Optimizing Wellfield Performance Through Smart Analytics: The Smart Wellfield

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A smart wellfield is capable of integrating supervisory control and data acquisition (SCADA) with a geographic information system (GIS), local hydrogeology, groundwater quality, energy consumption, and wellfield hydraulics information to perform analytics that will result in the optimization of wellfield operations. The optimized operations increase the useful life of the wells and ancillary infrastructure, and provide cost savings from increased energy efficiency and treatment of a consistent groundwater quality. The smart wellfield concept is intended to provide "actionable intelligence" and is not designed to control the wells or associated water treatment plants (WTPs). This responsibility continues to be performed by utilities operations staff.

As part of a strategic project undertaken by Palm Beach County Water Utilities Department (WUD), Black & Veatch was tasked with the identification and development of smart wellfield capabilities relevant to all wells at the four WUD wellfields that supply water to the WTPs (WTP-2, WTP-3, WTP-8, and WTP-9). The WUD already utilizes SCADA to provide some level of visualization of the WTPs and their associated wellfields. To convert the wellfields into smart wellfields, the project was designed to go beyond current capabilities and utilize analytics and reporting to improve the level of understanding of the operations and to allow optimization scenarios to be run and acted upon.

The ability to visualize the aquifer in the context of the wells contained within a wellfield provides the unique ability to integrate the SCADA data, as well as the information about the well itself. When used in conjunction with wellfield optimization, this enables the user to determine the best wells within a wellfield (or an entire wellfield) for peak operational efficiency, adequate water demand, and a reduction in unexpected downtime. For WUD, it's anticipated that the implementation of the smart wellfield project will extend the life of the assets (pumps and wells), facilitate decision making for the operators, maximize water quality, and reduce energy usage. Key features of WUD's smart wellfield include:

- Data capture and display of key performance indicators (KPIs)
- Well and wellfield optimization models
- Well/wellfield aquifer visualizer display

Key Performance Indicators

During the initial site investigations, Black & Veatch discussed with the operators the current wellfield operation scenarios and thoughts on which parameters should be included in the smart wellfield concept as KPIs. Since WTPs 2 and 8 are lime softening plants, and WTPs 3 and 9 are membrane softening treatment plants, some of the KPIs discussed varied between the plants. An example where one parameter might be more important at the membrane plants than the lime plants is using oxidation-reduction potential (ORP) to detect conditions favorable to blending for the membranes.

The following is a summary of the KPIs initially considered to be included in the development of the smart wellfield solution for WUD.

Well Status Key Performance Indicators

Static Water Level (ft) – This is a real-time measurement of the water level in the well as taken from the level transmitter measured in ft below land surface (BLS). This value will be based on logic using the measured water level in the well just prior to the pump status being changed to "on." This value is used in the calculations for total dynamic head (TDH), drawdown, specific capacity, pump efficiency, and energy use/cost per mil gal (MG) produced.

Operating Water Level (ft) – This is a real-time measurement of the water level in the well as taken from the level transmitter measured in ft BLS. This value will be based on logic using the water level measurement shortly after the pump is turned on (i.e., one hour) and in real time thereafter. This value is used in the calculations for TDH, drawdown, specific capacity, pump efficiency, and energy use/cost per MG produced.

Drawdown (ft) – This is the difference in water level in the well while the well pump is on (operating water level) and when the well is off (static water level).

$$Drawdown = Static\ Water\ Level - Operating\ Water\ Level$$

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Production Rate (Q mil gal per day [mgd] or gal per minute [gpm]) – This is a real-time measurement of the well production rate as measured by a flowmeter at the discharge of each well. This value is also used in the calculations for well-specific capacity, pump efficiency, and energy use/cost per MG produced.

Specific Capacity (gpm/ft) – This is the well production rate divided by the drawdown. Significant changes in this value over time (higher or lower) can be an indication of a problem with the well.

$$Specific\ Capacity = \frac{Q[gpm]}{Drawdown[ft]}$$

Water Quality Key Performance Indicators

ORP (millivolts [mV]) – Utilization of an ORP reading as input to the well supply system to determine proper treatment.

Conductivity (microsiemens per centimeter [uS/cm]) – This is a measurement of dissolved solids in the water, and is another indicator of water quality. It has the ability to take input from sensors as part of the overall measurement of well output water quality.

Temperature (°C) – Temperature affects the amount of dissolved solids the water can accept. In addition, odor, coagulation, and pH are all dependent.

Turbidity (nephelometric turbidity units [NTUs]) – Potential use of a turbidity measurement instrument to determine well sand level. Monitor the back flushing cycles to indicate when to stop/start a well.

Sand Filter Backflush Cycles – Monitor the number of backflushing cycles to indicate when to stop/start a well.

Silt Density Index (SDI) – This is a measurement for the fouling capacity of water in reverse osmosis systems, and is important for WTPs 3 and 9. The SDI is not measured by an instrument and therefore will be measured and tracked routinely at each well, based on the current testing frequency.

Sand Concentration (mg/L) – This concentration is a measure of the amount of fine particles in the water and is an indication of the amount of sand migrating through the well screen and into the water stream. High sand concentrations can lead to pump damage, as well as premature clogging of cartridge filters. The sand concentration is not measured by an instrument and therefore will be measured and tracked routinely at each well, based on the current testing frequency.

Well Pump/Motors Key Performance Indicators

Run Status (on/off) – In addition to simply providing an indication and record of when the pump is on, this status information can be used to support other calculations described in this proposed summary of wellfield KPIs, including well/pump runtime, well drawdown, operating time, idle time, etc.

Flow rate (mgd or gpm) – See previous description for well production rate.

Discharge Pressure (pounds per sq in. [psi]) – This is a real-time measurement of the pressure in the well pump discharge piping. This value is also used in the calculations for TDH, pump efficiency, and energy use/cost per MG produced.

TDH (ft) – The TDH is a calculation of the total head delivered by the pump, and the pump discharge flow rate can be plotted over the original manufacturer's pump curve in a chart to illustrate any degradation in pump performance over time. The chart can also illustrate whether or not the pump is typically being operated close to its best efficiency point (BEP) and within the manufacturer's allowable operating range for the pump.

$$TDH[ft] = \left(0.00259\,x\,\frac{Q[gpm]^2}{D[in]^4}\right) + \ Operating\ W.L.[ft] + h[ft] + (Discharge\ Pressure[psig]\ x\ 2.31)$$

Where h is the height of the pressure gauge above land surface (ALS) and D is the diameter of the pump discharge piping.

Speed (revolutions per minute [rpm]) – This is an indication of the pump speed for the well pumps that are equipped with variable frequency drives (VFDs). There is a potential reduction in sand churn/cavitation based on well pump speed and start-up speed to reduce turbulence, churn, and cavitation that capture events when pumps start up, capture turbidity, and analyze results.

Power (kilowatts [kW]) – This is a real-time indication of the actual power usage of the pump motor as measured by the VFDs, power meter, or calculation based on the measured operating conditions of the pump.

Phase Voltage (V) – This is a real-time indication of the individual voltage to each phase (A, B, and C) as measured by the VFDs or power meter. These values are used to calculate voltage imbalance and the resulting temperature rise in the motor windings.

