Source Water Investigation for the Coquina Coast Seawater Desalination Project

Richard Cowles, Scott Niekamp, Mike Black, and Paul Pagello

In the Coquina Coast region of northeast Florida, a group of municipalities, in partnership with the St. Johns River Water Management District, have been evaluating seawater as a means of meeting water supply demands, while continuing to serve as proper stewards of the environment. The Coquina Coast Seawater Desalination Alternative Water Supply Project is considering two main sources of seawater to supply a possible future seawater desalination plant. Conceptually, these options include a submerged and screened open ocean intake located at a yet-to-be-determined distance from the shore, and a series of land-based horizontal collector wells located along the beach that draw seawater into the aquifer through induced infiltration processes.

Richard Cowles is principal hydrogeologist, Scott Niekamp is a senior hydrogeologist, and Mike Black is a senior hydrogeologist at Pirnie-Arcadis. Paul Pagello is director of engineering at Marineland.

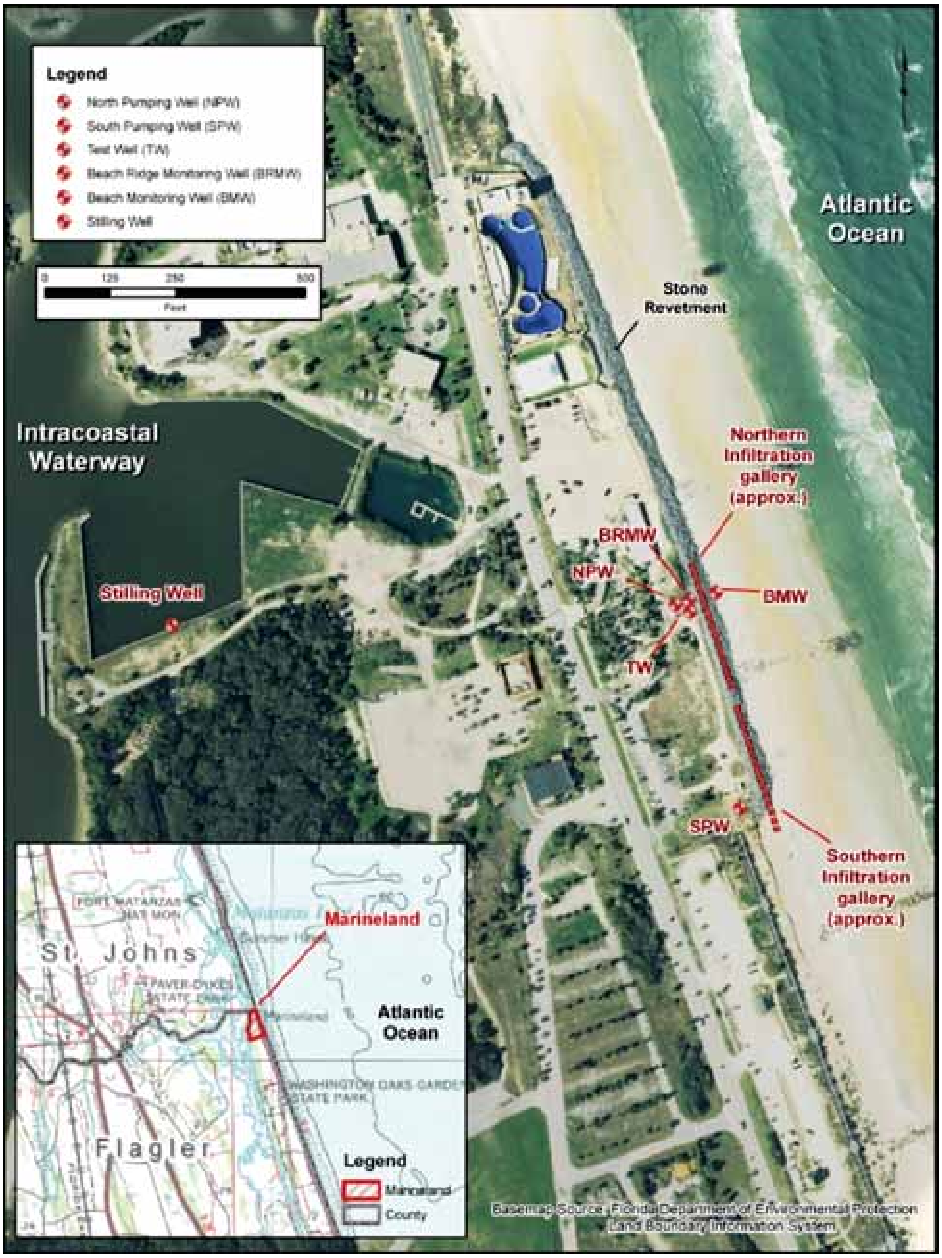

Figure 1: Site Location and Well System

To provide an initial understanding of the viability of a land-based source water supply option within the Coquina Coast region, a screening level aquifer performance test and water quality evaluation was conducted at Marineland, which is located at the northern boundary of Flagler County (Figure 1). The Marineland facility was the focus of the screening level hydrogeologic evaluation because it utilizes several supply wells. These wells are bounded by both the Atlantic Ocean and the Intracoastal Waterway and provide seawater to the facility's marine attractions. Currently, the facility relies on groundwater supplied from two horizontal infiltration galleries constructed parallel to the beach front. There also are two unused vertical production wells available as a backup to the infiltration galleries. The two vertical backup wells at the facility were used to perform aquifer performance testing and are designated the north pumping well (NPW) and the south pumping well (SPW). The facility will not be the final site for the land-based horizontal collector wells, but it is generally representative of the conditions that can be expected in the coastal aquifer systems of the Coquina Coast Region.

