Energy Research and Development Division
FINAL PROJECT REPORT

OPTIMIZATION OF ENERGY AND WATER QUALITY MANAGEMENT SYSTEMS FOR DRINKING WATER UTILITIES

Prepared for: Water Research Foundation and California Energy Commission
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MAY 2015
CEC-500-2015-088

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ACKNOWLEDGEMENTS

This project was funded by the Water Research Foundation (WRF) and the California Energy Commission. This study would not have been possible without the insights, efforts, and dedication of many individuals and organizations. These include the project advisory committee (PAC) members (as listed below), and the WRF and California Energy Commission project managers.

Project Managers:

- Linda Reekie, Water Research Foundation
- David Weightman, California Energy Commission

Project Advisory Committee:

- Joe Young
- Jack Jacobs
- Jeff Daniel
- Steve Conrad

The research team would like to thank the following agencies for their participation in the project:

- Eastern Municipal Water District, CA, USA
- East Bay Municipal Utility District, CA, USA
- El Paso Water Utilities, TX, USA
- Northumbrian Water Limited, U.K.
- Las Vegas Valley Water District, NV, USA
- Austin Water Utility, TX
- California-American Water Company, CA
- City of Aurora Utilities, CO
- City of Houston, Department of Public Works & Engineering, TX
- City of Lake Oswego, OR
- City of Riverside, CA
- Colorado Springs Utilities, CO
- Newport News Waterworks, VA
- North Texas Municipal Water District, TX

- San Antonio Water System, TX
- Tarrant Regional Water District, TX
- United Utilities, U.K.
- United Water, NJ

The authors would also like to thank the following individuals for their thoughtful contributions and support during the case study interviews and pilot operations: Joe Mouwad, Khos Ghaderi, Karen Evans, Becky Rathbone, and the Operations team from EMWD; Clifford Chan, David Beyer, Charmin Baaqee, and the Operations team from EBMUD. The authors are grateful to the following individuals for their contribution and input during the case study interviews: Manuel Perez and Victor Guzman from EPWU, Dennis Dellow from NWL, and Laura Jacobsen and Sri Kamojjala from LVVWD. The authors are also thankful to Bob Katin and the team of Katin Engineering Consulting for their contribution to the development of the project.

In conclusion, we would like to acknowledge the contribution of Dr. Paul Boulos of Innovyze and Phil Smith and Maria Chau of MWH

PREFACE

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Optimization of Energy And Water Quality Management Systems for Drinking Water Utilities is the final report for the Optimization Of Energy And Water Quality Management Systems For Drinking Water Utilities project (contract number 500-10-056) conducted by MWH Global. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

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ABSTRACT

The first pilot studies of integrated Energy and Water Quality Management Systems (system) were conducted in the early 1990s to simultaneously address water quality, water supply and energy management. Energy management focused on identifying strategies for energy peak load reduction and energy efficiency. The infrastructure of the system includes optimization software, hydraulic models, up-to-date supervisory control and data acquisition systems, and short term water demand forecasting tool(s). For utilities that installed these systems electricity cost savings of 5–20 percent were reported. These savings primarily resulted from operating pumps during cheaper tariff periods. Historically, these systems have been designed to minimize energy costs. Very little emphasis has been given to determine how the system could optimally reduce a combination of energy costs, energy consumption and greenhouse gas emissions. In this study, an existing system was modified so that the operations could be improved for any of the following scenarios: energy cost reduction optimization, maximum energy use reduction and greenhouse gas emissions reduction optimization. Researchers evaluated the modified system through offline simulations and pilot testing in two water utilities in California: the East Bay Municipal Utility District and Eastern Municipal Water Distric.

Both pilot test results indicate that the cost reduction optimization module significantly reduced energy costs and also reduced energy consumption and greenhouse gas emissions. Avoiding higher-priced tariff periods prevalent at daily peak electric demand periods and maximizing energy efficiencies achieved the cost reductions. This study suggests that to achieve the lowest greenhouse gas emissions, water utilities should focus primarily on energy efficiency. The study also suggests that a significant portion of the available greenhouse gas savings can be achieved by optimizing energy cost alone as a first step. Implementing electric load shifting and greenhouse gas emission management by using an energy water quality management system will benefit California ratepayers by lowering operational costs for water purveyors which will help stabilize rates, and peak demand reduction will contribute to the reliability of California's the electrical grid system.

Keywords: EWQMS, drinking water, energy efficiency, greenhouse gas emissions, cost optimization, water quality, demand forecasting

Please use the following citation for this report:

Badruzzaman, Mohammad, Carla Cherchi, Joan Oppenheimer, Christopher Bros, Matthew Gordon, Simon Bunn, Vessie Pencheva, Christophe Jay, Iyad Darcazalllie, Joseph G. Jacangelo. (2015). ***Optimization of Energy and Water Quality Management Systems for Drinking Water Utilities.*** Water Research Foundation and California Energy Commission. Publication number: CEC-500-2015-088.

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EXECUTIVE SUMMARY

Introduction

In the early 1990s, integrated energy and water quality management systems (EWQMS) were first introduced in pilot studies to provide drinking water utilities with a control management tool to cohesively address water quality and supply and also energy management within facility operational constraints such as water quality objectives, permits, regulations, and the maintenance of system hydraulic equilibrium (Jentgen et al., 2003). Using EWQMS, best practices for reducing energy use and costs are simultaneously implemented within the boundaries of water quality requirements and operating rules on a real-time basis. The system controls the pumping within water treatment steps through a collection of individual application software programs, which are user-developed or commercially available. An energy and water quality management system provides effective risk management for maintenance of water quality objectives and favorable cost–benefit solutions for energy. A EWQMS can produce tangible and intangible benefits, including cost savings (e.g., savings through energy consumption reduction), cost avoidance (e.g., demand charge avoidance), revenue based on electric utility financial incentives provided to demand response program participation), and intangible benefits (e.g., improved uniformity of operations). Although, historically, an EWQMS has been designed to maintain a proper relationship between managing water quality and reducing energy costs, very little emphasis has been given to identify how minimizing costs could reduce energy consumption as well. In addition, existing energy and water quality management systems do not include options to prioritize the reduction of kilowatt-hours (kWh) and greenhouse gas (GHG) emissions; essentially, overall accounting of GHG emissions is lacking. The relationship between reducing energy use and related costs has not been studied, particularly for utilities, such as those in California, where high differential tariffs result from time-of-use (TOU) electric rate structures. Therefore, it is paramount that the energy and water quality management system enables water utilities to consider operational options to identify the tradeoffs among energy management for cost reduction, carbon footprint reduction, and distribution system water quality.

Project Purpose

This study reviewed the current state of knowledge on the energy and water quality management system configurations, projects and practices and expands the existing configuration to include a GHG emissions module to address the nexus between energy cost management, energy and GHG emissions reduction, and system water quality. The specific objectives of this study were to:

- Integrate and assess the current state of knowledge on the existing energy and water quality management systems through review of projects and practices.
- Modify the energy and water quality management system to include and evaluate a GHG emissions reduction algorithm module and understand the tradeoffs between cost savings and GHG emissions reduction through pilot testing.

- Assess the benefits and challenges encountered by water utilities while implementing and operating energy and water quality management systems and identify recommended best practices.
- Understand the elements necessary to develop a business case for implementing an energy and water quality management system at drinking water utilities.
- Identify the knowledge gaps and future research needs for more effective energy and water quality management system practices.

Project Approach

The research team conducted the following tasks:

- *Literature Review*. Researchers reviewed literature to understand the progression and development of water quality control and energy management strategies at drinking water facilities. The research team collected relevant literature, including peer-reviewed publications, research reports, white papers, technical conference proceedings, software developer fact sheets, and case studies.
- *Utility Case Study*. The research team developed and distributed a survey questionnaire followed by an interview of individuals from five drinking water utilities with varied responsibilities (for example, operations, engineering, and management). Four water utilities are the United States and one is the United Kingdom. Information was collected to better understand the planning, design, implementation and operational aspects of energy and water quality management systems. Specific research data was collected from Eastern Municipal Water District (EMWD), Perris in Riverside County California, East Bay Municipal Utility District (EBMUD) in Oakland, El Paso Water Utilities (EPWU) in El Paso, Texas; the Las Vegas Valley Water District (LVVWD) in Las Vegas, Nevada and Northumbrian Water Limited (NWL) in the United Kingdom.
- *GHG Module Development and Integration*. The research team developed the functional specifications of the GHG module and evaluated it within the existing energy and water quality management system software.
- *Optimization (largest reduction) Scenario Selection*. The research team considered three optimization scenarios (cost optimization, electrical energy use optimization and GHG optimization) during the offline evaluations and pilot operations. The descriptions of these scenarios are provided in Table ES.1. The analysis compared historical manual (baseline) operation data with the optimization objectives of cost reduction, kilowatt hour (kWh) reduction, and GHG reduction.
- *Offline Simulation for System Performance and Water Quality Impact Predictions*. The research team performed a series of off-line simulations on specific portions of the distribution networks in selected pilot areas at two EBMUD and EMWD facilities in California prior to real-time piloting to define the best pumping schedule to simulate as a baseline comparison with the GHG module optimization scenarios, which included financial costs savings, GHG emission reduction and energy efficient operations.

- *GHG Module Assessment*: During real-time operations, an EWQMS modified with an added GHG emissions reductions optimization module was pilot tested at EBMUD and EMWD and the test results were compared with the historical data and those obtained from the offline simulation.

Table ES.1: Description of the Optimization Scenarios

Optimization Scenario	Description
Baseline	**Primary principle:** System under no EWQMS operation (manual control by operators)
Cost Optimization	**Primary principle:** Pump operated when the cost is minimum (selection order: off-peak, mid-peak, on-peak) **Secondary principle:** Pump operated at the lowest specific energy (kWh/MG pumped)
kWh Optimization	**Primary principle:** Pump operated at the lowest specific energy (kWh/MG pumped) **Secondary principle:** Assumes flat tariff operations *Note: KWh optimization is the GHG optimization when flat GHG emission factors are used*
GHG Optimization	**Primary principle:** Pump operated when the GHG emission factor (lbs-CO_2/MWh) is minimum **Secondary principle:** Pump operated at the lowest specific energy (kWh/MG pumped) *Note: Assumes that GHG emission factors vary depending on the energy sources*

Project Results

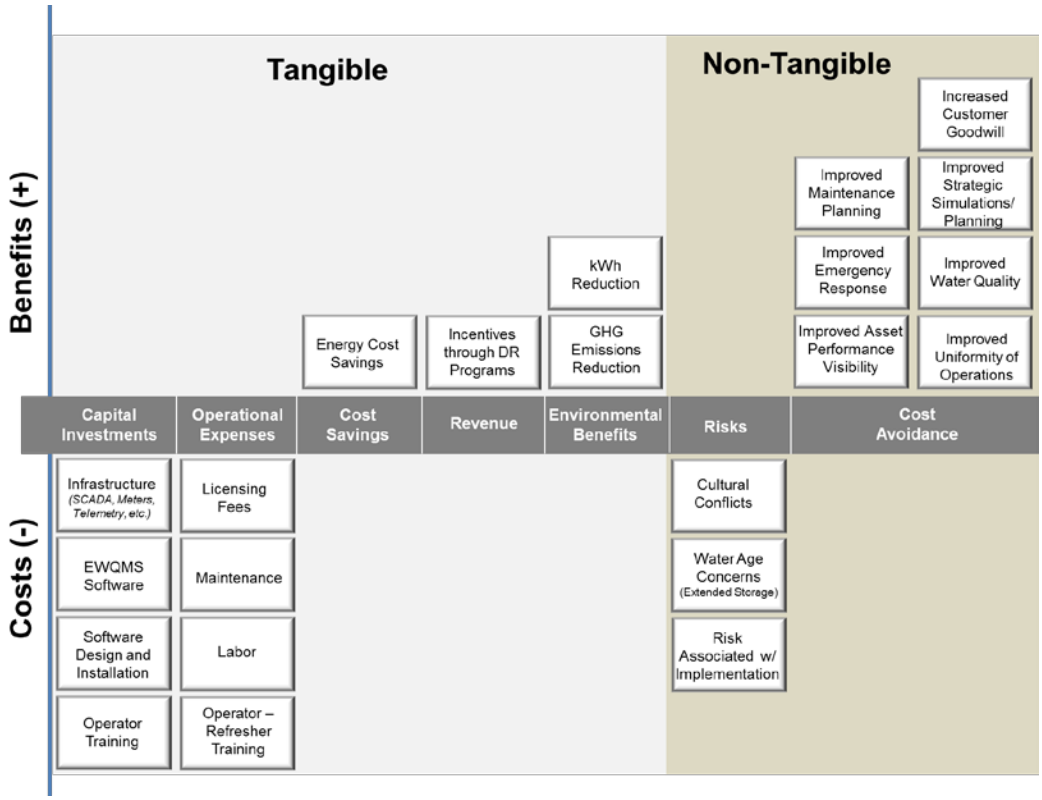
Key Findings From Literature Review and Case Studies

- About 20 water utilities worldwide have installed an energy and water quality management system at their facilities, seeking to minimize energy costs with respect to water quality goals and daily operational rules. Both commercial software and in-house solutions have been developed to enable EWQMS operations. Utilities need to have an energy and water quality management system, software package, an upgraded supervisory control and data acquisition system, in-house modeling capabilities, remote control equipment, interfacing between the different software packages, sufficient storage tanks or reservoirs, and dedicated skilled staff for EWQMS implementation and operation. The estimated project costs for EWQMS design and implementation (in other words, software license, implementation, configuration and personnel training) may

vary depending on the utility size and complexity of the system (for example, $0.75 million at EBMUD, $1.87 million at EMWD, $1.3 million at EPWU, and $3.75 million at NWL).