Voltage Imbalance (percent) – This is a calculation of the maximum difference in measured line-to-line voltages between each phase, divided by the average voltage across each phase. This is used to monitor power quality and to calculate the temperature rise in the motor windings caused by the imbalance.

$$Voltage\ Imbalance[\%] = \frac{Maximum\ Imbalance}{Average\ Voltage}\text{x }100$$

Temperature Rise (percent) – This is a calculation of the increase in temperature of the motor winding as a result of voltage imbalance. A voltage imbalance greater than 2 percent can result in a temperature rise in the winding that is beyond the motor specifications, decreasing motor life. The National Electrical Manufacturers Association (NEMA) requirements limit voltage imbalance to no more than 5 percent.

Pump Efficiency (percent) – This is a calculation of the real-time efficiency of the well pump. Monitoring and trending of the pump efficiency can be used to identify impeller wear or maintenance issues that are negatively impacting pump performance. Low pump efficiency values can also alert operations staff to operational conditions that are outside of the pump's allowable operating range.

Wire-to-Water Efficiency (percent) – This is a calculation of the real-time energy efficiency of the well pump/motor system. Monitoring of the wire-to-water efficiency can support the determination of optimized operating strategies for the well pumps, especially for pumps equipped with VFDs.

$$HP(water) = \frac{Q[gpm] * P[ft] * S.G.}{3960}$$

$$HP(input) = \left[\frac{V * I[amps] * PF * \sqrt{3}}{1000}\right] * 1.341$$

$$Wire - to - Water\ Efficiency = \frac{HP(water)}{HP(input)}$$

Where:

Q (gpm) = Pump Flow

P (ft) = Total Dynamic Head (Discharge Head – Suction Head)

S.G. (Specific Gravity) = 1.0

V = Line-to-Line Voltage

I(amps) = Line-to-Line Current

PF = Power Factor

Well Power Use/Costs

Power Demand (kW) –This is a real-time indication of the actual power usage of the pump motor as measured by the VFDs or motor control center (MCC). If no measured kW value is available, power demand can be calculated using the measured operating conditions of the pump. This value is also used in the calculations for pump efficiency, wire-to-water efficiency, and energy use/cost per MG produced.

Energy Use (kilowatt-hour [kWh]/MG) – This is a real-time calculation of the rate at which energy is being used to pump MG of supply.

Energy Cost ($/MG) – This value indicates the energy cost for pumping each MG of supply from the well. This value would be based on the average $/kWh rate that is associated with the power service at each well. By monitoring this value, the operators will determine which well pumps provide water supply at the lowest energy cost.

On-Peak/Off-Peak Energy Cost Rate – This is an indication of when the energy use at a well is occurring at a time when Florida Power and Light (FPL) is charging higher "on-peak" rates or discounted "off-peak" rates. On-peak and off-peak rates are only applicable for the wells that are on a specific FPL rate schedule.

Overall Wellfield Performance and Power Use/Costs

Wellfield Production Rate (mgd or gpm) – This is the total wellfield supply delivered to the WTP.

Wellfield Power Demand (kW) – This is the combined power demand of the wells in each wellfield, in addition to any air conditioning in the environment.

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Energy Use (kWh/MG) – This is a real-time calculation of the rate at which energy is being used throughout the wellfield to produce MG of supply.

Energy Cost ($/MG) – This is a real-time value that indicates the energy cost for pumping each MG of supply from the entire wellfield.

Wellfield Operations and Operational Analysis

The operating strategy for each wellfield can vary, based on many considerations. For example, emphasis can be given to managing the health of the well, increasing energy efficiency, or improving raw water quality to the WTPs. Each well may contribute differently to each of these areas; therefore, it can be difficult to determine the most optimum combination of wells to achieve the desired effect.

Monitoring and tracking the relevant KPIs of each well in real time allows operators to better understand how each well, or combination of wells, may contribute to the overall operation strategy; examples include:

- Operating wells with the highest specific capacity (gpm/ft)
- Operating wells with the best water quality to ensure reliable WTP operation
- Operating wells that provide the lowest energy cost per mil gal produced ($/MG).
- Operating well pumps at or near their BEP

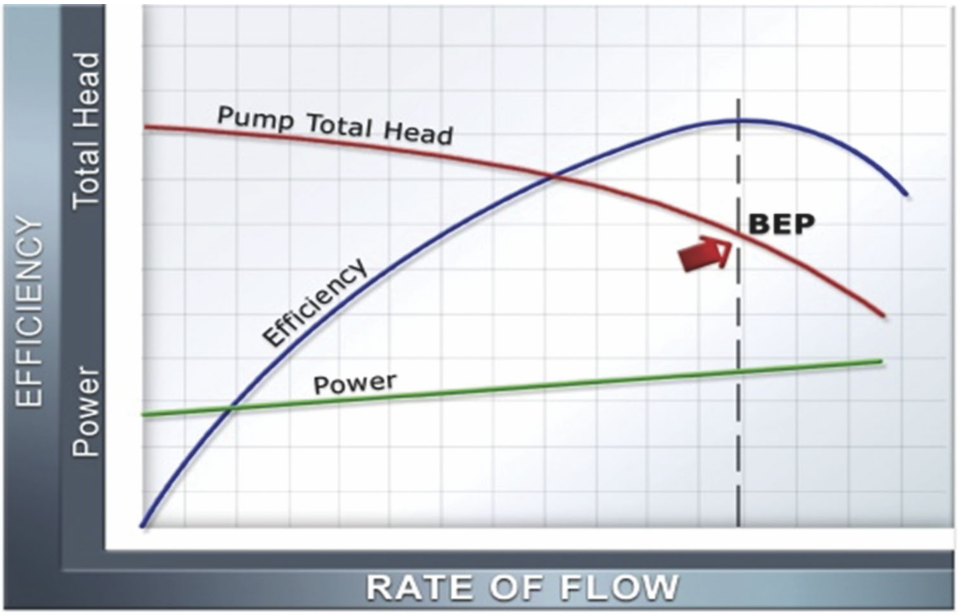

Figure 1. Illustration of Pump Efficiency Declining When a Pump Operates Away From its Best Efficiency Point

Operating Well Pumps to Maintain Asset Health

Maintaining the health of the well and the well pump is a priority to ensure reliable operation and extend the life of the well. As described earlier, some of the proposed KPIs are drawdown and capacity-specific. These values can be calculated in real time and trended to determine which wells are deteriorating and may be in need of rehabilitation. Similarly, these values can be used to determine the flow ranges of each well that result in allowable drawdown levels; the production rate of each well can then be limited through the operating speed of the pump to prevent operation at excessive drawdown levels. This can prolong the life of both the well and the pump, as well as effectively identify wells with degrading performance and prioritize rehabilitation projects.

Understanding the water quality of each well can also play a part in maintaining asset health. For example, excessive ORP values can lead to severe damage of the membranes, but monitoring the ORP at the plant inlet alone does not provide adequate notice of high ORP. Measuring and tracking the ORP at each individual well will allow the ability to identify which wells are experiencing high levels of ORP, as well as estimate the combined ORP from a group of wells operating at various flows and ORPs. This will help anticipate when high ORP conditions may occur and provide adequate time to react before damage occurs.