Regional Hydrogeology

The subsurface geologic formations can be generally divided into three units: a shallow unconfined aquifer system (post-Hawthorn sediments), a very low permeability confining unit (Hawthorn Formation and overlying clay, marl, and dolomite beds present in the post-Hawthorn sediments), and the deeper confined/leaky-confined Floridan Aquifer (Ocala Group and Avon Park Formation). The shallow and unconfined aquifer (Surficial Aquifer) is

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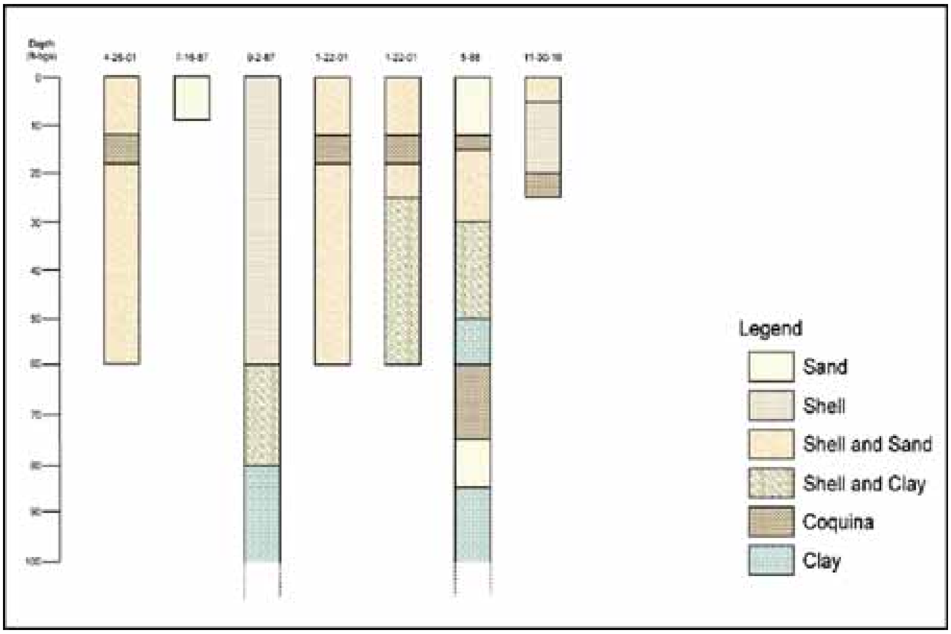


Figure 2: Geologic Sections

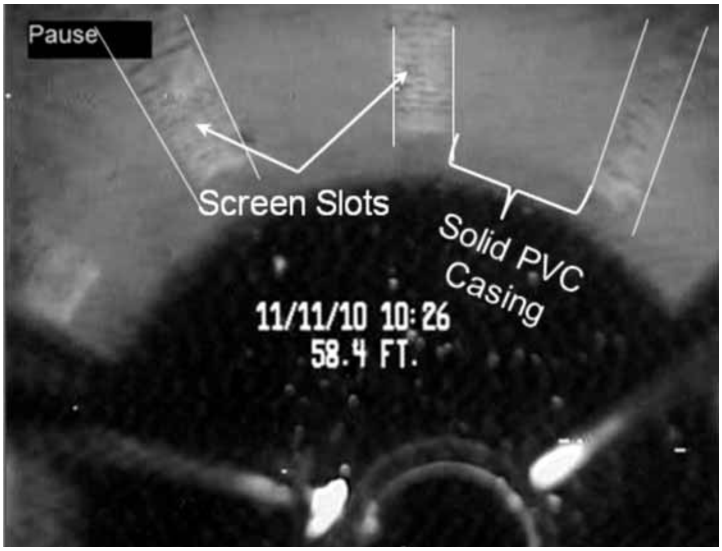
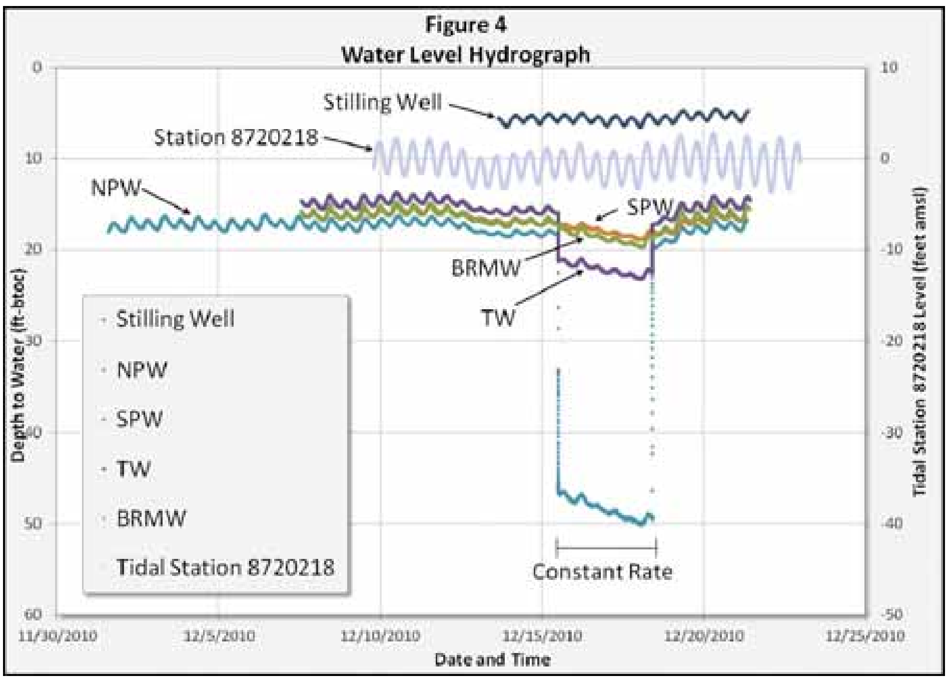