- Cost savings using an energy and water quality management system vary annually and are utility-dependent. For utilities with an energy and water quality management system, operating electricity cost savings of 5 percent–20 percent have been reported due to higher use of cheaper tariff periods and better operating efficiencies, resulting in an approximate reduction in energy consumption of 6 percent–15 percent (with potential simultaneous carbon emission reduction). In addition to these economic and environmental benefits, utilities with installed energy and water quality management systems have opportunities to better manage their water supply portfolios and simulate the impact of water demand patterns and energy market profiles on the utility water resources management for decision-making and planning. A conceptual cost-benefit analysis of implementing EWQMS is presented in Figure ES.1.

Figure ES.1: Conceptual Cost-Benefit Analysis of an EWQMS



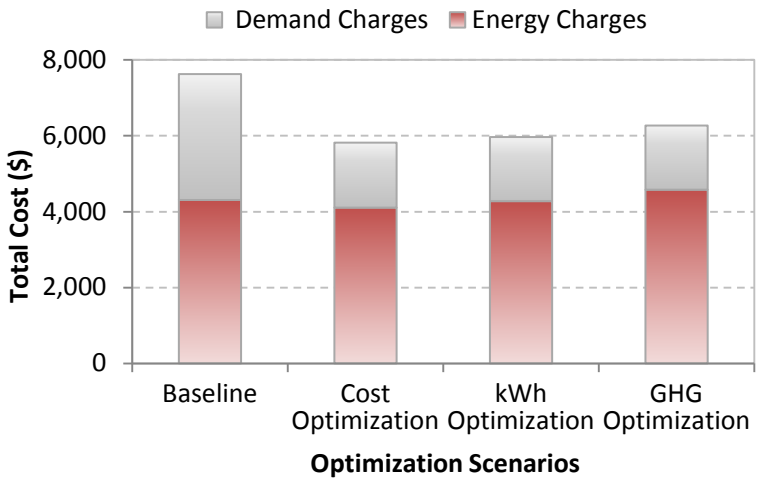
Source: MWH and Dercerto: the project Research Team

Key Findings from the Pilot Studies

The research team evaluated the energy and water quality management system modified with a GHG module through off-line and on-line evaluations at two pilot sites. The key findings are presented below:

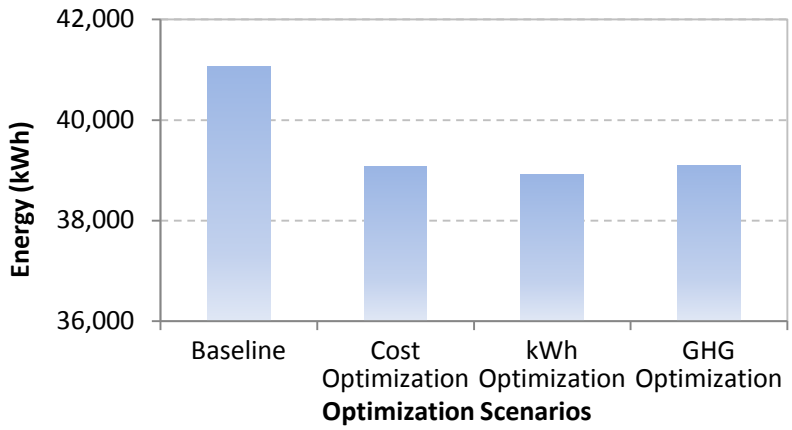
- In the pilots conducted at EMWD and EBMUD facilities, the cost optimization significantly reduced overall costs and reduced kWh and GHG consumption, even though these were not the prime goal of the optimization. The optimizer targeted both kWh and GHG minimization by avoiding higher priced tariff periods and minimizing energy consumption as both of these strategies lead to cost reductions.
- At EBMUD, optimizing for cost significantly reduced the cost associated with pumping if compared to the other optimization scenarios analyzed, with an overall 23.7 percent cost reduction over the baseline (Figure ES.2). Under the same optimization a 4.8 percent decrease in energy consumption and a consequential lowering of GHG emissions was observed compared to the baseline.

Figure ES.2: Biweekly Energy Costs and Demand Charges Associated With All Pump Stations of the EBMUD Pilot System Optimized for Cost, kWh, and GHG Minimization



- At EBMUD, the kWh optimization strategy was successfully able to find the lowest energy use operation for both pilot sites. The kWh optimization generated the lowest demand charge cost due to a more efficient pump operation (that is, using the lowest peak power [kW]), which also translated into an overall 21.8 percent cost reduction compared to the baseline value. In addition, it achieved a 5.3 percent reduction in energy usage and GHG emissions (Figure ES.3).

Figure ES.3: Biweekly Energy Consumption Associated with All Pump Stations of the EBMUD Pilot System Optimized for Cost, kWh, and GHG minimization



- At EMWD, optimizing for cost reduced the cost associated with pumping if compared to the other optimization scenarios analyzed, with an overall 7.8 percent cost reduction over the baseline (Figure ES.4). Under the same optimization a 2.9 percent decrease in energy consumption, thus also of GHG emissions, was observed compared to the baseline (Figure ES.5).

Figure ES.4: Biweekly Energy Costs and Demand Charges Associated with All Pump Stations of the EMWD Pilot System Optimized for Cost, kWh, and GHG Minimization

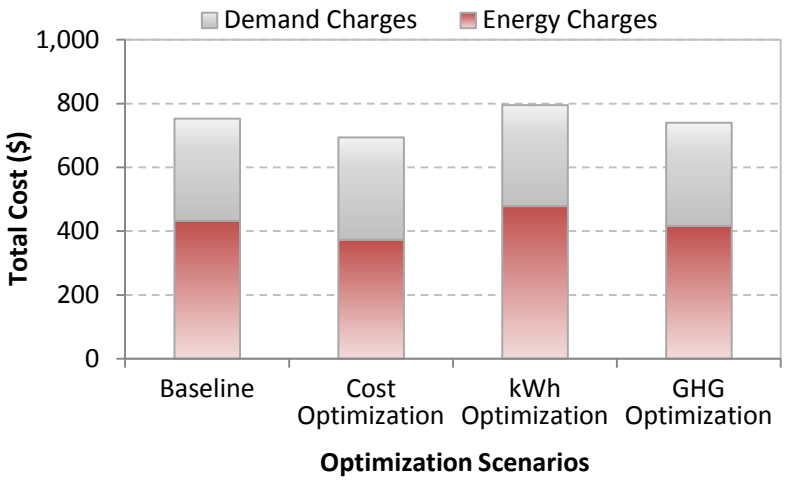
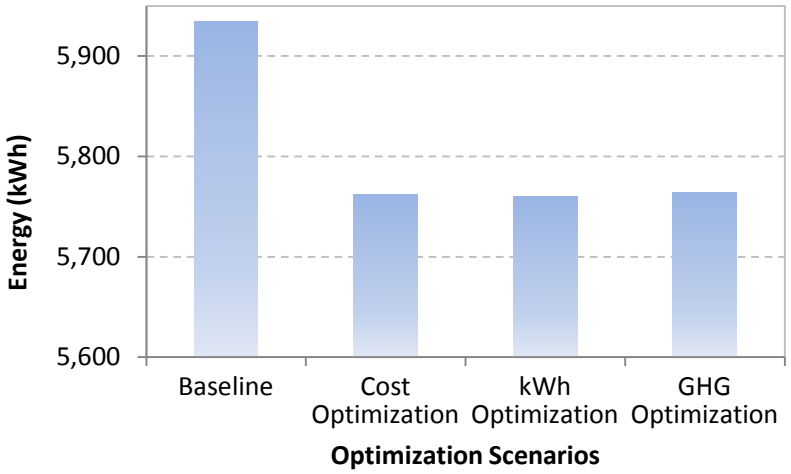


Figure ES.5: Biweekly Energy Consumption Associated with All Pump Stations of the EMWD Pilot System Optimized for Cost, kWh, and GHG minimization



- Offline simulations can be an effective tool for predicting the outcome of real-time operation for different optimization scenarios with different goals. The optimization involved using software to examine simulated results with different data inputs. When targeting cost savings, the online EBMUD simulations produced savings that were similar to the offline scenario predictions and actually reduced energy usage more than predicted by the offline scenario. The offline scenarios demonstrated that a pure kWh optimization approach could be more expensive than the cost optimization as it allowed pumps to operate when both peak kWh tariffs and peak kW demand charges applied (Table ES.2). However, the online scenarios showed that, at EBMUD with some pre-optimization rules that avoid peak tariff period pumping and with adequate storage availability, it was possible to optimize operations only during mid- and off-peak periods to achieve kWh/GHG optimization and still obtain cost savings similar to the cost optimization approach. From the utility's perspective when operating to minimize kWh or GHG emissions, some sacrifice of GHG emission optimization may be desirable to avoid peak period operation and, thereby, to minimize the effect on overall energy cost savings.

Table ES.2: Comparison Between the Baseline and the Offline Simulations and Pilot Operation Results at EBMUD[1]

Optimization Scenario	Cost (% reduction)		Energy (% reduction)		GHG (% reduction)	
	Offline Simulations[2]	Pilot[3]	Offline Simulations[2]	Pilot[3]	Offline Simulations[2]	Pilot[3]
Cost Optimization	25.3%	23.7%	-0.4%	4.8%	-0.4%	4.8%
kWh Optimization	-22.3%	21.8%[4]	6.1%	5.3%	6.1%	5.3%
GHG Optimization	-0.9%	17.8%[4]	3.3%	4.8%	3.3%	4.8%

[1] "-"indicates increase in value relative to baseline.

