aquifer system is a positive element in that it makes the hydraulic separation of the reservoir from the groundwater system much more viable. This hydraulic separation is critical to maintaining water in the reservoir for an extended period into the dry season and to eliminating the potential for adverse impacts to area wetland systems from the lowering of water levels in the reservoir during water withdrawal periods.

A number of observations during the pilot test support the case that the mine may provide for an effective reservoir system. First is the low K value determined from the groundwater drawdown data, which are supported by the limited areal extent of drawdown created by the lake withdrawals. Drawdowns in the lake exceeded 5 ft, while drawdowns in the surrounding groundwater system were essentially absent beyond a distance of 1,500 ft from the mine. Second is the fact that while water levels in the more distant groundwater system recovered relatively rapidly with the onset of the wet season rains, the mine lake water level did not recover for more than four weeks after the start of a strong rainy season, indicating a low rate of groundwater seepage. And finally, the apparent attenuating effect of the hydraulic barrier created by the filled shallow farm ditch just south of the mine property bodes well for the potential effectivity of a properly designed and constructed hydraulic barrier that is able to maintain water in storage and to minimize the potential for adverse impacts to surrounding wetland environments.

Conclusions

The pilot test of the mine as a possible reservoir to supplement irrigation-quality water to the city canal system had five principle objectives:

1. Evaluate the capacity of the existing mine lake to yield water during dry season months.
2. Evaluate the aquifer hydraulics of the groundwater system surrounding the mine.
3. Determine the potential impacts to surrounding areas from the lake water withdrawals.
4. Evaluate the potential of the U.S. 41 ditches to convey water from the mine to the city canal system.
5. Deliver irrigation-quality water to the city canal system during a severe drought period.

Pilot testing showed that the existing mined lake is capable of producing 20 mgd or more of irrigation-quality water on a sustained basis during a severe drought period. An average pumping rate of more than 15 mgd for over 40 days produced approximately 6 ft of drawdown in the mine lake, but at least twice that much water is estimated to be available from the lake, especially as the mine is expanded to completion over the next few years. Evaluation of the pumping and water-level response data indicates a relatively low K for the shallow aquifer system surrounding the mine. This low K will minimize the areal extent of impacts from operation of a reservoir at the site and facilitate creation of a hydraulic separation of the mine/reservoir from the surrounding aquifer system.

The use of the existing stormwater ditches along U.S. 41 provided a convenient and effective conveyance of water from the mine to the city canal system for the pilot test; however, water losses to groundwater seepage along the conveyance path averaged over one-third during the pilot test, indicating the need for a closed-pipe delivery system should a permanent reservoir system be implemented.

Water levels in the canal system were raised by approximately 1.5 ft over the course of the pilot testing. The increased water levels were of critical importance to the city, both for meeting ongoing irrigation demands and for maintaining fire flow protection reliability during a severe drought period. The pilot test showed the value of having a major water storage system for supplemental supply of irrigation-quality water and the potential viability for development of a reservoir at the mine site.

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