Operating Well Pumps to Reduce Energy Cost per Million Gallons Produced

One of the proposed KPIs is a calculation of the energy cost per MG produced ($/MG). This value can be calculated in real time and trend over long periods to illustrate which wells provide water at the lowest energy cost per MG produced. The calculation of this value takes into account numerous variables (including flow rate, power use rate, and unit cost for energy based on the power rate schedules) and provides a single value for each well that can be monitored and used to support decisions regarding energy-efficient operating plans for the wellfield.

It should be noted that the $/MG value will not remain constant for each well, as this value can change based on the varying conditions of the wellfield, its operations, and the power rate schedule (including on-peak versus off-peak times for wells on FPL's rate schedule). For example, changes in aquifer/drawdown levels, pump efficiencies, pump speeds, and head losses in the wellfield collection piping system (based on the selected combination of wells that are on at a given time) can impact the $/MG value for each well; however, trending and averaging the $/MG value over time and including other advanced data analytics within a smart wellfield can allow the $/MG value to be further leveraged to support operators in identifying the most energy-efficient wellfield operating plans.

Operating Well Pumps Near Best Efficiency Points

Each well pump has specific flow rate and pressure conditions that result in optimal energy efficiency for the pump, or BEP. A well pump may have a BEP of 85 percent efficiency, but that same well pump could run at 60 percent efficiency or less if it's operated significantly away from its BEP (Figure1). This is similar to how a car may run at a high-efficiency mi per gal (mpg) at 50 mi per hour (mph), but a much lower efficiency at 100 mph.

In order to support the operation of well pumps near their BEPs, one of the proposed KPIs is a real-time energy-efficiency calculation. A customized equation can be developed to automatically calculate this value from the following proposed monitoring data from each well: flow rate, well water level, discharge pressure, and power use rate. Monitoring and trending the actual efficiency value over time can support the operators in understanding the energy efficiencies of each well pump based on different operating conditions.

Observations of a low energy-efficiency value or a decreasing trend in efficiency over time can alert operators to an operational or mainte-

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nance issue with a well pump. If the wells are equipped with VFDs, the smart wellfield could also include additional analytics to support the identification of an optimal pump speed for each well to maximize operation near the BEP.

In addition to wellfield energy use and cost considerations, the smart wellfield must consider a number of additional factors and constraints. These may include:

- Regular rotation of well operations and exercising of well pumps to avoid regulatory, water quality, and maintenance issues.
- Conditions where specific wells may be temporarily out of service.
- Aquifer management considerations.
  - Aquifer drawdown
  - Changes in specific capacity
- Well management considerations, including:
  - Avoiding well interference
  - Production rates that may negatively impact water quality or well drawdowns
  - Total maximum permit
  - "Running to waste" for idle/restarted wells

Smart Wellfield Dashboard Concept

Smart Wellfield Dashboard/Modeling Prototype Benefits

Providing relevant information comparing actual to expected values will increase operational awareness and foster shared-system ownership across all departments within WUD. Easy access to data and analytical tools will encourage collaboration among operations, maintenance, and engineering, as well as offer a means to answer the following questions:

- Do I need to make a change to wellfield operations or rehabilitation schedules?
- Do I know what to change to achieve a successful outcome?
- How can this change be implemented in the most efficient way possible?

It's important to note that the smart wellfield dashboard is different from SCADA. The SCADA system is, and will continue to be, the exclusive point of operational information and the foundation for process data collection. The dashboard will build on this by providing a scalable analytics environment, along with the data integration, visualization, and mathematical tools necessary to solve complex operational challenges. These tools can be accessed by all individuals or departments within WUD and customized so that they are relevant to each for purposes of tracking, monitoring, and assessing the health and performance of a particular asset. The results can then be used to identify operational improvements, such as optimized pumping strategies and refined pump operating limits, which can be applied through the SCADA system by WUD operators.

Dashboard Access

The smart wellfield dashboard will be powered by ASSET360® (Figure 2), which is a cloud-based analytics platform that uses big data to maximize the capability of distributed assets and across a system. It can be accessed by any authorized person using a standard internet connection and relevant computer hardware, from iPad to desktop computer.

Visualization and Tracking of Key Performance Indicators

The power of the smart wellfield dashboard is the ability to look at the macro view of the entire system, as well as displaying specific information about a particular asset. This provides the capability of integrating multiple data sources into a common point and leveraging that data to provide tracking and trending KPIs for all systems and assets. The ability to view multiple data sources for all individual assets or the aggregate of those assets in one view makes the dashboard an essential tool. This enables the user to assess the status and optimization of the operation in one view. The dashboard will provide the ability to visualize an aggregate view of an entire wellfield, or specific wells within a wellfield. It provides the ability to visualize the metrics in an aggregate pie chart paradigm, as well as tracking the well and wellfield information over time, measuring such information as flow, energy consumption, well/wellfield production.

The dashboard can retrieve a specific set of data from a specific well, in addition to the wellfield. These data can be combined with other system data to create custom time series comparisons. This enables comparing nominal and nonregular events to other points in time for the causal of an event, system performance during a specific time/event, and optimization of the system. Inherent to the system is the ability to recognize and leverage usage and other metrics being captured.

Operational Intelligence

An operational intelligence (OI) solution suite gives users a significant strategic edge by transforming information into insights that enable timely and dynamic decision making. The suite includes:

- *Alerts* – Provide early warning of emerging performance and reliability issues through advanced pattern recognition.
- *Issues Management* – Collects, prioritizes, and tracks the emergence of asset and equipment issues to expedite their resolution.
- *Performance Analysis* – Evaluates the performance and reliability of selected assets with advanced trending, plotting, and data exploration.
- *Business Intelligence* – Enables powerful data exploration and custom, dynamic dashboards and reports.
- *Monitoring and Diagnostics* – Provides total plant coverage to detect and diagnose equipment and performance issues before they become costly problems.

Aquifer: Summary/Bi Screen

One of the key areas of interest for WUD was the ability to visualize, in one view, the parameters of the well and wellfield that included well capacity, flow rate, well depth, well-causing depth, pump/screen elevation, and well screen depth. This view provides the ability to visualize