[2] Percentage based on the baseline selected for offline simulations

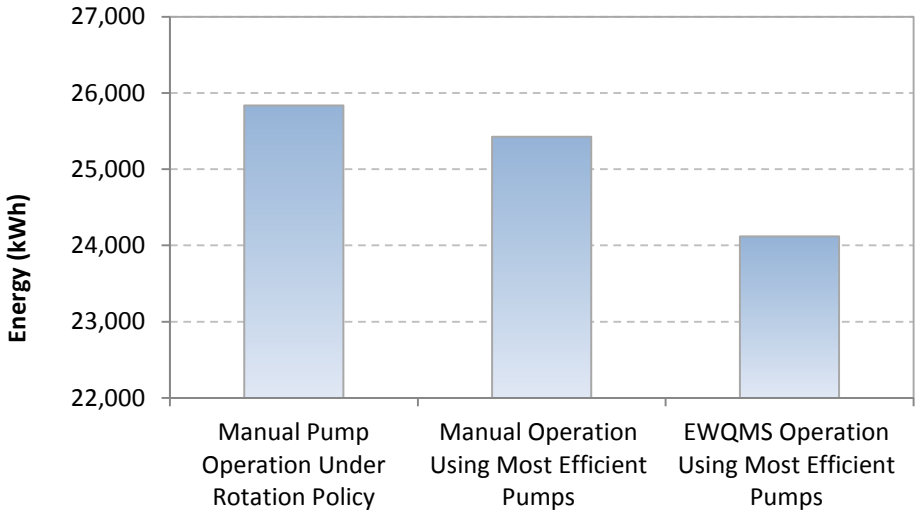
[3] Percentage based on the baseline selected for pilot operations

[4] High differences from offline simulation since pumps were not operated during the peak tariff period for the kWh and the GHG optimization scenarios

- This study suggests that there may be a clear trade-off between energy reduction and costs. According to the EBMUD pilot results, by implementing cost optimization, the pumping energy consumption could be decreased from 590 to 561 kWh/million gallons (MG) with corresponding cost reduction from $110 to $84 per MG. By implementing energy optimization, an additional 3 kWh/MG reduction was achieved (from 561 to 558 kWh/MG) but with an additional cost of $2/MG. On the other hand, the EMWD pilot results suggest that simultaneous reduction of pumping energy consumption (from 609 to 591 kWh/MG) and cost reduction (from $77 to $71 per MG) was possible by implementing cost optimization. By implementing purely energy optimization, no additional energy reductions were achieved over cost optimization but resulted in a cost increase of $11/MG. It is important that water utilities conduct independent studies to evaluate the significance of this trade-off for their operations.
- The GHG optimization generated higher GHG emissions than the kWh optimization scenario. The explanation for this observation lies on the understanding of the optimization principles presented in Table ES.1. The GHG optimization is based on the assumption that emission factors vary throughout the day. Under this optimization, the operational goal was to run the pumps when the emission factors were minimal, regardless of the energy consumption. Thus, unlike kWh optimization, the GHG optimization was not the lowest energy operation and required more energy compared to the kWh optimization. Therefore, the GHG optimization produced higher emissions compared to kWh optimization. Based on these results, the data suggest that water utilities should just focus on kWh optimization to achieve the lowest GHG operation until the variability of GHG emission factors for specific water utility are well established by the electric utilities.
- Typically, water utilities select pumps based on a rotation strategy that evenly rotates all the pumps within a pumping station. At EBMUD, the pump stations (Blackhawk, Blackhawk East and Acorn) used to rotate three pumps based on balanced run hours.

The pilot testing was conducted to determine the benefits available from selecting the most efficient pumps within each station, rather than using a rotation policy to evenly spread run time over all pumps. The results indicate that there may be near term cost and energy benefits if the pumps are selected based on efficiency instead of the rotation policy (run hours). For instance, when the cost optimization was conducted with an EWQMS system and an efficiency-based rotation policy (selecting the most efficient pump), about 1.8 percent additional energy consumption reduction was possible on top of the energy savings observed by the manually operated run-time based pump rotation policy (Figure ES.7). Extrapolating the results to all pump stations in the East of Hills region, resulted in a cost savings of $50,400 on an annual bill of $2.8 million. When the EWQMS was allowed to select which pump to operate, it improved efficiency by an additional 1.8 percent taking it from the 4.8 percent improvement achieved to the new total of 6.6 percent. This analysis demonstrates that there is potential for improvement. The savings associated with the efficiency-based pump selection may not appear to be substantial; however, this finding provides an indication that in-depth analysis of efficiency-based pump selection is warranted during implementing an EWQMS. Additional research should be performed to confirm whether such cost savings can be observed in other pumping stations. The impact of other factors such as reliability (having all pumps in similar condition) and maintenance cost (including pump refurbishment) to keep pumps efficient should be incorporated in more detailed cost-benefit analysis of pump selection.

Figure ES.7: Energy consumption associated with various operating conditions during the pump prioritization test at EBMUD pilot



- EWQMS operations may have the potential to negatively influence water quality across water supply networks by decreasing turnover in tanks or by changing the way customers receive water (direct pumped versus gravity supply). This has been recognized by EWQMS

operators and strategies such as deep cycling or pulse flow operation have been used to overcome such deficiencies. The strategies are typically implemented as operating rules rather than optimization objectives. The impacts of the optimization scenarios on the distribution system water quality were evaluated based on water age simulations through offline hydraulic modeling and on residual chlorine monitoring during online operations. The results indicate that the overall impact on the water quality when running the optimizer was slight or not detectable. This study did not observe any adverse water quality effects of pump schedule optimization, either for minimization of cost, energy or GHG. However, some evidence of increased water age and stratification was observed in the EBMUD study. Due to the short pilot study periods, changing demand, and seasonal temperature differences between each mode of operation, it was not possible to attribute these factors directly to any results of the optimized operations.

Recommendations

Major recommendations for future research on the implementation of EWQMS are presented below:

- The current version of EWQMS is complex and can provide an attractive payback (less than three years) on investment only for utilities with large annual electricity bills ($2 Million and higher). Thus, simplified EWQMS suitable for small utilities needs to be developed for a wider application of the energy and water management framework. Future research should develop and conduct pilot testing of the simplified EWQMS.

- The emission factors commonly employed in calculating the carbon footprint of water supply systems are regional and are typically expressed as a flat rate in pounds of carbon dioxide per kilowatt hour of electricity (lbs-CO2-e/kWh) regardless of time of use. Average emissions rates vary by season, but do not vary substantially between on- and off-peak hours. In contrast, marginal emissions rates (i.e., those of the last generator to enter the energy market) vary between on-and off-peak hours, but do not vary substantially by season. Thus, real-time GHG emissions profiles should be further defined.

- Current EWQMS do not include chemical water quality parameters (e.g., chlorine residual) in the objective function or as constraints in the optimization algorithms. Water quality issues are generally addressed by using explicit hydraulic operating rules, such as cascade pumping, reservoir operating levels, deep cycling and pulse flow, to influence retention times within the distribution system and in tanks. Actual system compliance with regulatory standards is then monitored. This is a pragmatic approach. Existing hydraulic models (e.g., IWLive) has the capability for real-time chlorine modelling; however, models are difficult to calibrate and the calibration goes out of range as raw water quality changes. Future research is needed to demonstrate whether simultaneous energy and water quality optimization, based on chemical water quality parameters (not only water age), could be included in the objective function of the EWQMS.

- An important challenge of implementing EWQMS is the conflict in organizational culture acceptability. For instance, "operators" and "engineers," have different perceptions about system control, often giving rise to conflicting evaluations of the benefits of an EWQMS. Thus, cultural differences between operators and engineers need to be addressed for widespread application of EWQMS. Future research should develop key performance indicators (KPIs) for operators so that they are encouraged and rewarded for achieving simultaneous water quality management and energy cost and use reductions.
- Further research is needed to understand how an EWQMS may assist in the development of joint programs between the energy and water sectors, which could result in adoption of energy efficiency strategies, increasing savings of both energy and water resources, and permit the financial burdens to be shared between the two sectors. Power utility incentive programs and benefit allocations can be developed to support Permanent Load Shifting (PLS) solutions that would be beneficial for both water and electric utilities.
- Water utilities are often impacted by watershed events (e.g., drought/rain cycles which impact source water portfolios), national and/or regional regulations (e.g., water quality, air quality issues), budgetary constraints, and electric utility tariff structure changes that force them to make major operational changes from year to year. Further research is needed to document the long-term performance and operation using EWQMS with constant, controlled operating conditions, instead of the unexpected variable conditions often encountered during water utility operations (e.g., raw water source quality, demand, energy tariff structure, etc.).

CHAPTER 1: Introduction

1.1 Background

Climate change is of great concern to the water community because it can adversely alter the quantity and quality of source water available within a localized service area. Further, over the past several decades, water organizations have been challenged by new stringent environmental regulatory requirements, dwindling traditional water supply sources and increasing energy costs and demand. Water utilities have become increasingly energy intensive and responsible for an approximate 3% share of United States (U.S.) annual electricity consumption (Boulos and Bros, 2010; U.S. Environmental Protection Agency [EPA], 2012; Sanders and Webber, 2012). Future projections estimate this percentage to double to 6% due to higher water demand and more energy intensive treatment processes (Chaudhry and Shrier, 2010). In states where water is moved across large distances and elevations, this energy usage can become substantially higher. For example, in California, the water-related energy use accounts for 7.7% of the state's energy usage (GEI, 2010).

Estimates indicate that approximately 90% of the electricity purchased by U.S. water utilities, $10 billion per year, is required for pumping water through the various stages of extraction, treatment, and final distribution to consumers (Bunn, 2011; Skeens et al., 2009). Another study showed that pumping is responsible for approximately 99% of the electricity use at groundwater source plants and 91% at surface water source plants (Carlson and Walburger, 2007). Groundwater facilities were observed to use approximately 1.3% more energy per gallon of water produced than surface water utilities. The energy intensities reported for various water cycle segments range from 0-14,000 kWh/MG for water supply and conveyance, 100-16,000 kWh/MG for water treatment, and 250-1,200 kWh/MG for water distribution (McGuckin et al., 2012). These quantities translate to a range of energy intensities for the entirety of municipal water supplies from 350-31,200 kWh/MG. Electricity consumption at Massachusetts water treatment and distribution facilities was estimated at 1,500 kWh/MG (U.S. EPA, 2008). In the state of New York, the energy consumption at drinking water facilities ranges from 600-1,080 kWh/MG (New Yok State Energy Research and Development Authority [NYSERDA], 2008). In a typical drinking water facility more than 90% of GHG emissions can be due to electricity usage. The energy use, with the exclusion of energy use for water heating by residential and commercial users, contributes significantly to an increasing carbon footprint with an estimated 45 million tons of GHG emitted annually by drinking water utilities in the U.S. into the atmosphere (Griffiths-Sattenspiel and Wilson, 2009; Wallis et al., 2008).

Regional and national regulations have been promulgated in the U.S. and other parts of the world to achieve GHG emissions reduction. The California Air Resources Board (CARB) has designed a cap-and-trade program that is enforceable and meets the requirements of AB 32 (CARB, 2012). The program started on January 1, 2012, with an enforceable compliance obligation beginning with 2013 GHG emissions. A cap-and trade program is a policy tool to more efficiently control the amount of GHG emissions than a source-by-source, categorical

regulatory approach. The reduction in emissions is achieved by placing a cap on the amount of emissions and reducing that cap amount over time. These limits are coupled with corresponding allowances given to individual sources of emissions. In a cap-and trade scenario, when an emissions source does not emit as much GHG as its allowance, the source can trade the excess allowance to a different emission source. The California cap-and trade program is expected to cover 85 percent of the state's GHG emissions. Water utilities may be able to take advantage of cap and trade by reducing emissions and selling the created allowances on the trading market. When a utility reduces its GHG output, the resulting allowance has a monetary value associated with it. Utilities might capitalize on the worth of these assets by selling them to other emitters on the trading market. Although water utilities are currently not qualified to participate in the cap and trade program, any change in future regulation may result in revenue streams that could potentially be used to finance capital improvements, reduce utility rates, or for any other purpose the utility deems appropriate. Thus, this research project is critical to providing a more perspicuous understanding of the opportunities available for water utilities to reduce energy consumption and GHG emissions.