Figure 3: NPW Screen



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the focus of this study since this unit provides the greatest potential for the direct infiltration of seawater. The greatest yield potential from the Surficial Aquifer is in the high average permeability zone along the coastline where the shell beds are the most thick and coarse. Relatively impermeable beds exist within this area that may locally confine the lower portions of the aquifer; however, these units are generally sporadic and discontinuous and do not represent a regionally extensive confining unit.

Local Hydrogeology

Records for local wells were obtained for the area surrounding the Marineland facility to characterize the hydrogeology of the area. In addition to the infiltration galleries and the backup vertical wells, numerous other wells have been constructed at the facility for irrigation or to supply its marine attractions. Most of these wells have been abandoned, sealed, or are no longer in use. Because the well completion reports could not be correlated to individual wells at the facility, strip logs were constructed from the completion reports based on depths below ground surface (bgs) and do not represent the relative position of the wells to each other (Figure 2). The strip logs are identified by the date they were installed. Two of the logs were from wells constructed in the Floridan Aquifer, whereas the remaining wells were constructed in the Surficial Aquifer. The strip logs show that the Surficial Aquifer consists predominantly of shell, sand, and mixtures of the two. The exception is a hard cemented coquina layer that was identified in most of the completion reports, with a reported thickness of 3 to 6 feet and depth ranges from 12 to 25 feet bgs. This appears to place the elevation of this unit near or just below mean sea level (msl).

General Well Construction

A condition assessment of the NPW was conducted prior to aquifer testing. It was determined that the well was completed with 12.25-inch diameter polyvinyl chloride (PVC) casing and screened to a depth of approximately 63 feet. The well screen extends from approximately 28 to 58 feet below land surface and a five-foot long blank section is present at the bottom of the screen. This assessment indicated that NPW was not constructed as a long-term high capacity production well because of a deficient screen construction and resultant clogging of the screen slots (Figure 3). The screen slot openings appear to be either 10-slot (0.01 inch) or 20-slot (0.02 inch) and approximately one inch wide. Each slotted section is separated by

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Table 1: Estimated Tidal Efficiencies and Lag Times

Tidal Efficiency and Lag Time Relative to Intracoastal Waterway				
	Pre-Test		*Post-Test*	
	Efficiency	*Lag (min)*	*Efficiency*	*Lag (min)*
NPW	62.7%	72.7	89.1%	-42.7
SPW	44.6%	18.7	70.8%	-21.7
TW	73.3%	-6.3	104.6%	-53.8
BRMW	82.7%	15.3	126.7%	-41.5

Tidal Efficiency and Lag Time Relative to Station 8720218				
	Pre-Test		*Post-Test*	
	Efficiency	*Lag (min)*	*Efficiency*	*Lag (min)*
NPW	15.0%	162.0	17.9%	66.7
SPW	10.8%	108.0	14.3%	87.7
TW	17.5%	83.0	21.1%	55.5
BRMW	19.7%	104.7	25.5%	67.8

Well	Ambient Trend
NPW	0.000080 ft/min
SPW	0.000085 ft/min
TW	0.000070 ft/min
BRMW	0.000098 ft/min