Figure 2. Wellfield 9 Production Dashboard

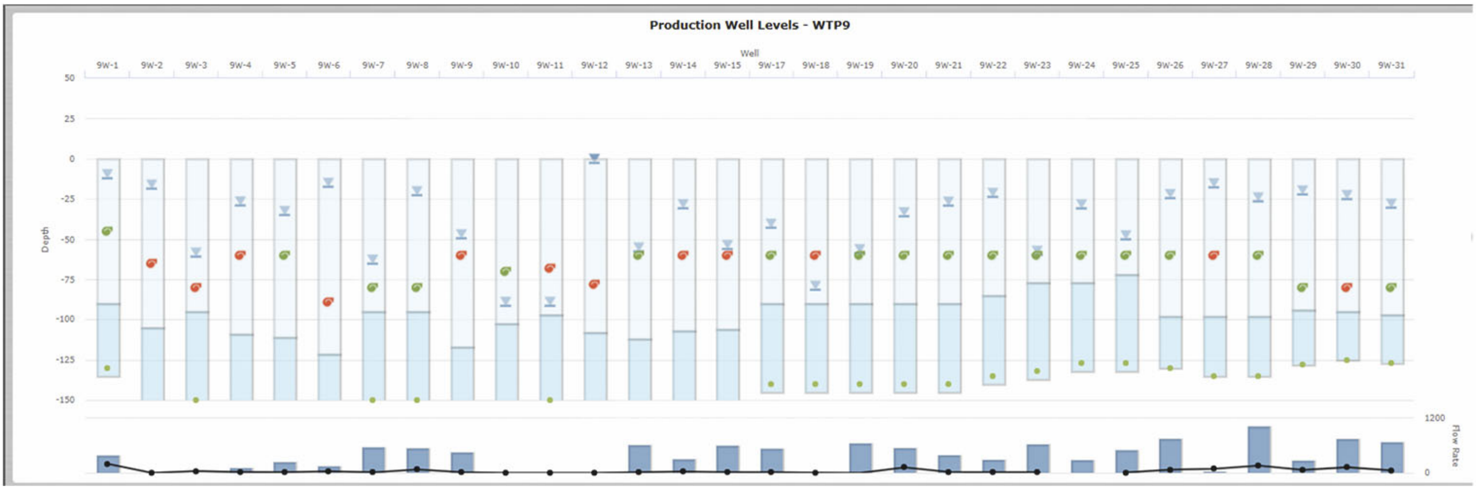

Figure 3. Production Well Levels: Water Treatment Plant 9

all of the wells and the characteristics and limits listed for each well. It also provides the ability to view the water quality parameters by hovering the cursor over a particular well, which enables a quick view of the specific well static and dynamic parameters without having to utilize another tool or view. The ability to simultaneously view multiple vital parameters at a glance may reduce the potential of overpumping, resulting in excessive drawdown.

As part of the overall view presentation of the total cost by asset, source, and energy used by active wells is the availability above the cross sectional view of the wells and wellfield (Figure3). In one view, the user is able to determine well metrics and, with use of the well optimization tool, determine which wells within a wellfield (or an entire wellfield) to use to meet customer demand, operational efficiency, energy usage, and pump maintenance parameters. This is just one view of the well/wellfield that is possible through the dashboard.

Water Quality: Summary/Bi Screen

The ability of the system to incorporate, integrate, and simultaneously display the real-time data coming from the ORP sensors or other quality systems (in addition to the laboratory data displays) shows its power beyond the traditional capture of real-time systems.

There are three major variables that affect the pH and ORP of the water: the water's source, the voltage applied to the water during electrolysis (if applicable), and the flow rate. The system enables the capture of each of these variables incorporating the measured flow rate, ORP, and pressure. The system is capable of using both the real-time instrument data (such as ORP), conductivity, temperature, and turbidity, as well as periodic sampling data, such as iron, hydrogen sulfide, sand, or silt density index (SDI), to display and predetermine the type of water quality coming from each of the wellfields that will better prepare the water treatment process.

The system also has the ability to integrate and utilize the data from new sensors and equipment without the need for the recreation of existing trends and charts. The ability to integrate the instrument and laboratory data enables the direct comparison of these readings into a single view, with the ability to compare the performance of the delivery of water at other points in time. This has significance if there are events, such as significant weather or usage, that cause differences in the aquifer and subsequently the output from each well/wellfield.

Pump Performance: Summary/Bi Screen

The ability to integrate and display the pump characteristics is vital to the efficient operation, maintenance, and performance of the pumps in the system. The prototype is able to utilize the data produced by the pumps themselves to track and produce how the pump is performing in the context of capacity, flow, energy usage, and efficiency. The prototype also has the ability to display the manufacturer's pump curves as part of the system. The use of this information provides the user with the ability to visualize how the pump is performing in real-world conditions and within the parameters set by utility.

This demonstrates the ability of the system to utilize all data sources regardless of static or real time and provides the comparison capability to pump specifications, enabling determination of pump capability for the particular well. This capability, combined with the optimization capability of the prototype (Figure 4), provides (for example) the ability to predict the resistance or capability each pump faces compared to other pumps, or how the pump performance is changing over time based on the type of well it's installed on. This ability to capture and compare the change in performance might drive difference maintenance routines or schedules, reducing unscheduled downtime due to failure.

Network Collection: Geographic Information System/Map Tab

A satellite view or graphical representation of the system provides a logical way to improve the operator's ability to visualize where a potential issue may be. Many systems that provide a satellite or graphical representation of an asset do not integrate the operational data for that asset; in this case, the well or wellfield. The GIS/map tab (Figure 5) will provide a satellite view showing all of the wells within a selected wellfield in a satellite display of their actual location. In addition, the same real-time operational data for each well or wellfield that is used in other views of the system can be visualized on that map.

Users can configure limits on any of these parameters and represent those limits with color-changing indicators. Values for parameters, such as pump-run status, well flow rate, well-specific capacity, water quality, and well drawdown can all be color-coded to quickly and easily visualize how a particular well is operating relative to those defined thresholds. At a glance, the operator can see if that well or wellfield is operating correctly or requires attention from within that view without navigating to another part of the system.

Alerting: Future Application Capability

In any system, alerting is a major factor in

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avoiding conditions that go outside operating ranges or parameters. Most alerting systems depend on static thresholds that are set according to parameters that do not take into account variations that might violate a static threshold, but are acceptable given the conditions at the time.

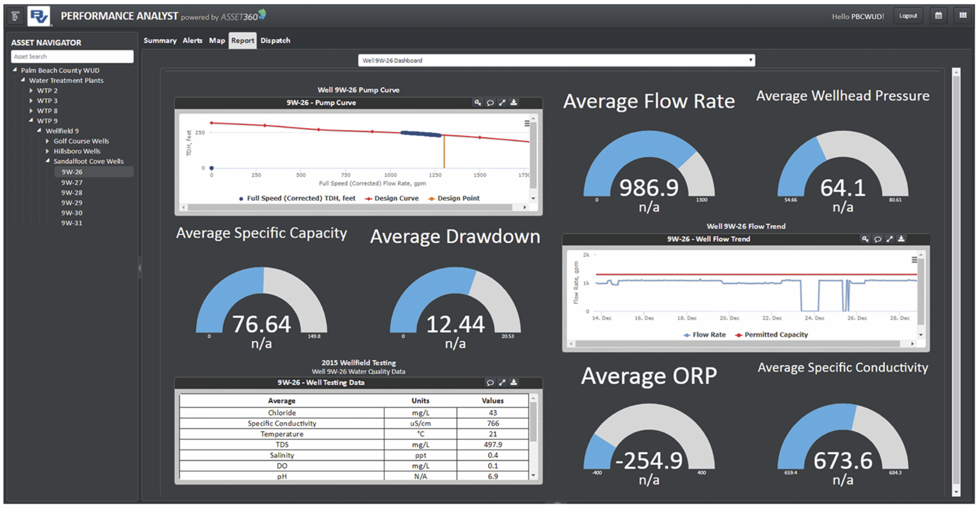
While most SCADA systems provide static threshold alerting, the number of nonconditional alerts based on static thresholds ultimately results in the alerting function not being utilized and turned off, except for extreme conditions. The prototype has the capability, with its time-based trend-capture capability, to interpret those dynamic conditions and provide (or not provide) thresholds based on past occurrences or situations.