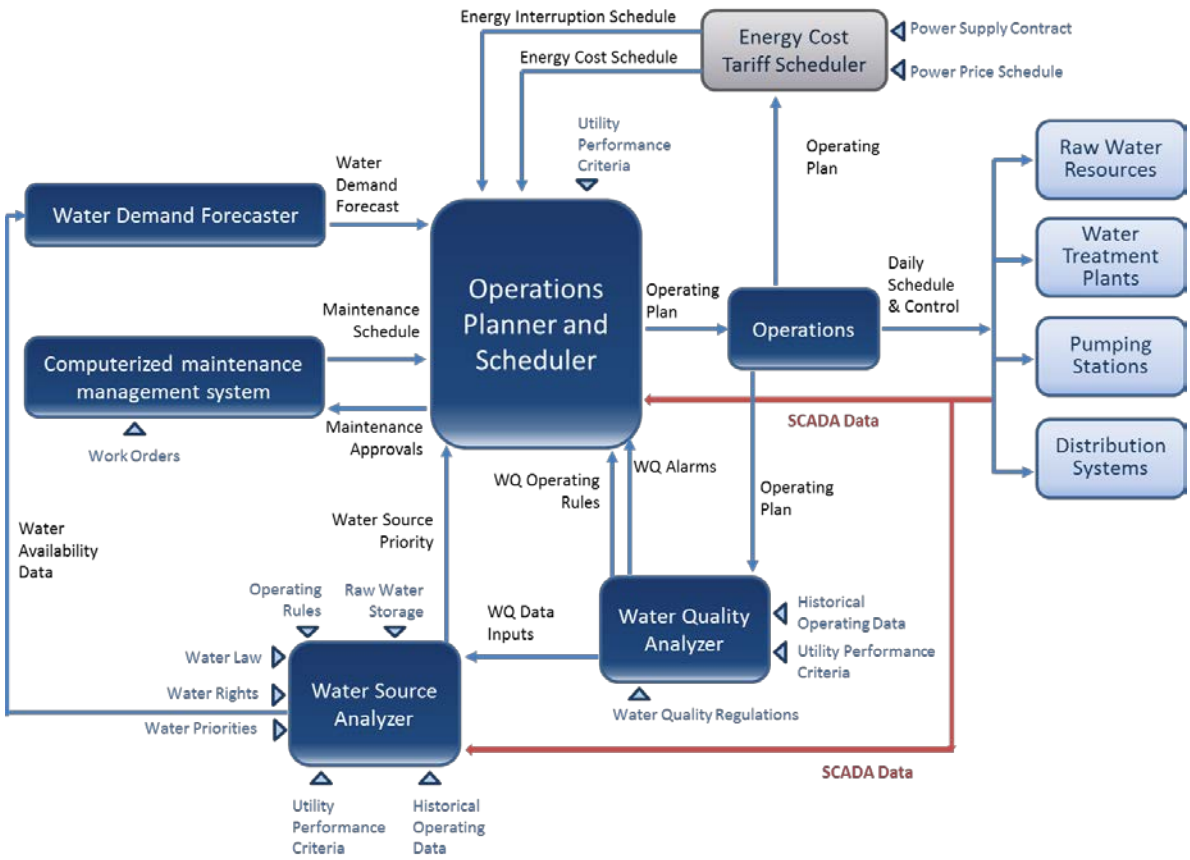
In anticipation of federal and state legislation that may impact future GHG emissions from drinking water facilities and due to increasing energy costs, energy management practices are becoming an integral part of effective water utility management. Energy management in a water utility cannot be implemented without meeting the water quality goals, even if focusing on GHG emissions reduction. In the early 1990s, the framework of an integrated EWQMS was introduced to provide drinking water utilities with the foundation for a system control management tool to cohesively address water quality, supply and energy management within operational constraints (Jentgen et al., 2003). In EWQMS, best efficiency practices for energy and cost reduction are simultaneously implemented within the boundaries of water quality requirements and operating rules on a real-time basis. An EWQMS controls the water system through a collection of individual application software programs, which are user-developed or commercially available. A conceptual schematic of the EWQMS is presented in Figure 1.1. The programs interface with the existing Supervisory Control and Data Acquisition (SCADA) to schedule the shifting of electrical loads to lower cost tariff periods, reduce peak electric demand charges, achieve efficiency gains, and reduce water age to improve water quality. Real-time communications with pre-existing SCADA systems allow the EWQMS software to monitor and proactively provide recommendations or direct control regarding system operation (e.g., pumping, storage tank turnover, etc.) based on time-of-day electrical consumption and associated tariffs and forecasted short-term water demand (Barnett et al., 2004).

To date, approximately twenty drinking water utilities worldwide have installed the EWQMS architecture at their facilities, confirming an increasing interest in EWQMS as energy prices and demand continue to increase. To date, there is no comprehensive document summarizing these EWQMS projects and only sparse and fragmented documentation exists. In addition, EWQMS operational practices, benefits and implementation challenges, and lessons learned within the water industry are lacking.

EWQMS provides effective cost-benefit solutions and risk management for maintenance of water quality objectives. An EWQMS, in fact, produces tangible and intangible benefits,

including cost savings (e.g., savings through energy consumption reduction), cost avoidance (e.g., demand charge avoidance), revenue increase (e.g., electric utility incentive through demand response program), and intangible benefits (e.g., improved uniformity of operations). Although, historically an EWQMS has been designed to maintain a proper relationship between water quality management and energy cost minimization, very little emphasis has been given to identify how cost optimization could result in energy consumption reduction as well. In addition, existing EWQMS do not include operational options to prioritize the reduction of kilowatt-hours and GHG emissions and overall accounting of GHG emissions is lacking. Energy optimization, in fact, does not necessarily directly relate to cost optimization, particularly for utilities, such as those in California, where high differential tariffs result from TOU electric rate structures. Therefore, it is of paramount importance that the EWQMS enables water utilities to consider operational options to reduce GHG emissions and identify the tradeoffs between energy management for cost reduction, energy and carbon footprint reduction, and distribution system water quality.

Figure 1.1: Conceptual schematic of a EWQMS module



Source: Adapted from Jentgen et al., 2003, Derceto, 2013.

1.2 Objectives

This research study reviews the current state of knowledge on EWQMS framework, projects and practice and expands the existing framework to include a GHG emissions module in order to address the nexus between energy cost management, energy and GHG emissions reduction, and system water quality. The specific objectives of this study are to: • Synthesize and assess the current state of knowledge on the existing EWQMS through review of projects and practices;

- Modify EWQMS with a GHG module and understand the tradeoffs between cost savings and GHG emissions reduction through pilot testing;
- Assess the benefits and challenges encountered by water utilities during implementation and operation of an EWQMS and identify recommended best practices;
- Understand the elements necessary to develop a business case for EWQMS implementation at drinking water utilities; and
- Identify the knowledge gaps and future research needs for more effective EWQMS practices.

This work has been conducted through different tasks:

- *Literature Review*. A literature review was conducted to obtain a critical understanding of the development and practice of water quality and energy management optimization at water facilities. Relevant literature was collected and included peer-reviewed publications, research reports, whitepapers, technical conference proceedings, software developer fact sheets, and case studies;
- *Utility Case Study*. A survey questionnaire followed by interview with individuals from various levels of the organization (e.g., operations, engineering, and management) was developed and distributed to four water utilities in the U.S. and one in the U.K. to collect information on the planning, design, implementation and operational aspects of an EWQMS project. The utilities selected as case studies were Eastern Municipal Water District (EMWD), East Bay Municipal Utility District (EBMUD), El Paso Water Utilities (EPWU), Las Vegas Valley Water District (LVVWD) and U.K.- based Northumbrian Water Limited (NWL);
- *GHG Module Development and Integration*. The functional specifications of the GHG module were developed and the module was evaluated within the existing EWQMS software product.
- *Offline Simulation for System Performance and Water Quality Impact Predictions*. A series of off-line simulations on specific portions of the distribution network in selected pilot areas at EBMUD and EMWD in California were performed prior to piloting to define the optimal pumping schedule to simulate as a baseline comparison with the GHG module various optimization scenarios, which included financial costs savings, GHG emission reduction and efficient operations.

- *GHG Module Assessment through Pilot*. Assessment of the integrated EWQMS modified with a GHG module was performed through pilot testing at EBMUD and EMWD and the results compared with the historical data and those obtained with the offline simulations.

1.3 Organization of the Report

This report guidebook is organized into the following chapters:

- Chapter 1: Introduction;
- Chapter 2: Fundamental Concept of EWQMS;
- Chapter 3: Research Approach for Evaluation of an EWQMS Modified with a GHG Module;
- Chapter 4: Implementation of EWQMS Modified with a GHG Module at Eastern Municipal Water District;
- Chapter 5: Implementation of EWQMS Modified with a GHG Module at East Bay Municipal Utility District;
- Chapter 6: EWQMS Implementation Guidance at Water Utilities;
- Chapter 7: Conclusions and Recommendations.

CHAPTER 2: Introduction

2.1 Background

Climate change is of great concern to the water community because it can adversely alter the quantity and quality of source water available within a localized service area. Further, over the past several decades, water organizations have been challenged by new stringent environmental regulatory requirements, dwindling traditional water supply sources and increasing energy costs and demand. Water utilities have become increasingly energy intensive and responsible for an approximate 3 percent share of annual electricity consumption in the U.S. (Boulos and Bros, 2010; U.S. EPA, 2012; Sanders and Webber, 2012). Future projections estimate this percentage to double to 6 percent due to higher water demand and more energy intensive treatment processes (Chaudhry and Shrier, 2010). In states where water is moved across large distances and elevations, this energy usage can become substantially higher. For example, in California, the water-related energy use accounts for 7.7 percent of the state's energy usage (GEI, 2010).

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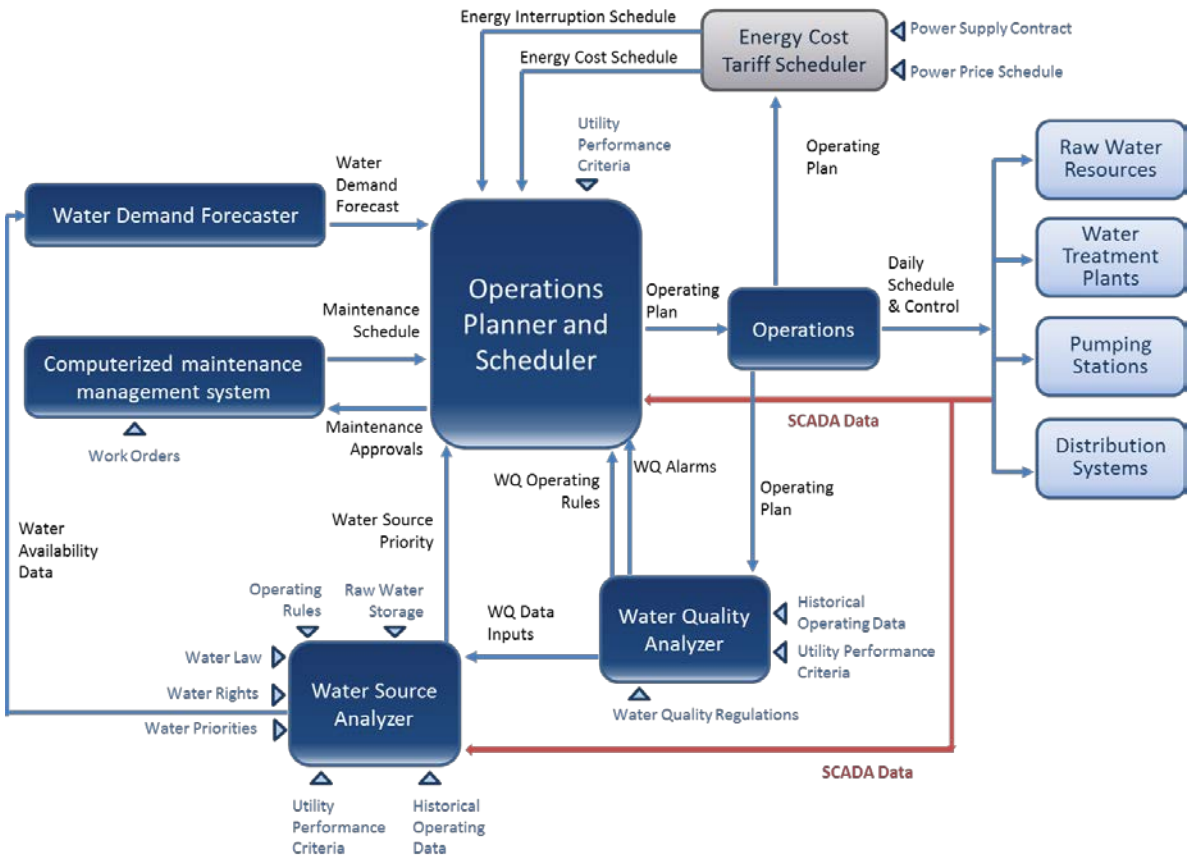

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- *Utility Case Study*. A survey questionnaire followed by interview with individuals from various levels of the organization (e.g., operations, engineering, and management) was developed and distributed to four water utilities in the U.S. and one in the U.K. to collect information on the planning, design, implementation and operational aspects of an EWQMS project. The utilities selected as case studies were EMWDEBMUD, EPWU, LVVWD and U.K- based NWL;
- *GHG Module Development and Integration*. The functional specifications of the GHG module were developed and the module was evaluated within the existing EWQMS software product.
- *Offline Simulation for System Performance and Water Quality Impact Predictions*. A series of off-line simulations on specific portions of the distribution network in selected pilot areas at EBMUD and EMWD in California were performed prior to piloting to define the optimal pumping schedule to simulate as a baseline comparison with the GHG module various optimization scenarios, which included financial costs savings, GHG emission reduction and efficient operations.