Table 2
Estimated
Ambient Trends

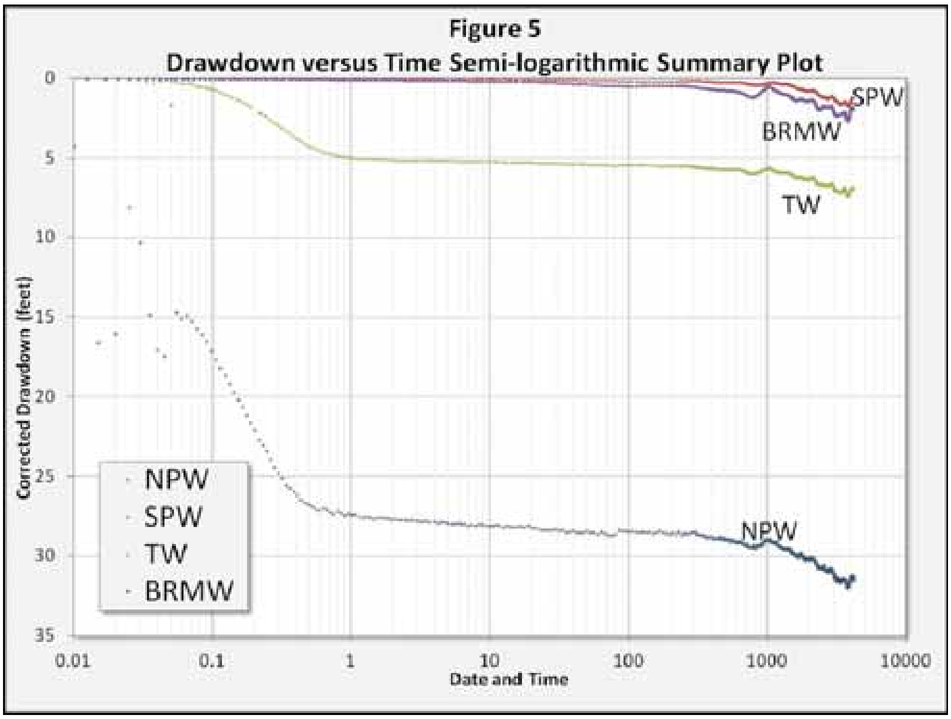

Figure 5
Drawdown versus Time Semi-logarithmic Summary Plot

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approximately 2 inches of solid PVC. The condition of the NPW limited the production rate that could be achieved and reduced the stress that could be placed on the Surficial Aquifer. Nevertheless, the NPW was deemed to be sufficient for the purposes of aquifer performance testing for this screening level evaluation.

Pumping and Observation Wells

Aquifer performance testing was conducted on the NPW at the Marineland facility to evaluate the feasibility of developing an induced source of seawater from the Surficial Aquifer. In addition to the NPW, the SPW and the test well (TW) at the facility were used as water level and water quality observation points during the aquifer testing (see Figure 1). The SPW is located approximately 400 feet south of the NPW and the TW is located approximately 30 feet to the east of NPW.

Two additional 2-inch PVC observation wells were installed in a line between well NPW and the Atlantic Ocean. A beach ridge monitoring well (BRMW) was installed on top of the beach ridge on the landward side of a protective revetment barrier and approximately 28 feet to the east of the NPW; the BRMW was installed to a depth of 25 feet within the cemented coquina layer. The second observation well, designated as beach monitoring well (BMW), was installed at the base of the protective revetment barrier at the head of the beach. Ground surface at this location is approximately 15 feet lower in elevation than the top of the beach ridge. The well was installed by hand digging through the beach sands to a refusal depth of 4.5 feet. In addition, a temporary stilling well was installed in the Intercoastal Waterway just west of NPW to monitor tidal changes throughout the testing period.

Aquifer Performance Test

Water Level Monitoring

Water levels were measured in wells NPW, SPW, TW, BRMW, BMW, and the stilling well, both electronically and manually. Electronic measurements were collected automatically at frequent intervals utilizing pressure transducers. The electronic measurements were supplemented with manual measurements and collected with an electric water level tape. Pre- and post-test water levels were monitored in the wells to assess whether external influences not related to the test pumping of well NPW existed, including tidal changes, barometric pressure changes, and pumping changes in the southern infiltration gallery. Tidal effects were monitored at a stilling well installed in the Intracoastal Waterway and tidal data were obtained from the nearest tide station at Mayport (Station 8720218), which is approximately 47 miles from the test site. A hydrograph of the water levels from the wells, along with the stilling well and the tidal data from Station 8720218, is provided in Figure 4.

Tidal Variations

A direct correlation was apparent between groundwater levels, the water level in the stilling well, and the level of the Atlantic Ocean at Station 8720218, which demonstrates that water levels in the Surficial Aquifer are influenced by ocean tides. From Figure 4, it is apparent that the magnitude of the fluctuation in both the groundwater levels and the water level in the Intracoastal Waterway is less than the fluctuation in the Atlantic Ocean levels. The fluctuation of the Intracoastal Waterway is dampened because there is a fair distance between the Marineland facility and the nearest Intracoastal outlet (approximately 2.5 miles) and water cannot travel through the waterway instantaneously. Tidal efficiencies relative to both the stilling well level and the Station 8720218 level are summarized in Table 1.