The system has the capability of learning these situations or conditions, in addition to user input to create intelligent alerting. The system could provide the capability of an alert on the degradation of a well or pump based on past performance of that well or pump. The system has the capability to look at past trends and use them to create the alerts that fall outside of current or past conditions that would realistically create damage to the well or pump, as well as an unacceptable water quality level. This level of intelligent alerting enables the proper and efficient use of resources to focus on substantive alerts based on actual conditions at a well, wellfield, pump, or other asset in the system.

Well Optimization

The smart wellfield optimization tool will perform predictive simulations using past and current data to create, compare, and inform complex planning, operational, and infrastructure decisions. Smart wellfield optimization solutions provide a dynamic, flexible planning framework that enables utilities and communities to rapidly adapt to changes in present conditions and strategically plan for potential future conditions. Adaptive planning solutions that can be provided with the smart wellfield include:

- *Strategic Options Assessment* – Advanced scenario creation and comparison analytics evaluate capital investment, infrastructure resilience, maintenance, operations, consumables, and compliance options against a wide range of metrics for strategic planning.
- *Operational Planning* – Recurring planning analytics predict performance variances and provide an understanding of variance sources and improvement opportunities for operational planning, such as responding to unexpected or upset conditions.
- *Asset Planning* – Probabilistic analytics inform asset investment and maintenance plans with an understanding of risks, impacts, and criticality for operational and strategic planning.



2015 Wellfield Testing
Well 9W-26 Water Quality Data
9W-26 - Well Testing Data

Average	Units	Values
Chloride	mg/L	43
Specific Conductivity	uS/cm	766
Temperature	°C	21
TDS	mg/L	497.9
Salinity	ppt	0.4
DO	mg/L	0.1
pH	N/A	6.9

Figure 4. Prototype Dashboard

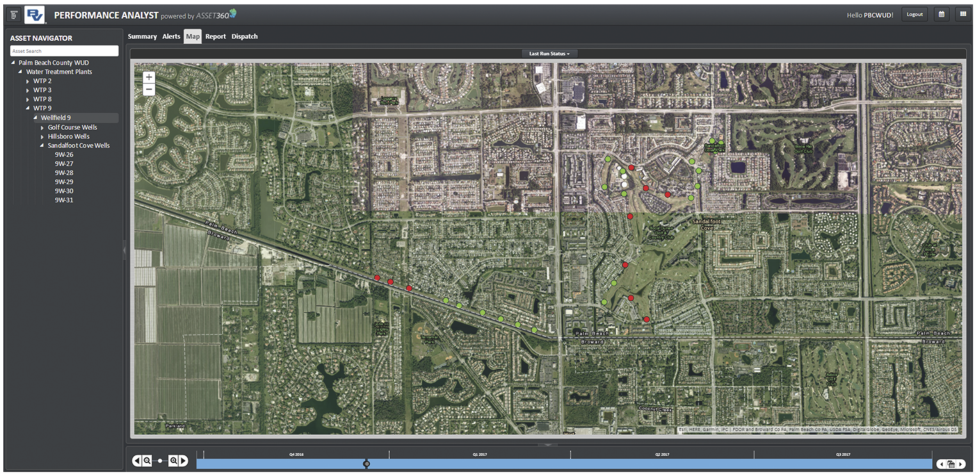


Figure 5. Aerial Map View of Wellfield 9

Define Operating Rules and Scenarios

Optimization technology can greatly assist operators when there are a large number of decisions or combinations of decisions. In such cases, operators often rely on years of valuable operational experience. Unfortunately, areas of decision may be left unexplored, leaving opportunity for savings in energy, cost, quality, and efficiency. When producing a recommendation from an optimizer, it's critical that the optimization model (model) represents the decisions and constraints as best as possible; if an important constraint is not considered, a recommendation may yield a suboptimal result.

Outlined here are operating rules and constraints that have been so-far envisaged in the prototype model. It's expected that these constraints would be refined and expanded upon in the final dashboard tool to best reflect actual operations at the wellfields and wells.

The prototype model considered constraints at the pump, well, and wellfield levels. Starting at the pump level, each pump curve was uploaded, defining the maximum pressure available with varying flow. The pump curve also relates the pump flow and pressure with the pump efficiency. As improved instrumentation is installed, the as-tested pump curves used in the model would be updated or calibrated with measured pump performance parameters. The model also treats single-speed (SS) pumps differently than VFD pumps, which have the advantage of maintaining high pump efficiency across a wider range of flow and pressure. The pump affinity laws are applied in the model to calculate pump performance across the speed range.

Each well's specific capacity and maximum drawdown are also considered by the model. As the pump flow increases, the water level in the well decreases, increasing the hydrostatic pressure the pump must overcome. Water quality parameters can also be specified at each well.

At the wellfield level, the model considers a time-based water flow requirement and water quality limitations. The wellfield flow is calculated simply as the sum of each well's flow, and the water quality is a weighted average of the well flow and its respective quality value.

The model considers operational constraints, such as a minimum runtime and off-time of 24 hours, and a maximum runtime of 72 hours. Pumps can be scheduled to be forced online or offline for rotation or maintenance purposes. Longer time-horizon considerations, such as pump rotation, are not currently envisaged in the model.

Electricity tariffs are assigned to each pump. Currently the energy charges are included in the model, including flat and time-of-use structures; demand charges are not included in the prototype. Each pump is also considered to be on its own electricity meter—an assumption that would need to be validated once demand charges are introduced.

Currently, the model can be configured to maximize specific capacity, minimize electricity costs and consumption, or optimize water quality parameters, such as ORP and turbidity.

Moving forward, there are some additional constraints and considerations the model should consider; for example, there may be significant opportunity to reduce demand charges if multiple pumps are on the same electricity meter. It may be important to more accurately predict the system resistance each pump faces, based on which other pumps are delivering into the system. The hydrostatic pressure each pump faces changes over time with the well static level.

Changes and deterioration of pump and motor performance are likely to be important to the quality of the model and additional or composite optimization objectives may be defined. Finally, the scope of the questions that can be answered by the optimizer should be explored, from maintenance rotation optimization to defining how valuable it would be to shape the wellfield water flow rate throughout the day to respond to time-of-use rates.

Dispatch Tab: Optimization

A prototype dashboard was created to visualize the optimization results and compare them to actual operation. An example screenshot is displayed in Figure 6.