- *GHG Module Assessment through Pilot*. Assessment of the integrated EWQMS modified with a GHG module was performed through pilot testing at EBMUD and EMWD and the results compared with the historical data and those obtained with the offline simulations.

2.2 Organization of the Report

This report guidebook is organized into the following chapters:

- Chapter 1: Introduction;
- Chapter 2: Fundamental Concept of EWQMS;
- Chapter 3: Research Approach for Evaluation of an EWQMS Modified with a GHG Module;
- Chapter 4: Implementation of EWQMS Modified with a GHG Module at Eastern Municipal Water District;
- Chapter 5: Implementation of EWQMS Modified with a GHG Module at East Bay Municipal Utility District;
- Chapter 6: EWQMS Implementation Guidance at Water Utilities;
- Chapter 7: Conclusions and Recommendations.

CHAPTER 3:
Fundamental Concept of EWQMS

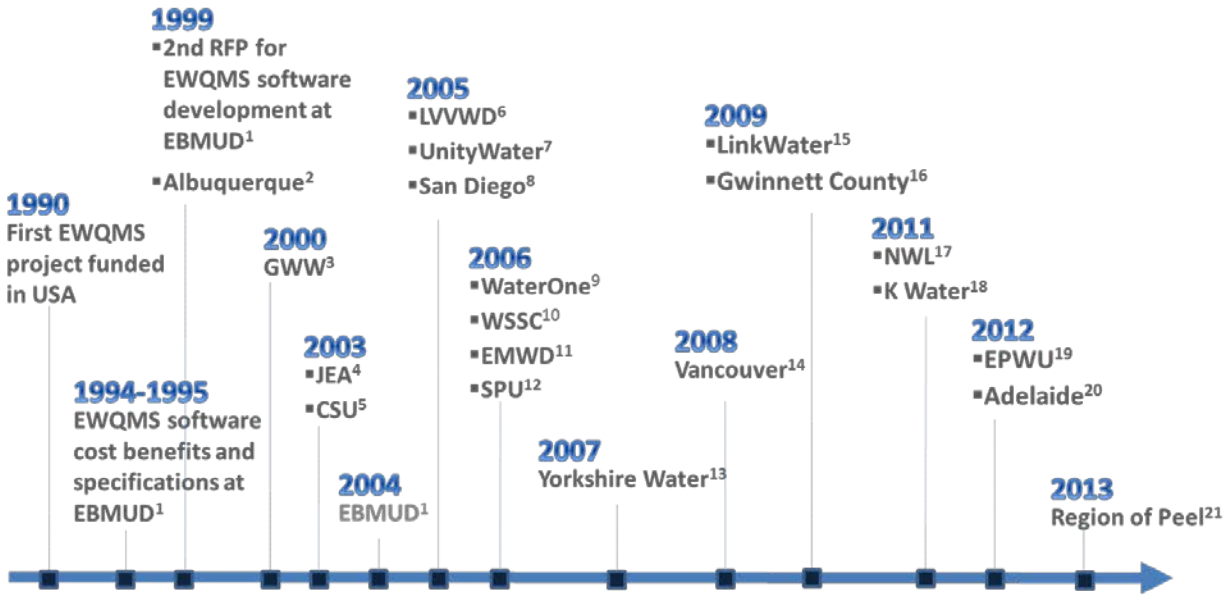
An EWQMS is a collection of individual application software programs that interface with existing monitoring and control systems to cohesively address water quality, supply and energy management within operational constraints (Jentgen et al., 2003). The objective of this chapter is to integrate the fundamental concepts of energy, water demand and supply, and water resources management to provide a more perspicuous understanding of the structure of the EWQMS platform at drinking water utilities. This chapter discusses the historical development and modules of EWQMS and assesses the major optimization strategies for EWQMS operation based on distinctive mathematical models. The information presented here was collected through review of relevant literature and interview of case study utilities and EWQMS solutions providers.

3.1 Historical Development of EWQMS

Pump energy management systems have been investigated by the water industry and academic researchers for more than two decades. In the early 1990s, the Water Research Foundation (previously the American Water Works Association Research Foundation), the Electric Power Research Institute's Community Environmental Center and the EBMUD (California, U.S.) funded the first EWQMS project in the U.S. and outlined the key components of a practical EWQMS for water facilities (Morley et al., 2009). In 1996, a group of water and electric utilities, academics and consulting engineers began developing the functional specifications of a more formalized EWQMS prototype followed by the software installation at EBMUD. However, the difficulties encountered during the implementation required additional research efforts. In 2003, Colorado Springs Utilities developed an off–line EWQMS by building on the lessons learned from the EBMUD prototype and created a customized Operations Planner and Scheduler and related organizational processes (Jentgen et al., 2003). This off–line study demonstrated the feasibility of an EWQMS for control of the system's daily operations. In the years 2000–2004, the installation of commercially developed software at Greater Wellington Regional Council, New Zealand and EBMUD were the first of several other EWQMS implementations at other water utilities across the world (e.g., U.K., Canada, Australia, and South Korea). The timeline of historical development and implementation of EWQMS in water utilities worldwide is presented in Figure 3.1.

Although a majority of the utilities are currently utilizing commercial software platforms for their EWQMS (e.g., *Aquadapt* from Derceto, Inc.), a number of water utilities such as Las Vegas Valley Water District (Murphy et al., 2007), Yorkshire Water Services (Penny, 2011), Albuquerque Bernalillo County Water Utility (EMA, 2013), Metro Vancouver (EMA, 2013) and Jacksonville Electric Authority (Jentgen et al., 2005) have developed solutions in–house. In-house development of the software, such as occurred at LVVWD, is possible when on-site specialized staff engineers are available to pioneer the internal effort (Jacobsen, 2013a).

Figure 3.1: Timeline of historical development and implementation of EWQMS in water utilities worldwide



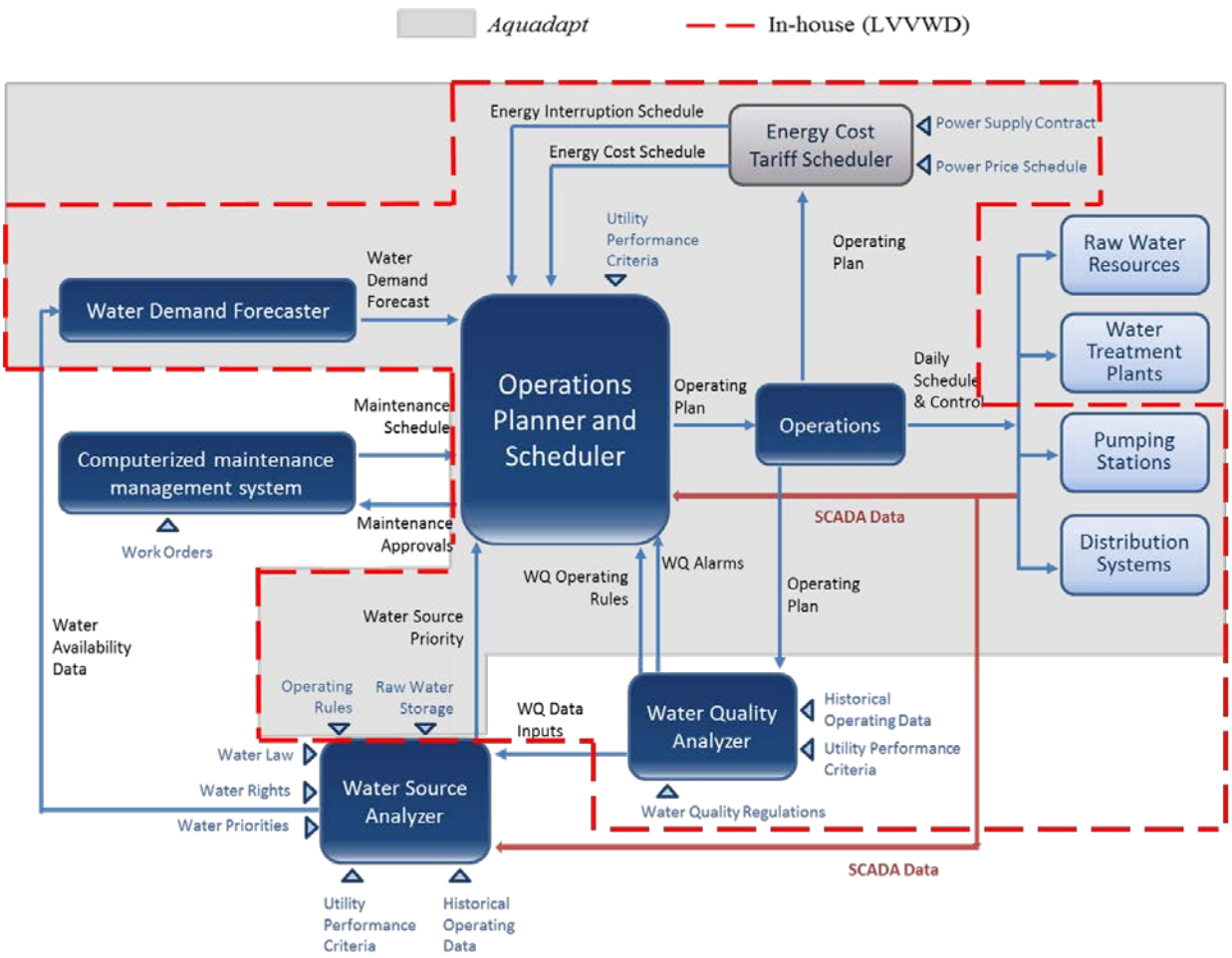
[1] **EBMUD** – East Bay Municipal Utility District, CA
[2] **Albuquerque** - Albuquerque Water Utility Authority, NY
[3] **GWW** – Greater Wellington Water, NZ
[4] **JEA**- Jacksonville Electric Authority, FL
[5] **CSU** – Colorado Springs Utilities, CO
[6] **LVVWD** – Las Vegas Valley Water District, NV
[7] **UnityWater** – Queensland, AU
[8] **San Diego** – City of San Diego, CA
[9] **WaterOne** – Johnson County, KS
[10] **WSSC** – Washington Suburban Sanitary Commission, MD
[11] **EMWD** – Eastern Municipal Water District, CA
[12] **SPU** - Seattle Public Utility, WA
[13] **Yorkshire Water** - Yorkshire, UK
[14] **Vancouver** – Vancouver Water Utility, CA
[15] **LinkWater** - Queensland, AU
[16] **Gwinnett County** - Gwinnet County Dept. Water Resources, GA
[17] **NWL** - Northumbrian Water Limited, UK
[18] **K Water Cheongju** – Cheongju, KR
[19] **EPWU** – El Paso Water Utility, TX
[20] **Adelaide** - Adelaide, AU
[21] **Region of Peel** – Ontario, CA

Source: Cherchi, C., M. Badruzzaman, J. Oppenheimer, C.M. Bros, and J.G. Jacangelo. 2015. Energy and Water Quality Management Systems for Drinking Water Utility's Operational Cost Reduction: A Review. *Journal of Environmental Management*, 153, 108-120.