The average magnitude of the fluctuation in the Station 8720218 level was approximately 3.75 feet during the December 12-18 period and slightly more than 5 feet during the December 18-22 post-test monitoring period; both periods were in 2010. In general, the deeper wells (NPW, SPW, and TW) had lesser tidal efficiencies and greater lag times than the shallower well BRMW. Tidal fluctuations were corrected to tide data collected at the stilling well.

Water Level Correction

Following correction of water level data for tidal influences, it was apparent that groundwater levels were experiencing a general increasing trend during the test. This trend was assumed to be approximately linear and was corrected by applying a linear ambient trend line to the pre- and post-test groundwater level data. The estimated rate of groundwater level increase for each well is summarized in Table 2.

Figure 6
Well TW Logarithmic Curve-Matching Plot

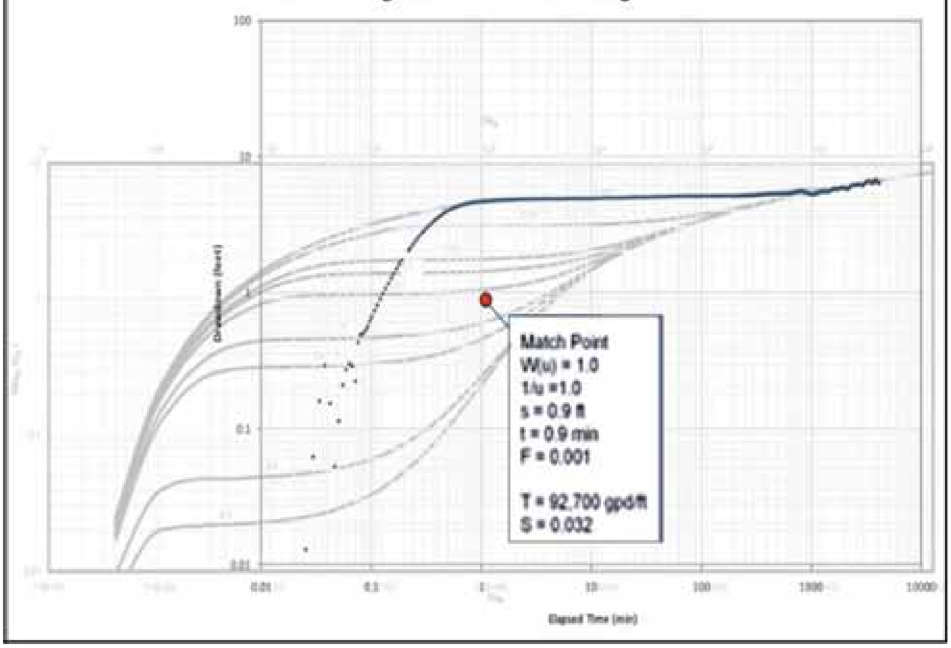
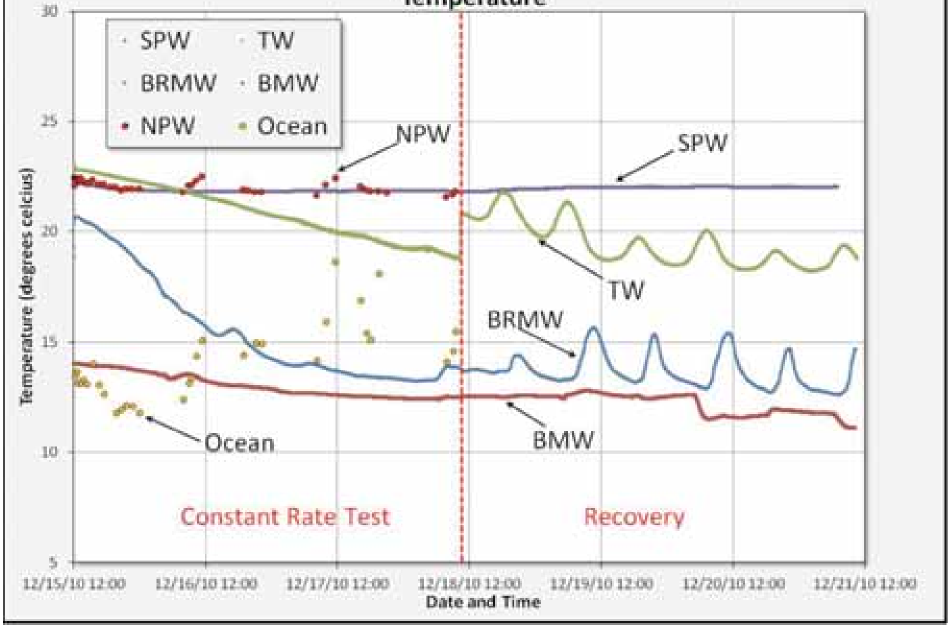


Figure 7
Temperature



Variable Rate Pumping Test

A variable rate pumping test was initially conducted to assess the specific capacity of NPW and to select the optimal pumping rate for the constant rate. The variable rate pumping test was performed on Dec. 1, 2010, at 417, 583, 784, and 1,000 gpm for approximately a one-hour per-flow adjustment. The resulting specific capacities were 28.6, 25.7, 27.2, and 32.2 gpm per foot of drawdown (gpm/ft), respectively. The specific capacities increased from the second to third and from the third to fourth steps. Specific capacities and well efficiency typically decline with increasing pumping rates, and the observed opposite trend indicates that NPW was being redeveloped during the variable rate test. Based on the results of the variable rate test, it was determined that a pumping rate between 700 and 800 gpm could be sustained during the three-day constant rate test.