Wellfield 9-Electricity Cost
37.44$
25.04$
Difference: 12.41$

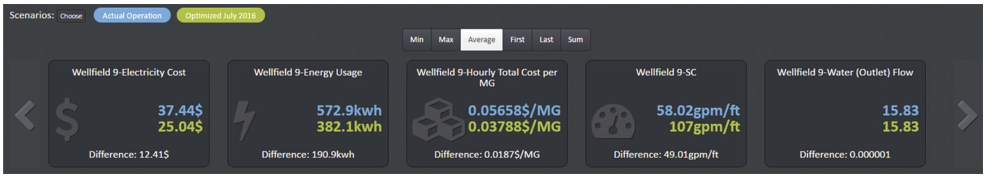
Wellfield 9-Energy Usage
572.9kwh
382.1kwh
Difference: 190.9kwh

Wellfield 9-Hourly Total Cost per MG
0.05658$/MG
0.03788$/MG
Difference: 0.0187$/MG

Wellfield 9-SC
58.02gpm/ft
107gpm/ft
Difference: 49.01gpm/ft

Wellfield 9-Water (Outlet) Flow
15.83
15.83
Difference: 0.000001

Figure 6. Prototype Dashboard Created to Visualize Optimization Results Compared to Actual Operations



Wellfield 9-Electricity Cost
37.44$
25.04$
Difference: 12.41$

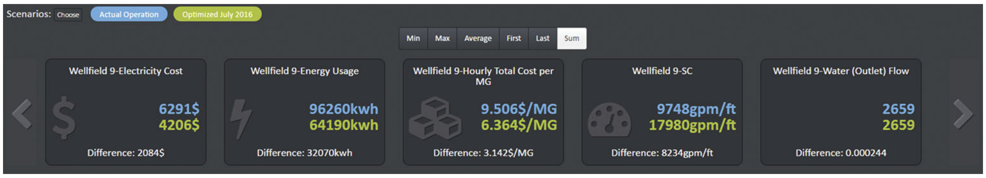
Wellfield 9-Energy Usage
572.9kwh
382.1kwh
Difference: 190.9kwh

Wellfield 9-Hourly Total Cost per MG
0.05658$/MG
0.03788$/MG
Difference: 0.0187$/MG

Wellfield 9-SC
58.02gpm/ft
107gpm/ft
Difference: 49.01gpm/ft

Wellfield 9-Water (Outlet) Flow
15.83
15.83
Difference: 0.000001

Figure 7. Comparison of Actual Operation and Optimization Result Minimizing Cost (Average Variation)



Wellfield 9-Electricity Cost
6291$
4206$
Difference: 2084$

Wellfield 9-Energy Usage
96260kwh
64190kwh
Difference: 32070kwh

Wellfield 9-Hourly Total Cost per MG
9.506$/MG
6.364$/MG
Difference: 3.142$/MG

Wellfield 9-SC
9748gpm/ft
17980gpm/ft
Difference: 8234gpm/ft

Wellfield 9-Water (Outlet) Flow
2659
2659
Difference: 0.000244

Figure 8. Comparison of Actual Operation and Optimization Result Minimizing Cost (Sum of Optimization)

This dashboard allows users to see how KPIs compare across scenarios, as well as inspect charts to understand the differences in more detail. In the top left of the tab, users select which scenarios they want to compare; in this example, the user is comparing an actual operation and the optimized scenario from July 2016, which minimizes cost. Tiles across the top allow the user to compare KPIs across the selected time range.

For the prototype, actual operation was to the optimization recommendations. Power consumption was not measured at the pumps; therefore, measurement data from individual pumps was analyzed with pump curve test data to develop the costs and energy usage for each pump. Pump flow measurements were used to look up pump water horsepower on pump curves. Where available, pump VFD speed measurements were used, with the affinity laws to alter the estimated water horsepower. The time frame of July 1 through July 7, 2016, was used in this prototype example; the optimization model required that the hourly system flow matched the measurement data.

Three different optimization scenarios were evaluated and compared in the prototype dashboard: the first scenario minimized energy costs, the second minimized energy consumption, and the third maximized the water quality.

Comparing Actual Readings to Optimized Predictions

For the purposes of this prototype, when comparing the actual measured operation to the optimized operation, it's important to recognize the opportunities for operational improvement, while understanding that the optimization model

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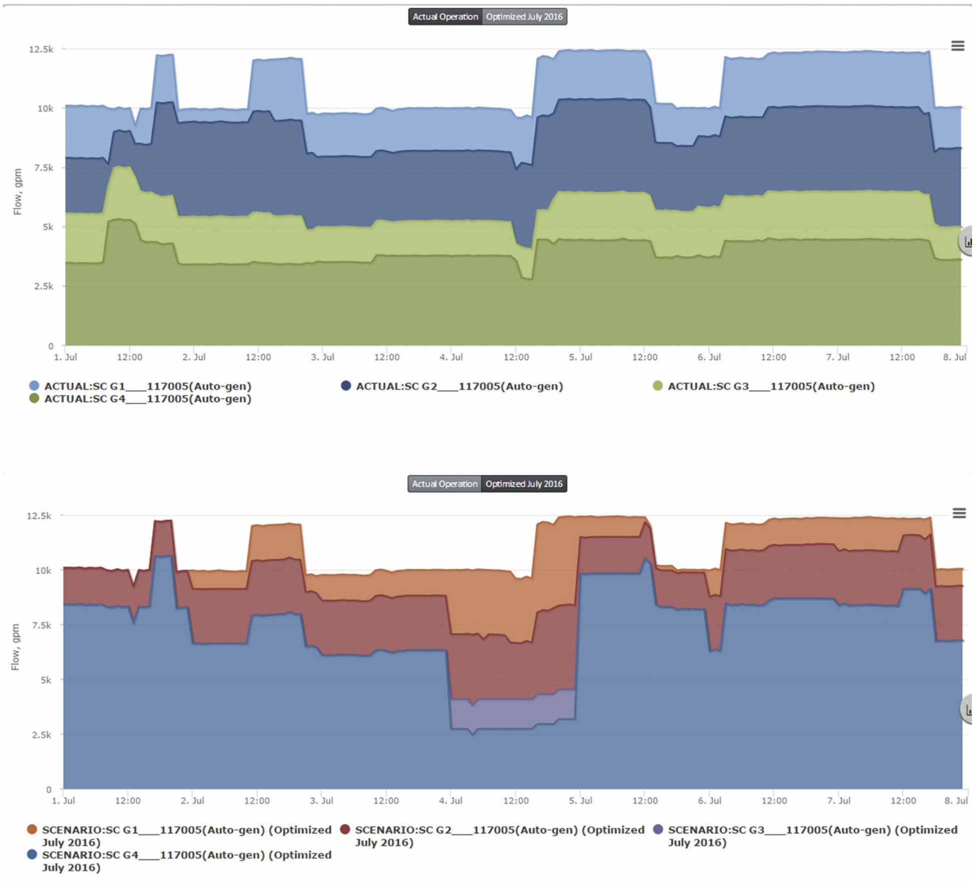

Figure 9. Illustration of the Hourly Flow Throughout the Week, Segmented by Specific Capacity