3.2 Structure of an EWQMS

A typical EWQMS framework consists of similar structural modules regardless of differences in operational characteristics at different utility installations. The schematic in Figure 2.2 illustrates the interconnection of the components of the EWQMS framework initially conceptualized by Jentgen et al. (2003) overlaid by those of a commercial (*Aquadapt*) and an in-house (LVVWD) architecture. As Figure 2.2 shows, both the commercial and the in-house application include the majority of the modules of the conceptual EWQMS. Currently, the water quality analyzer is not part of the commercial software; however it is part of the LVVWD system. The water source analyzer is lacking in both the commercial and in-house EWQMS. LVVWD does not control the raw water resources and the treatment plant operations, which are managed by the Southern Nevada Water Authority (SNWA).

Figure 3.2: Conceptual schematic of an EWQMS module with overlaid Aquadapt and LVVWD in-house frameworks



Source: Cherchi, C., M. Badruzzaman, J. Oppenheimer, C.M. Bros, and J.G. Jacangelo. 2015. Energy and Water Quality Management Systems for Drinking Water Utility's Operational Cost Reduction: A Review. *Journal of Environmental Management*, 153, 108-120. (Also adapted from Jentgen et al., 2003, Derceto, 2013)

Note: The gray shaded area indicates typical components of the commercial Aquadapt software EWQMS tool. Red dashed area refers to the in-house LVVWD software architecture

Briefly, water utility operations are coordinated by an Operations Planner and Scheduler whose primary role is to develop a daily operating plan for the entire system (Jentgen et al., 2003). The Operations Planner and Scheduler software integrates and communicates with the SCADA and the approach relies on hydraulic predictions and accurate forecasting of hydraulic performance, pump performance, electricity tariff structure, system demand and water quality (Jentgen et al., 2003).

The short-term water demand forecaster is a critical functional component for an EWQMS that allows the leveraging of multiple energy management strategies to reduce costs by accurately forecasting consumption at 15–60 minute intervals. A summary of optimization techniques (e.g., regression methods, artificial intelligence techniques, heuristic models, etc.) applied for demand forecasting in EWQMS models is provided in the following Section 2.4. The short-term demand forecasting is typically created by the software developer and forecasts daily demand by analyzing and extrapolating previous years' trends. For utilities using *Aquadapt*, the model forecasts water demand separately for each pressure zone for the next 48 hours of operation.

Aquadapt uses past historical data for up to two years with separate diurnal curves for each pressure zone/ pump station. These are then grouped into week day and weekend curves, and further segregated into seasons. This information provides "shape" information for the forecaster. It uses either average historical demand for the day type and season for each zone, or the operator can select "yesterday" as the starting point for today, or enter an over-ride total system demand estimate. Regardless of the starting point the software re-calculates water demand every 30 minutes using a combination of the starting point and the last 6 hours of measured values. This has been demonstrated to be more than capable of detecting fast changing trends and handling sudden weather changes. The module is, therefore, independent of human judgment and relies on manual input only when operators need to accommodate a large change in the demand due to weather variability or other exceptional circumstances.

Water utilities employ full-sized all mains hydraulic models for planning and off-line operations. A cut-down or skeletonized strategic model is commonly used within the EWQMS, to ensure faster simulation times. Hydraulic modeling provides the EWQMS with pressure, flow and reservoir level predictions for each scheduling strategy generated by the energy optimizer. The model simulation output is compared with constraints such as pressure and volume of flow to ensure compliance with a utility's operating targets. Table 2.1 presents typical hydraulic models implemented in selected water utilities. With the exception of Piccolo at NWL, the hydraulic models that utilities installed are EPANET-based and fully integrated with the EWQMS process. EPANET is the numerical engine employed by many commercial hydraulic software systems (Rossman, 1994) and it is found to be accurate and robust for EWQMS applications. A hydraulic model is essential for predicting the behavior of a complex distribution system. Initial attempts by the LVVWD to use empirical data to predict water flow yielded unsatisfactory results due to the abundance of alternate flow routes, variable demand conditions, and many instances of multiple pumping stations feeding multiple reservoirs hydraulically linked within the same pressure zones (Jacobsen, 2013a). LVVWD models water age on a daily basis, but does not model other water quality constituents. For other utilities using the commercial software, water quality modeling is generally not undertaken in the

embedded hydraulic models, but proper tank turnover is targeted by the EWQMS to ensure minimal water age.

The accuracy of flow data is important for the mass balance techniques used in the EWQMS. Thus, an up-to-date and calibrated control infrastructure (pump station flow meters, pressure, reservoir levels, remote terminal units, telemetry and remote controls) is necessary. Drinking water utilities may require modifications to existing control systems and monitoring equipment. Before implementing EWQMS, EMWD had to invest in new flow meters, particularly to cover the boundary of the distribution network, considered more critical for system monitoring (Ghaderi, 2013). NWL deferred the implementation of EWQMS on the Essex distribution system for two months due to incomplete automation and data availability, noting the need for 100 percent coverage to ensure a successful EWQMS project in this highly interconnected system (Dellow, 2013a). To date, the small Suffolk region of NWL, supplying 300,000 of NWL's 4.5M customers is still not under EWQMS operation pending completion of telemetry upgrade projects (Dellow, 2013a).

An EWQMS operation may not deliver all of the expected savings if the equipment in place are not calibrated (Chan, 2013; Ghaderi, 2013). EWQMS software requires up to date, calibrated pump curves for all pumping systems and the hydraulic model utilized to find optimal solutions. Actual system curves generated based on the flow and pressure data from telemetry records are compared to the manufacturers pump curves to operate the pumping system close to the best efficiency point (BEP). EPWU performed an intensive pump curve testing program to check for system calibration and accuracy before the actual EWQMS implementation started (Perez, 2013).

Table 3.1: EWQMS Software Details and Hydraulic Modeling

Utility	Optimization Software	Hydraulic Model[1]	SCADA	Short-term Demand Forecasting
EMWD	*Aquadapt*[2]	InfoWater, Innovyze	OASyS, Schneider Electric	Derceto
EBMUD	*Aquadapt*[2]	InfoWater, Innovyze	OASyS, Schneider Electric	Derceto
EPWU	*Aquadapt*[2]	H_2Omap, Innovyze	RSVIEW32, Rockwell	Derceto
NWL	*Aquadapt*[2]	Piccolo, Safege	SERCK, Schneider Electric	Derceto
LVVWD	In-house	H2OMap, Innovyze	OASyS, Schneider Electric	In-house

[1]Although individual utilities use different hydraulic models; Aquadapt's water age calculation is based on EPANET mode.

[2]Product of Derceto, Inc.

3.3 Optimization Strategies

An EWQMS provides a framework to implement a water utility's energy management strategy on a real–time basis. Recently, decision support system tools that quantify energy, emissions

and costs have been developed to help utilities make decisions to achieve energy and GHG emission reduction goals and lead to the best portfolio of options (Conrad et al., 2011). Further details on energy cost reduction opportunities that have been considered in EWQMS operations are discussed below.

3.3.1 Optimizing Operations Around Electric Tariff Structures

Electric utility rates have been increasing over time (Brueck and Geisenhoff, 2010). Understanding electric utility rate structures is essential for efficient energy cost management of complex water operations (NYSERDA, 2010). In general, 30–60 percent of the electric cost is based upon the instantaneous peak demand for electricity, with the remaining cost based on the actual energy used (NYSERDA, 2010). Different energy markets offer water utilities a variety of electricity purchasing options, which may consist of: i) standard contracts with variable or flat annual rates; ii) time–of–use (electricity generation price varies depending on the season, day and time-of-day); iii) energy and demand charges (billing includes charges for the amount of electricity consumed and respective rate of consumption during the billing period); iv) dynamic pricing such as critical–peak pricing and real–time pricing (electricity prices may reflect the costs of generating and/or purchasing electricity at the wholesale level); v) demand bidding (load reduction bids on an hourly basis for specific events without financial penalties) (RMI, 2006); vi) negotiated hedge contracts for fixed blocks of energy use; and vii) and real–time electricity market options such as hourly prices set in a day–ahead market. In some markets, these different options may be applied to specific portions of a distribution system, i.e., one part may be running on a flat rate tariff while another is operating on a TOU contract. As an example, pump stations at EMWD with yearly bills under $50,000 are typically charged with flat rates by Southern California Edison (e.g., Olivas, Brosseau), whereas larger pump stations are generally operating on a TOU contract (e.g., Redlands) (Derceto and EMWD, 2010). By reviewing the electricity rates available for a given service area, the EWQMS identifies and solves for the most economical combination to minimize energy costs.

Many water utilities that have implemented EWQMS are charged with TOU options that offer considerably lower rates during "off–peak" periods when the demand is lower, and reward customers that have predictable energy demands over time (Thorstensen, 2007; NYSERDA, 2010). A summary of electric tariffs applied to selected utilities during 2013 are presented in Table 2.2. For these utilities, electrical loads are often moved to lower cost tariff blocks (e.g., overnight), for intra–day operations, or from season to season where long–term raw water storage is practical (Raucher et al., 2008). This practice is most available to water providers with sufficient storage to shift pumping loads to off–peak hours and then draw from storage tanks or reservoirs during high cost periods (Bunn and Reynolds, 2009; Raucher et al., 2008).

Figure 3.3 shows weekly and daily variations of TOU tariffs at EBMUD and NWL (EBMUD, 2010; Dellow, 2013b). When looking at the pricing data applied to EBMUD, it is evident that pumping should be avoided as much as possible between 8:30 a.m. and 9:30 p.m. in winter time or between noon and 6 p.m. in summer. Differences in climates between EBMUD and NWL influence the trends of seasonal peak and off-peak rates, with higher electricity rates during winter for NWL, reflecting the heating load in the U.K., and peaks during summer at EBMUD,

reflecting air-conditioning load as the peak annual load in California. A study conducted by NWL showed that more complicated tariff structures result in greater benefits from the optimization (Dellow, 2013a). NWL currently has 24 different tariffs, or rate schedules (every 30 minutes), the maximum allowed by the Haven Power energy provider for different pump stations and times of the year (Figure 3.3).

Water utilities can also significantly reduce their electricity bills by flattening the energy demand curve, particularly during peak pricing periods (NYSERDA, 2010). Power bills include an energy fee, based on kWh usage, and a demand fee based on instantaneous peak electric power demand. The demand portion is typically on a 15 minute basis, and a user is charged based on the highest 15 minutes (or 30 minutes) of demand in a given period of time. Unless carefully managed, the demand portion of a bill may be higher than the energy portion of the bill. This is because the power utility has to build their systems to meet the maximum electric power demand that may be needed at any given point in time. As Table 2.2 shows, the Southern California Edison (SCE), electricity provider for EMWD, offers a range of different TOU rates with significant demand charges that apply during peak periods in summer. Demand charges can exceed 40% of the monthly costs, and reach up to 80% for some pump stations with low utilization of the installed pumps. The TOU-PA-SOP (Time-of-Use, Pumping and Agricultural Rate, option Super Off Peak) tariff has peak demand charge up to 23 dollars per kilowatt (SCE, 2013), adding thousands of dollars in energy cost per month at the pump stations during the four hour summer super peak periods if the pump is operated even briefly.

Water utilities are under different block pricing programs on energy and demand charges. Some of the utilities order and buy blocks of energy in advance, such as in the case of LVVWD (3 to 5 days depending on weekends and holidays; Jacobsen, 2013a) and NWL (2.5 years; Dellow, 2013a).

Recently, Demand Response (DR) Programs have been developed by electric utilities to promote an efficient distribution of electricity to end–users while providing incentives for demand reduction (PLMA, 2002). In addition, DR programs balance supply and demand in real–time, which helps overcome the uncertainties of intermittent electricity generation, particularly when provided by renewable sources, such as wind energy, that are unpredictable (Kärkkäinen and Ikäheimo, 2009). Water utilities are increasingly cooperating with the electricity supplier's DR programs to manage their energy consumption. EWQMS evaluates all tariff rate structures including DR programs (if applicable) and finds the lowest energy cost solution.