Constant Rate Pumping Test

The final pumping rate for the constant rate test was 728 gpm. The constant rate test was conducted for a total duration of 70 hours. Small cyclical fluctuations are noticeable in the drawdown data, which are the result of the variability in the tidal correction, but the overall drawdown trend is still apparent. The semi-logarithmic drawdown curves exhibited by the wells are representative of an unconfined aquifer that experiences a delayed water table response.

Aquifer Coefficient Analysis

Because of space limitations, a detailed discussion of the aquifer test analysis, as well as a large number of plots of the data, cannot be provided here. Consequently, a summary of aquifer test analysis is outlined below. Drawdown versus distance and drawdown versus time data from the constant rate pumping test were analyzed to estimate the hydraulic properties of the Surficial Aquifer at the Marineland facility.

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Table 3 Aquifer Coefficient Summary

Cooper and Jacob (1946)		
Well	T (gpd/ft)	S
NPW	60000	
SPW	96900	0.087
TW	85300	0.078
BRMW	100500	1.1

Neuman (1975)		
Well	T (gpd/ft)	S
TW	92700	0.032

Cooper and Jacob (1946) Dist-Draw		
SPW, TW	76800	0.093

Theis (1935) Recovery	
Well	T (gpd/ft)
NPW	86500
SPW	93200
TW	104300
BRMW	101000

Summary	T (gpd/ft)	S
Mean (all)	***89700***	***0.072***

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Standard curve fitting and linear regression methods were used to analyze the data and estimate the transmissivity, storativity, hydraulic conductivity, and other hydraulic properties of the Surficial Aquifer. Since drawdown trends exhibited an unconfined, delayed-yield-type response, the data were analyzed using the following applicable methods:

- Cooper and Jacob (1946) linear regression method
- Neuman (1972) curve matching method
- Theis (1935) recovery linear regression method

The pumping test and recovery data were analyzed using drawdown vs. distance, semi-log plots of drawdown vs. time, log-log plots of drawdown vs. time, groundwater recovery plots, and distance to line-source-of-recharge method. The equations for these methods are not provided.

The drawdown versus distance plot was used to estimate the aquifer transmissivity and storage. Drawdown versus time data from wells NPW, SPW, TW, and BRMW were also used to estimate aquifer transmissivity and storage coefficient with both the Cooper and Jacob (1946) method and the Neuman (1972) method. A semi-logarithmic summary plot of the data is provided in Figure 5. Linear regressions were performed using the late-time portion of the data on the semi-logarithmic plots, and the aquifer transmissivity and storage coefficient were estimated.

The drawdown versus time data were also analyzed using logarithmic curve matching methods and using the drawdown data from well TW (Figure 6); the aquifer transmissivity and storage coefficient were estimated using Neuman (1972). It is important to note that because the early-time data was affected by casing storage, curve matching was conducted to the late-time data.

The recovery period following the constant rate test was also monitored to provide an additional confirmatory estimate of the aquifer transmissivity. The Theis recovery analysis was applied to the late time recovery trend, and the aquifer transmissivity was estimated using Theis (1935).