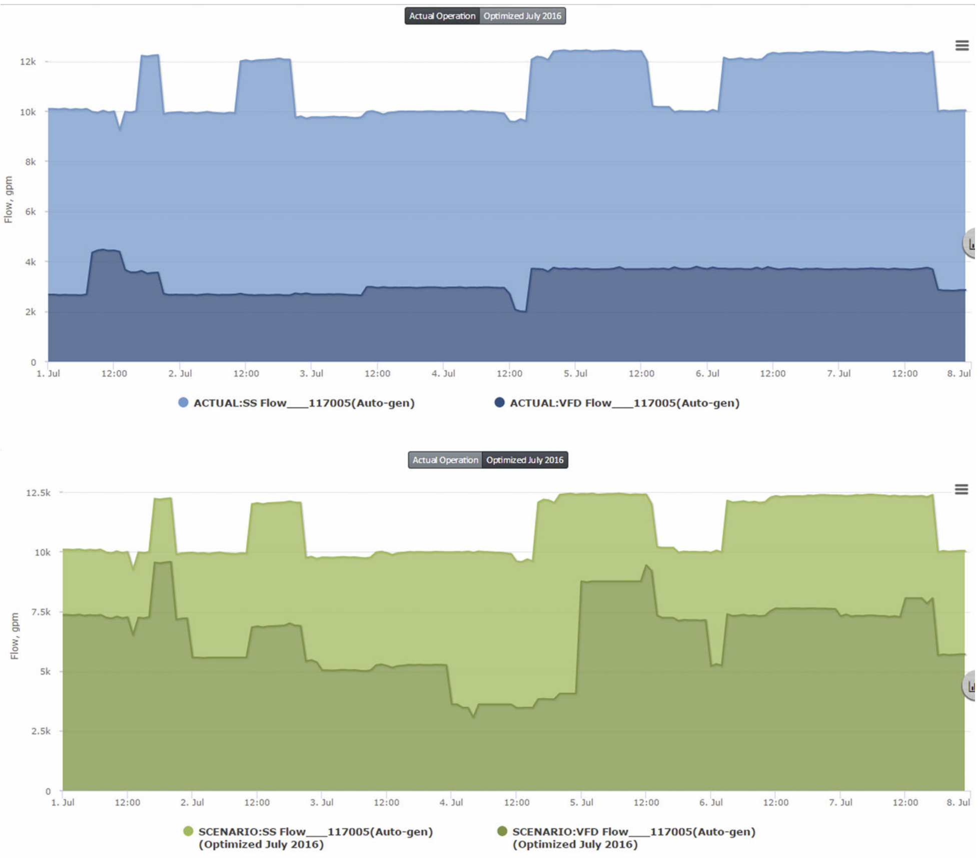

Figure 10. Comparison of How the Model Uses Variable Frequency Drive Pumps Versus Single-Speed Pumps

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is a prototype model and does not yet include all the constraints and considerations that a comprehensive and robust model would consider.

The following details how users can inspect and compare two scenarios using the prototype dashboard. In this case, the actual operation and optimization result that minimizes cost will be compared (Figure 7).

One of the first items to observe is that the average water flow for the week is identical. This is because the optimizer constrained the system flow to match the measured data. The optimizer selected wells with favorable specific capacities because drawdown in the well affects the efficiency and cost of pump operation. On average, the optimizer was able to reduce the cost per thousand gal (kgal) from 5.658c/kcal to 3.788 c/kgal.

While some KPIs make sense to compare on an average basis, others make more sense using different aggregation means. Selecting "sum" on the aggregation bar allows users to see how the sums of the KPIs over the time range compare (Figure 8). In this case, the optimizer reduced the cost from $6,291 to $4,206 and energy usage from 96 megawatt-hour (MWh) to 64MWh. As mentioned, since this is a prototype optimization model that does not yet consider all operational factors or cost-savings opportunities, such as demand-charge management, the weekly savings is expected to be less than $2,000 per week.

Comparison of Results Based on Specific Capacity

Various charts were developed to understand and illustrate where the model achieved its savings. Figure 9 illustrates the hourly flow throughout the week, segmented by specific capacity.

The pumps were organized into specific capacity categories according to the following:

- Pumps with specific capacity between 10-15 gpm/ft were placed in group 1 (G1)
- Pumps with specific capacity between 15-20 gpm/ft were placed in group 2 (G2)
- Pumps with specific capacity between 20-40 gpm/ft were placed in group 3 (G3)
- Pumps with specific capacity above 40 gpm/ft were placed in group 4 (G4)

In the optimization recommendation, the most efficient pumps (G4) were utilized much more than in the actual operation. There is a substantial drop in G4 pumps in the middle day for the optimized chart. This is an artifact of the operational rules used in the model; namely, that pumps cannot be online for more than 72 hours and must be online or offline for a minimum of 24 hours. In this case, the optimizer is using the most efficient wells for days one through three, turning them off on day four, then turning them back on for the remaining three days of the evaluation. When the model is further developed to understand more operational rules, it's likely that these sorts of decisions will not be allowed to implement, for example, a longer-time horizon rotation strategy.

Comparison of Results Based on Pump Speed

Figure 10 compares how the model used pumps with VFDs versus pumps with single-speed motors.

This figure illustrates that the optimizer generally prefers pumps with VFD motors over pumps with only single-speed motors. The VFD motor allows the pump to operate at high efficiency over a range of flows, meeting the needs of the system more efficiently, and therefore, with less energy costs.

Comparison of Results Based on Electricity Rates

Figure 11 illustrates how the optimizer made decisions based on the different electricity tariffs that were available.

As described, most pumps are on a specific tariff, where energy costs are on the order of 6.8c/kWh. Only seven of the pumps are on a specialized tariff, which has on-peak and off-peak energy prices on the order of 9.3¢/kWh and 5.7¢/kWh, respectively. In 2016, July 1 fell on a Friday, where the tariff had on-peak and off-peak prices. The days of July 2-4 were weekends or a holiday (Monday, July 4), and therefore pumps on the tariff only faced the low off-peak energy price. July 5-7 were nonholiday weekdays, and therefore were subject to on-peak and off-peak prices for the tariff.

In the results, the optimizer shaped its utilization of pumps on the tariff to respond to the time-of-use incentives. If cost minimization is the primary objective, there is an opportunity to explore operational constraints and flexibility to understand when pumps are allowed to come online and offline. This may allow better response to the time-of-use rates and save on energy costs.

Comparison of Results Based on Operating Costs

Figure 12 created for this prototype dashboard compares how the system's cost and power efficiency vary over time.

These figures illustrate that, in the measured data, energy efficiency remained relatively flat, while the cost efficiency increased and decreased with the on-peak time-of-use rates. In contrast, the optimizer considered individual pump efficiency, as well as the tariff schedule, to determine the best way to minimize energy costs.

Optimization Scenarios

The prototype optimization model was also configured to minimize energy and maxi-