Table 3.2: Electric and gas rates for selected utilities
(Adapted from Derceto, 2014; Jacobsen, 2013a; Dellow, 2013a; Perez, 2013)

Utility	Energy Sources[1]	Electric Tariffs and Rates				Gas Tariffs and Rates	
		Electricity Supplier	Demand Charges ($/kW)	TOU Bands	Electricity Unit Cost – (2013) ($/kWh)	Gas Supplier	Gas Unit Cost (2013) (c/Therm)
EMWD	Grid Natural Gas	Southern California Edison	Peak: 10.42 – 22.99 (S) Anytime: 8 – 14.19 (S,W) Charge (%): 58% (S,W)[2]	- S-W - ToD	Peak: 0.08-0.13 (S) Shoulder: 0.06-0.08 (S), 0.05-0.09 (W) Off Peak: 0.04-0.06 (S, W) Flat Rate: 0.09-0.14 (S), 0.07-0.14 (W)	Southern California Gas	18 - 45
EBMUD	Grid	PG&E	Peak: 13.9-14.2 (S) Anytime: 9.4-11.7(S), 5.6-11.7 (W)	- S-W - ToD - WD-WE	Peak: 0.123-0.443 (S) Shoulder: 0.091-0.225 (S), 0.086-0.152 (W) Off Peak: 0.07-0.136 (S), 0.07-0.127 (W) Flat Rate: 0.1374-0.205 (S), 0.103-0.143 (W)	N/A	N/A
EPWU	Grid Natural Gas	El Paso Electric Co.	NO[5]	- S-W - WD-WE - ToD	Peak: 0.22 – 0.2297 (S) Shoulder: 0.1212 – 0.1309 (S) Off Peak: 0.0367 – 0.0460 (S) Flat Rate: 0.0549 – 0.0642 (S), 0.0453 – 0.0546 (W)	Texas Gas Service	40– 42
NWL	Grid Biogas[3] Hydropower	Haven Power[4]	Based on Triads Charges	- S-MY-W - WD-WE - ToD	Peak: 0.219 – 0.394 (W), 0.122 – 0.262 (S) Shoulder: 0.102 – 0.149 (S), 0.114 – 0.165 (W) Off-Peak: 0.095 – 0.148 (W)	N/A	N/A
LVVWD	Grid Natural Gas Solar	Silver State Energy Assoc. NV Energy	Peak:15.39- 20.73 (S) Shoulder: 15.39-20.73 (S) Winter: 0.40-0.60	- S-W - ToD	Peak Range: 0.081 -0.115 (S) Shoulder: 0.067 – 0.084 (S) Off Peak: 0.043 – 0.056 (S) Winter: 0.045 – 0.063	Southwest Gas	42 - 54[6]

Notes: S: Summer; W: Winter; MY: Mid-year; WD: Weekday; WE: Weekend; ToD: Time of the Day; N/A: Not Applicable

[1]Energy sources for pumping in water distribution systems.

[2]It has high variability from station to station.

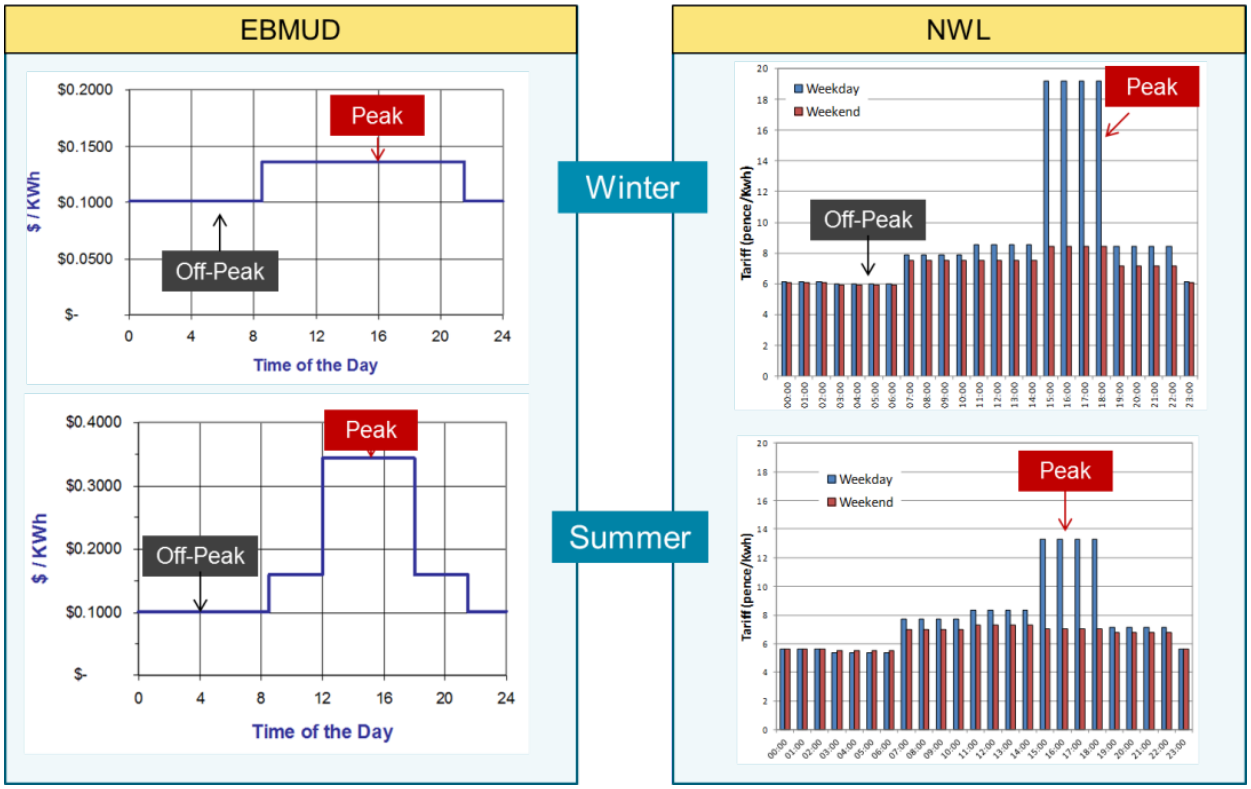
[3]Product of anaerobic digestion.

[4]Scottish & Southern Energy before April 2013.

[5]With the exception of the Rogers WTP (60 MGD), which is on an Interruptible Rate (IR) and subject to demand charge and low power factor charges.

[6]www.swgas.com/tariffs/nevada_rates_and_tariffs.php

Figure 3.3: Typical daily, weekly and seasonal electric tariff rates fluctuation for EBMUD and NWL



Source: Adapted from EBMUD, 2010 and Dellow, 2013b

3.3.2 Selecting Low Cost Energy Mix

Water utilities often diversify their energy portfolios not only to increase their electricity reliability, but also to increase their energy efficiency and reduce their contribution to GHG emissions (Raucher et al., 2008). Among the various opportunities available, in–conduit hydropower generators, natural gas–driven pumps and alternative renewable options on-site and connected to the grid, such as solar and wind, are the most utilized (Klein, 2009). The EWQMS optimization finds the lowest cost energy mix within the operational constraints.

Trading between gas and electric pumps becomes important to achieve cost savings in utilities that have availability of gas on site, particularly during peak demand periods (e.g., summer). Water utilities can reduce their electrical demand, thus seasonal electric costs and risks, by operating natural gas–driven power in a sole or a dual fuel mode. Natural gas is one of the major fuels consumed by the water sector within the U.S. (17 million therms of natural gas use in 2010, Southern California Gas Company estimation) predominantly to power pumping (Water Energy Innovation, 2013).

For water utilities that use natural gas, such as EMWD and EPWU, natural gas tariffs also contribute to the utility's annual bills (Ghaderi, 2013; Perez, 2013). In California, natural gas does not usually have TOU components and, during summer, its purchase price is generally lower than that of electricity (Water Energy Innovation, 2013). Additionally, natural gas charges

are less volatile over long periods of time and they are not subjected to real–time supply and unpredicted demand influences (Water Energy Innovation, 2013). For instance, EMWD purchases gas on the spot market using a bulk month-ahead contract with variable price. EPWU had gas fired pumps installed originally to meet the state requirement for redundancy in case of a natural disaster and, recently, gas pumping has been actively included in normal day-to-day operation (Perez, 2013).

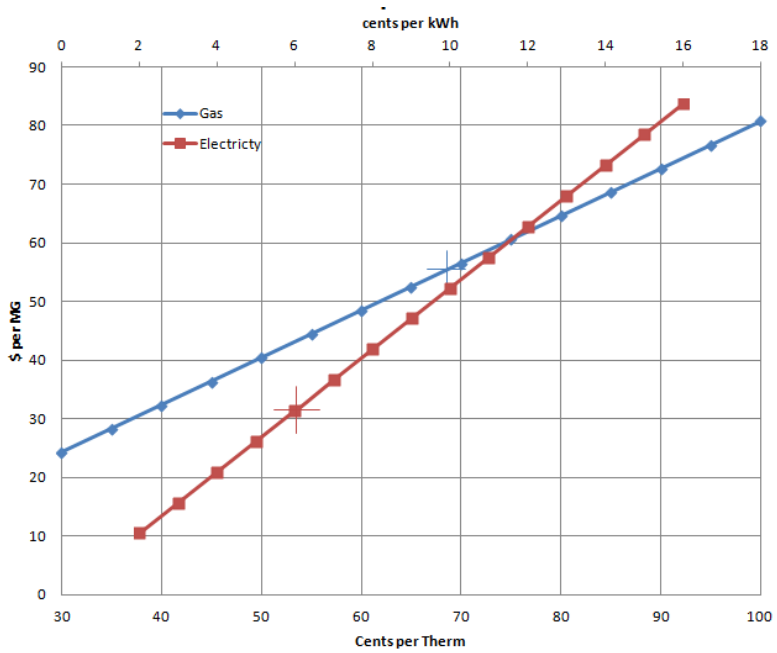
Natural gas-fueled engines are remarkably less efficient than electric motors (18–30 percent compared with 95 percent); however, they may provide approximately 52 percent cost savings over electricity (Goonetilleke, 2011). Thus, the natural gas alternative only becomes more economically favorable if it is less costly than electricity in delivering the same volume of water (Bunn et al., 2006). EMWD and EPWU use their EWQMS to balance a mix of electric and gas driven power (e.g., pumping) to avoid peak demand electricity charges (Perez et al., 2012). At these utilities, EWQMS is able to prioritize the pumping between the drive types to reduce energy costs (Derceto, 2013). At EMWD approximately half of the total volume of water was pumped by gas engines and the second half by electricity driven motors (65percent on TOU rates and 35 percent with flat rates) (Derceto and EMWD, 2008; Derceto, 2014). EMWD typically uses a breakpoint analysis technique to determine the point at which the use of gas driven pumping becomes more economic than electricity. Figure 3.4 shows a recent (2013) gas vs. electricity breakpoint analysis developed by Derceto for EMWD (with the "+" marks indicating current pricing) demonstrating that electric pumps are significantly cheaper than gas pumps per million gallons (MG) delivered, a complete turn-around from 2012 when the opposite was true (MWH and Derceto, 2013).

In addition to natural gas, diesel is often considered as an electricity load shaving alternative and it is a common backup generation option for water utilities in non-attainment zones under the Clean Air Act. Diesel is used as a standby generation option in U.K., however it is only operated by NWL approximately 30 times per year for only one hour during critical peak electricity demand charge periods (called Triads), so it is not considered a significant part of the energy mix for NWL (Dellow, 2013a).

Hydropower is one of the least expensive energy generating options that water utilities are considering, as it plays an important role in stabilizing the electrical transmission grids and in meeting peak loads, reserve requirements and additional ancillary needs (Jentgen et al., 2003). New "microhydro" applications (low head dams or hydrodynamic propellers) have also been introduced on existing water storage or conveyance structures and typically provide up to 100 kW of electricity using natural water flows without the purchase of fuel (Chaudhry and Shrier, 2010). In California, a vast publicly and privately–owned network of reservoirs, dams, and pumped storage generate about 13% of the power used in the state and represents about 25 percent of the in–state generation capacity (Klein, 2009). If available, EWQMS strategies can be used to maximize the value of hydroelectric generation to gain financial benefits. Colorado Springs Utilities (Colorado Springs, U.S.) is an example of how a prototype EWQMS could reach substantial dollar savings by maximizing the supply of electricity from the 28 MW Tesla hydroelectric plant (Jentgen et al., 2003).