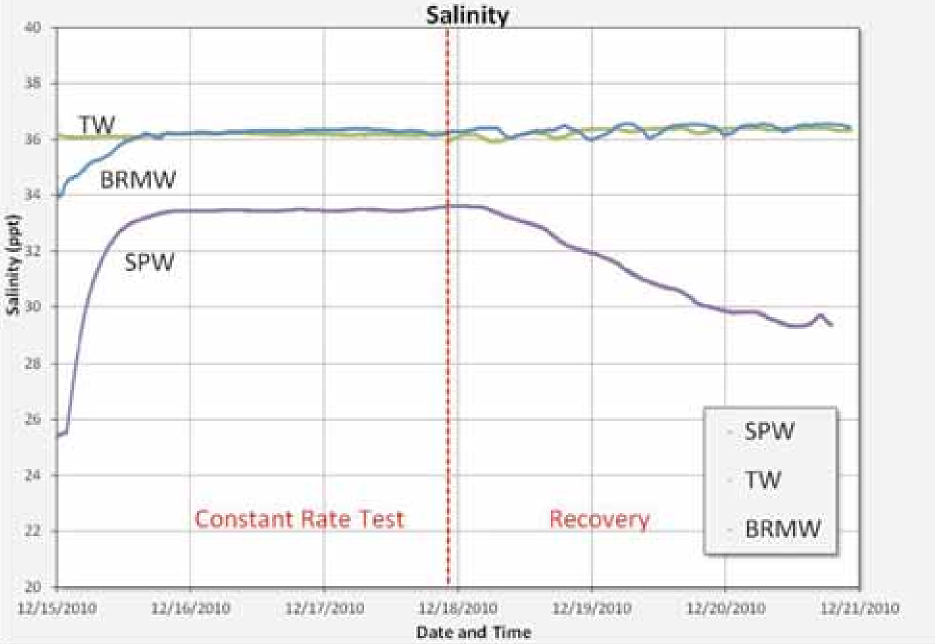
Aquifer Coefficient Summary

A summary of the aquifer coefficients estimated from the constant rate test and recovery data is provided in Table 3. Transmissivities ranged from 60,000 gpd/ft to 104,300 gpd/ft and averaged 89,700 gpd/ft; storage coefficients ranged from 0.032 to 0.09, with an average of 0.072. Assuming a saturated aquifer thickness of 42 ft (depth of well NPW minus static water level), the average hydraulic conductivity of the Surficial Aquifer was 2,140 gpd/ft[2].

The Surficial Aquifer exhibited drawdown trends typical of an unconfined aquifer. The aquifer is a relatively high system at the Marineland facility, with an estimated transmissivity of 89,700 gpd/ft, an estimated storage coefficient of 0.072, and an estimated hydraulic conductivity of 2,140 gpd/ft[2]. The ratio of the vertical hydraulic conductivity to the horizontal hydraulic conductivity of the aquifer was determined to be low. Drawdowns measured in the wells during the constant rate test did not stabilize. Though induced infiltration of seawater occurred during the test, the quantity of infiltration was not sufficient to offset the volume of pumping during the test. The vertical stratification within the aquifer is a likely cause of the lack of stabilization; however, other artificially limiting factors also contributed. These include:

- The relatively short duration of the pumping test
- The inability to stress the aquifer at higher pumping rates because of poor efficiency of well NPW

Figure 8
Salinity



Well Efficiency

The efficiency of well NPW was estimated from the pumping test data using both the ratio of the theoretical drawdown to the actual drawdown in well NPW and the ratio of the theoretical specific capacity estimated from the pumping test to the actual specific capacity for NPW. The efficiency estimated from the former method was 51 percent; the theoretical specific capacity for the latter method was estimated based on Walton (1962). Utilizing the average transmissivity and storage coefficient from the constant rate test, the theoretical specific capacity was estimated to be 52.2 gpm/ft. Based on the end-of-test actual specific capacity (22.7 gpm/ft), the efficiency estimated from the latter method was approximately 43 percent. Both methods indicate that well NPW has a very poor efficiency and demonstrates that much higher pumping rates could have been sustained during the pumping test from a high efficiency pumping well.

Water Quality

Water quality monitoring was conducted before and during the constant rate test to determine the interconnectivity between the aquifer system and the Atlantic Ocean. Water quality data were collected from the NPW and observation wells since water quality changes can provide a good indicator of whether induced infiltration is occurring. Field measurements of water quality were periodically collected from the observation wells using YSI 600 XLM multi-parameter water quality sondes suspended in the wells. The water quality in well NPW was periodically measured with an YSI 556 multi-parameter water quality meter with a flow-through cell. Grab water quality samples were also collected from the Atlantic Ocean and measured periodically with the YSI 556 multi-parameter meter. In addition to field-measured water quality, laboratory water quality samples were collected from wells NPW, SPW, and TW, and the Atlantic Ocean, and were immediately couriered to the laboratory for analysis.

Water Quality Trends During Constant Rate Test

Field water quality parameters were measured at rapid intervals in wells TW and BRMW during the pre- and post-test monitoring period to determine if any external influences not related to pumping during the constant rate test were affecting water quality in the Surficial Aquifer. Water quality hydrographs of temperature salinity and total dissolved solids (TDS) were plotted to evaluate trends during the constant rate testing and the following recovery period; figures 7 and 8 show two of these plots (temperature and salinity). A tidal influence was apparent for each of the field-measured parameters in both wells TW and BRMW; however, the tidal influence was greatest on the shallower well BRMW. Similar to influence on water levels, the tidal influence on water quality appeared to become dampened with increasing depth.

Field measured groundwater quality parameters changed during the constant rate test and became more similar to measurements collected from the Atlantic Ocean. This demonstrated that infiltration of seawater on the aquifer was occurring during the test. The change in water quality tended to be less distinct in the deeper wells than the shallower wells, suggesting that some vertical stratification is present in the Surficial Aquifer. This trend, however, may also be partially due to the position of the wells relative to the pumping wells (the shallower wells are directly between

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well NPW and the Atlantic Ocean where seawater recharge would tend to be the greatest). Laboratory-measured water quality parameters from well NPW were very similar to parameters measured from the Atlantic Ocean, both at the beginning and near the end of the constant rate test. Table 4 is a general summary of laboratory results.