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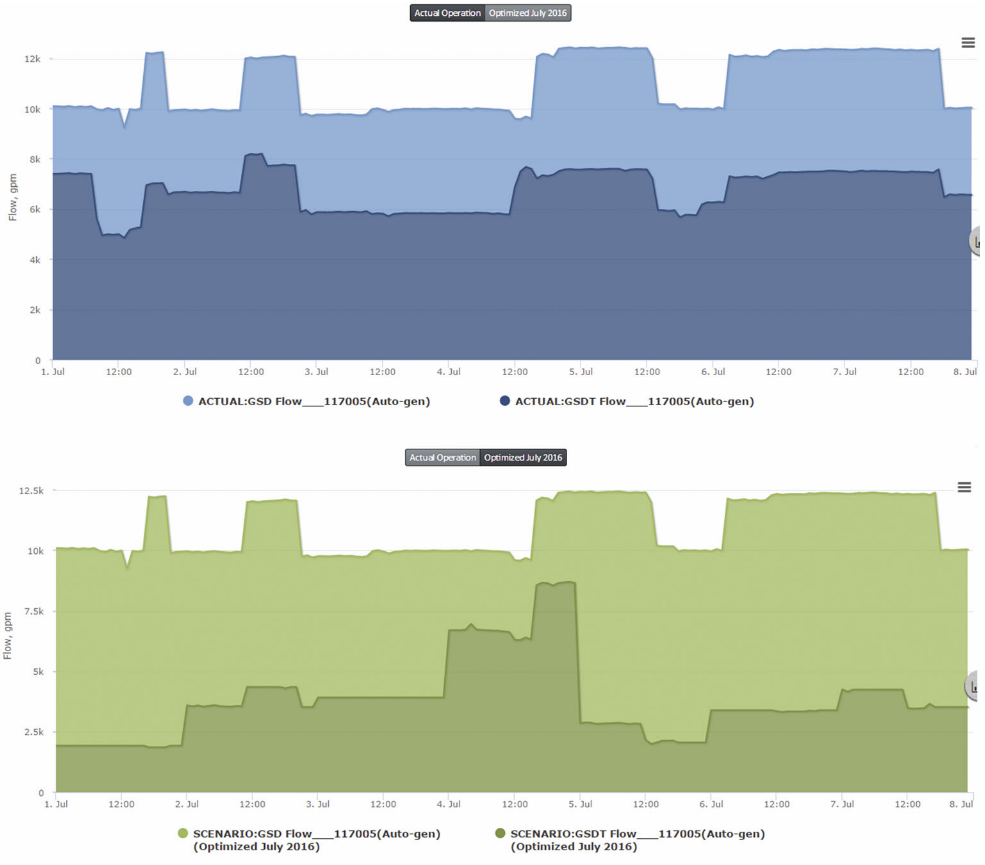

Figure 11. Illustration of Optimizer Decision Making Based on Different Electricity Tariffs

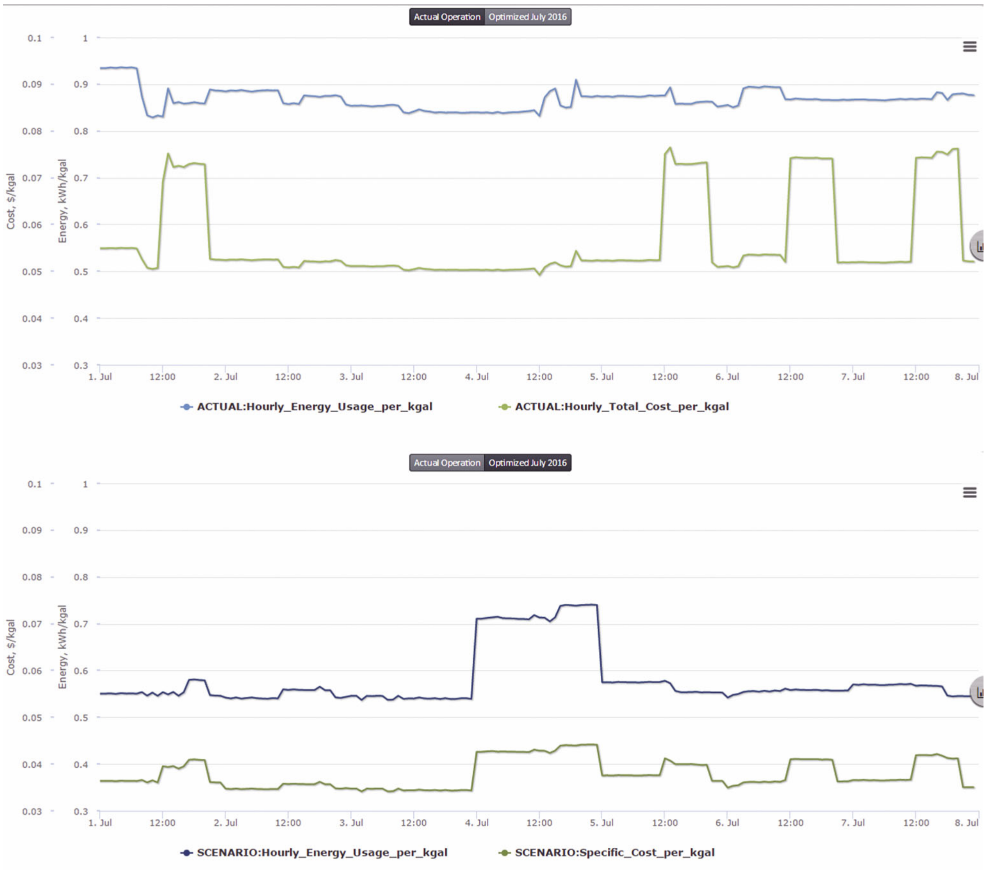

Figure 12. Comparison of System Cost and Power Efficiency Variance Over Time

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mize water quality. Figure 13 compares the actual operation with the three different optimization results.

The minimum energy scenario was very similar to the minimal cost scenario, and maximizing water quality yielded a different set of recommendations; when inspecting the KPI tiles across the top of the dashboard, the actual operation remains the highest cost. The minimum energy scenario (in green) is only slightly higher in cost than the minimum cost scenario (in gray). Specific capacity remained high for the minimum energy and minimum cost scenarios, but suffered in the maximum water quality scenario. For the final dispatch tool, it's likely that multiple objectives will be configured, weighted against one another, and applied in one multiple-objective optimization model.

Conclusion

The WUD's smart wellfields were developed in support of its mission to provide the "best water, best service, and best environmental stewardship" to its customers. This visionary concept also supports WUD's environment, infrastructure, and operational excellence initiatives intended to assist it in achieving the utopia of becoming a smart utility. ◆

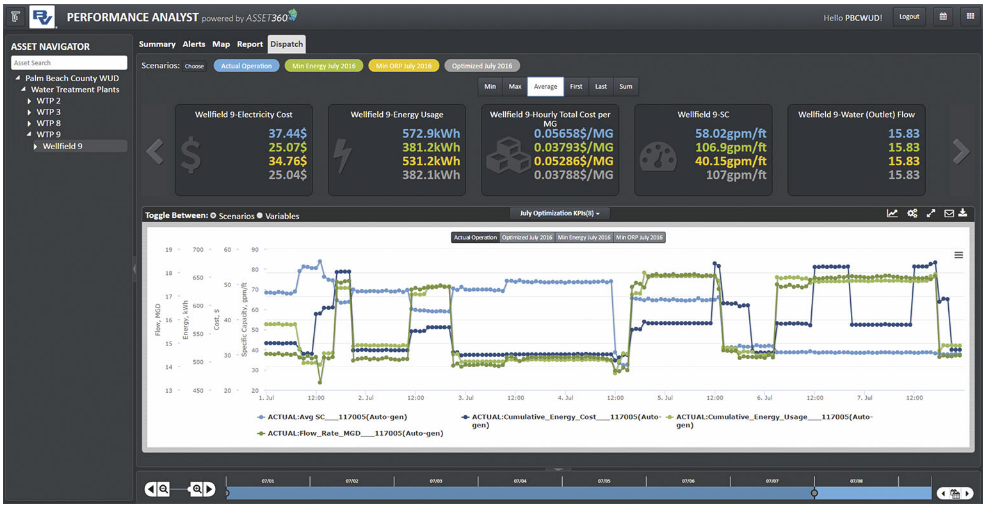

Figure 13. Comparison of Actual Operations With Three Different Optimization Results