Specific conductance (conductivity normalized to temperature), salinity, and total dissolved solids (TDS) are related parameters that depend on the concentration of dissolved constituents. Since these parameters are closely related, the trends for each of these parameters were similar for each well during the test and therefore are discussed jointly.

Minimal change occurred in the specific conductance, salinity, and TDS in wells TW and BRMW during the test, likely because there is little difference between the concentrations of dissolved constituents in the Atlantic Ocean and the initial concentrations of dissolved constituents in the wells. There was a temporary decrease in the specific conductance, salinity, and TDS at the beginning of the test in well BRMW; however, these parameters returned to their pre-test concentrations within the first 12 hours of the test. The cause of the temporary decrease at the beginning of the test is not clear. Because of the similarity between the Atlantic Ocean and the native groundwater, these parameters were generally not good indicators of whether induced infiltration was occurring, though the similarity does indicate that the water quality of the aquifer is influenced by seawater.

The specific conductance, salinity, and TDS trends in well SPW were slightly different than the other wells during the constant rate test. The concentrations of these parameters were initially much lower than the other wells; however, concentrations in the SPW approached the concentrations in the BRWMD and TW during the test. This was again attributed to the influence of the actively pumping southern infiltration gallery drawing less saline water from the landward side of well SPW. Similar to the temperature, pH, and dissolved oxygen, the specific conductance, salinity, and TDS in well SPW began to return to its original level following the cessation of pumping, whereas these parameters remained stable in the other wells. Because of the differing behavior in well SPW, the specific conductance, salinity, and TDS concentrations measured from this well do provide evidence that induced infiltration of seawater is occurring.

Summary

The Surficial Aquifer exhibited drawdown trends typical of an unconfined aquifer. The aquifer has a relatively high productivity at the Marineland facility, with an estimated transmissivity of 89,700 gpd/ft, an estimated storage coefficient of 0.072, and an estimated hydraulic conductivity of 2,140 gpd/ft^2. The ratio of the vertical hydraulic conductivity to the horizontal hydraulic conductivity of the aquifer was determined to be low. The vertical stratification within the aquifer is a likely cause of the lack of stabilization.

A more detailed investigation as part of future phases of work will be required. Despite the limitations of this screening level evaluation, a wealth of useful information was generated that will be used to guide future investigations. Based on the results of this screening level pumping test, induced infiltration of seawater will be possible from the coastal aquifers in the Coquina Coast region and the quality of water is anticipated to be generally similar to that of seawater. The Surficial Aquifer has a relatively high productivity along the Atlantic Ocean, though preference should be given to sites where vertical stratification within the aquifer is the least to maximize the quantities of induced seawater infiltration. Future phases of exploration will focus on characterizing the site-specific geology and vertical stratification of the potential sites. Additional work includes the installation of test borings, test pumping wells, and conducting long-term aquifer tests utilizing a well-defined observation well network.

Table 4: Laboratory Results

	Units	Minimum Detection Limit	NPW Beginning of Test	NPW End of Test	Atlantic Ocean End of Test	SPW End of Test	TW End of Test
Date Collected			12/15/2010 13:00	12/17/2010 12:30	12/17/2010 12:00	12/17/2010 12:15	12/17/2010 12:10
Barium	mg/L	0.0023	0.022	0.024	0.013	NS	NS
Calcium	mg/L	0.096	340	340	350	NS	NS
Strontium	mg/L	0.00080	7.9	7.7	7.7	NS	NS
Potassium	mg/L	2.2	480	430	460	NS	NS
Magnesium	mg/L	0.99	1,600	1,400	1,500	NS	NS
Sodium	mg/L	250	12,000	13,000	12,000	NS	NS
Silica	mg/L	0.050	2.0	2.4	2.0	NS	NS
Total Hardness (as $CaCO_3$)	mg/L	3.3	910	920	920	NS	NS
Chloride	mg/L	100	23,000	21,000	22,000	NS	NS
Sulfate	mg/L	26	3,100	2,900	3,000	NS	NS
Bromide	mg/L	1.0	70	69	71	NS	NS
Ammonia as Nitrogen	mg/L	0.026	0.12	0.11	0.11	NS	NS
Dissolved Organic Carbon	mg/L	0.50	bdl	1.0	1.5	2.3	1.4
Color	PCU	5.0	20	25 [1]	25 [2]	NS	NS
Turbidity	NTU	0.10	0.23	0.2 [1]	1.1 [2]	NS	NS
Total Alkalinity	mg/L	5.0	120	90	120	NS	NS
Bicarbonate (as $CaCO_3$)	mg/L	5.0	120	89	120	NS	NS
Salinity	ppt	2	40	39 [1]	40 [2]	NS	NS
Total Dissolved Solids	mg/L	100	36,000	38,000	41,000	NS	NS
Total Suspended Solids	mg/L	5.0	11	8.0	100	NS	NS

Acknowledgement

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