Figure 3.4: Gas vs. electricity breakpoint analysis during TOU periods at EMWD

(Data from year 2013)



Water facilities with renewable energy assets and under EWQMS automation have opted for shifting power demand to the available renewable source (e.g., wind) at night and favoring solar contributions during daytime hours (Chaudhry and Shrier, 2010). The renewable source selection and time of use is based on a real–time or programmed interval comparison of the price of fuel, the price of purchased electricity and the price of net–metered electricity sold back to the grid. California water utilities, for example, have been able to sell renewable energy back to their electricity provider during peak times and purchase cheaper electricity during off–peak periods. Utilities may have specific agreements with local regulatory agencies that require a certain percentage of alternative energy to be part of their overall energy portfolio. For example, LVVWD has on-site solar power (3 MW capacity), of which a minimum of 50 percent must be used on site and the rest wheeled to the local NV energy grid connection (Jacobsen, 2013a). The Northeast area of NWL is 20 percent self-sufficient due to their use of gas generated from two large anaerobic digestion sources (Dellow, 2013a).

3.3.3 Selecting Operating Schemes to Lower Energy Consumption

Energy cost reduction by improving energy efficiency of operation is one of the EWQMS objectives. In most EWQMS operations, efficient pump scheduling and network optimization are significant contributors to efficiency practices.

3.3.3.1 Energy Efficient Operation of Pump Stations

In order to ensure energy efficiency of a pump station, a comprehensive understanding of the system requirements is important. In addition, it is important to tailor the pumps to the system

operating requirements to ensure that the Best Efficiency Point (BEP) is located close to design or near the operating point of the system curve where the pump operates most often. A recent study performing 150 water pump tests (sizes ranged from 30 to 4000 horsepower) in eight municipal water supply and distribution systems demonstrated that the average efficiency gap (i.e., the difference between the manufacturer's original best efficiency point and actual point of operation in the field) is around 12.7 percent and that average efficiency loss, (i.e., the difference between the manufacturer's original BEP and the tested BEP) is 9.3 percent (Papa et al., 2013). Thus, there is an opportunity for potential energy savings in pumping system operations.

An EWQMS reduces energy costs by operating pumping systems more efficiently than simple level or pressure controls are able to. This approach is particularly important in energy tariff markets where the differential between peak and off–peak rates is low. In such cases, the lowest cost strategy is associated with running pumps efficiently rather than focusing on utilizing lowest tariff periods (Reynolds and Bunn, 2010). When targeting cost savings by energy efficiency gains, the commercial software selects a pump or a combination of pumps that supply the water demanded at the lowest specific energy (e.g., lowest kWh per MG).

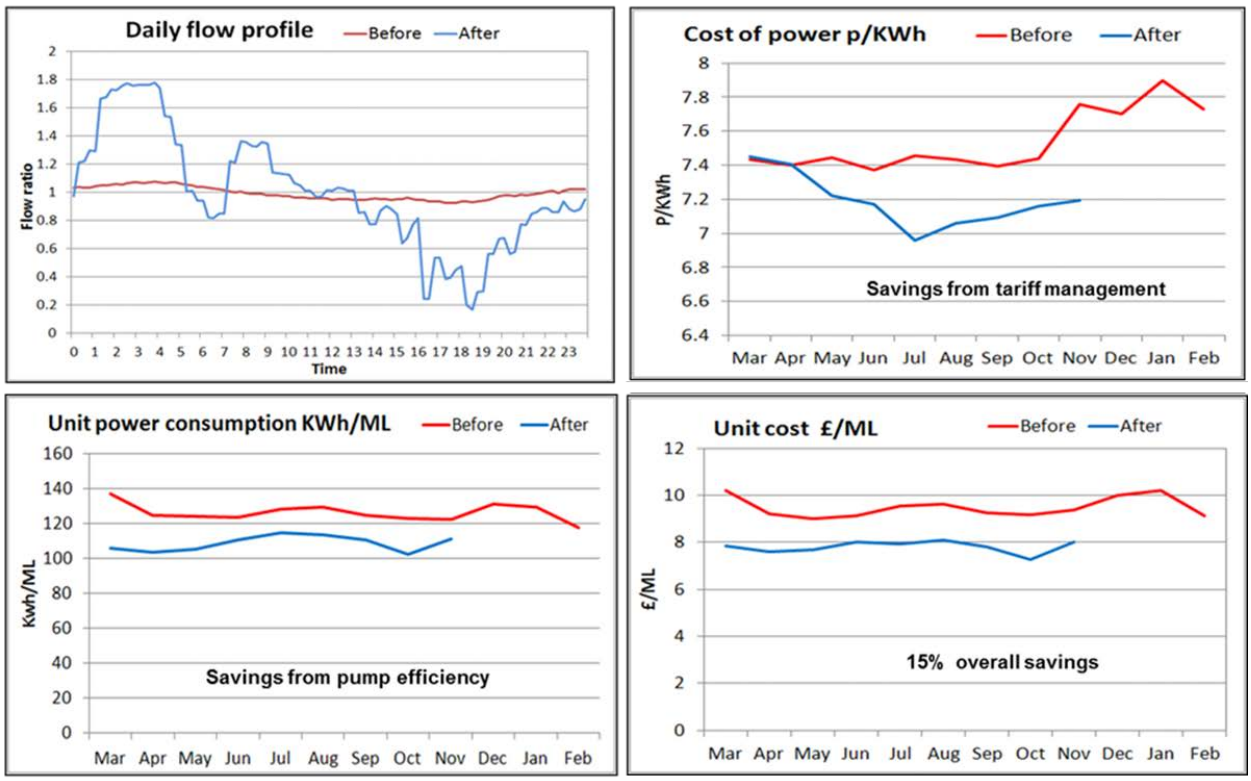
Where variable speed drives are available (e.g., EPWU), the software is able to select and operate pumps close to their BEP at minimum to maximum flow conditions on a real–time basis (minimization of kWh per MG delivered) (Derceto and EPWU, 2008). Pump operation (e.g., pump start and stop, etc.) at these utilities is agreed to in the constraints identification process, and later enforced in the EWQMS. Historically, pumps have been scheduled based on the "maximum flow" (i.e., run the pump until it can no longer handle the system requirement) or based on the "percent of maximum speed" (i.e., select a percent of the maximum speed and select the combination of pumps based on that criteria). However, none of these traditional methods provide an accurate estimation of the operational efficiency of the pumping system. In applications where multiple pumps are arranged in parallel operating in a lead–lag sequence, the specific energy (energy consumed per unit volume of water pumped as expressed in kWh/MG or kWh/kgal) is used in the EWQMS to determine the most energy efficient control timing to start or stop a lag pump. Therefore, the combination of pumps is selected in a manner that minimizes the specific energy consumption of the entire station within operational constraints.

A commercial EWQMS tool has the ability to store calibrated pump and efficiency curves in order to predict pump operational performance relative to pump curves for half hour intervals over a 24 hour period (Reynolds and Bunn, 2010). Selection of pumps based on the lowest specific energy consumption is still prone to a number of constraints in any real world system. These include: minimum run times; maximum starts per hour; minimum cool down times; minimum flow rates and maximum discharge pressures for valve stations; minimum and maximum plant production rates; pump station pressure rules (e.g., starting the smallest pumps first); and inter-pump stagger timing to prevent surges or water hammering. When the solution of the optimization generates a pumping schedule with too frequent pump start/stop cycles, operators might be concerned for higher equipment wear and tear, which results in higher maintenance cost and lower pump availability (Perez, 2013). EBMUD is also concerned about start/stop frequency staying within the pump manufactures' specifications where proper cool

down is necessary to prevent premature breakdown of the windings insulation. Further analysis of EWQMS performance and additional discussion with pump manufacturers might elucidate whether this mode of operation is ideal for pumps and whether this is actually the best efficiency option. At EBMUD, where constant speed pumps operate the majority of the system, pump selection is generally not based on energy efficiency but on achieving balanced run hours. Thus, pump efficiency optimization for this utility is limited by this constraint, as well as constraints on the maximum permissible number of pump starts per day (Chan, 2013).

An example of cost savings associated with tariff management practices and pump efficiency measures at the Hullbridge pumping station in NWL is showed in Figure 3.5. After EWQMS implementation, the daily flow profile at Hullbridge responded to the applied tariff management and best efficiency strategies. Together, the reduction in the monthly average cost of power and pump efficiency strategies contribute to the overall 15 percent cost savings observed.

Figure 3.5: Savings from pump efficiency measures (left) and tariff management practices (right) at the Hullbridge pumping station, Essex Region of NWL



Source: Dellow, 2013b

3.3.3.2 Network Optimization

A significant percentage of energy input to a water distribution system is lost in pipes due to friction, pressure and flow control valves, and consumer taps (Innovyze, 2013). Boulos and Bros (2010) show that the majority of the energy losses in a mid-size system occur at the consumer

tap (85 percent) and the remaining 15 percent is lost by friction (7 percent) and pressure management (8%). Network modifications and changes in operating rules may be combined with water resource and treatment management planning to provide a holistic source–to–tap assessment. Thus, EWQMS is best implemented in parallel with conventional energy audits, pump replacements or refurbishment and the analysis of system constraints and pinch points. In general, water network optimization practices vary according to utility needs.

Table 3.3 shows typical network and operational modifications in water utility optimization practices. Changes made for energy management purposes also need to comply with water quality, flexibility and security objectives; thus, risk management plays a role in ensuring a balance between energy optimization and operational flexibility.

Various metrics can be used to assess Water Network Energy Efficiency, including the evaluation of kWh/MG supplied (or grams of carbon dioxide per million gallons [gCO_2/MG]), the proportion of input energy utilized in pumping (wire–to–water efficiency) and transport (friction, tap and discrete energy losses) and, more broadly, the comparison of the minimum theoretical energy required with actual system performance (Hernández et al., 2010; Boulos and Bros, 2010). An understanding of the energy input and the spatial utilization of energy in water supply systems is required for water network optimization and accounting of associated energy savings. In general, only the operating areas with the greatest potential for savings are subject to optimization.

The energy distribution in a system can be estimated using hydraulic network models, such as EPANET (Rossman, 1994) or embedded energy calculations (e.g., Water Network Energy Efficiency concept) in existing commercial software (such as InfoWater and InfoWorks WS, Innovyze). Some commercial EWQMS software does not have built–in hydraulic network modeling. In other cases, a hydraulic model is integrated with the EWQMS system to identify energy efficient routes for water transport through the distribution system. For instance, EWQMS finds the shortest path to supply water to the distribution system network, reducing the number of times the same water is pumped to reach its final destination (Thorstensen, 2007). In a well–connected network system where water can be easily moved through multiple transport routes, the shortest flow path might provide a more energy efficient operation. Thus, cost savings can be achieved through selection of the cheapest flow paths (e.g., such as those initially considered as emergency routes) (Jacobsen, 2013a; Dellow, 2013a) and the maximization of cheapest water production sources (Dellow, 2013a).

Table 3.3: Typical network and operational modifications employed in water utility optimization

Network Modifications	Operational Modifications
• Reconfiguration of pressure zones (e.g., revalving or installation of new control valves, changes to force main connectivity); • Removal of hydraulic bottlenecks or pinch points (e.g., main reinforcement, replacement or new connections); • Pump and motor refurbishment or replacement (e.g., use of variable frequency drives (VFDs); • In–line booster pumping stations with or without disinfectant[1] • Construction of new or extension of existing reservoirs or hydropneumatic tanks (e.g., improve circulation) • Use of Energy Recovery Units (ERUs) (e.g., in–line turbines) to generate grid power from the water supply network	• Water resource management (e.g., exploiting low cost sources); • Water treatment optimization (e.g., improving chemical usage and in–process power use); • Pump scheduling (e.g., improved manual or local closed–loop operating rules); • Storage tank cycling (e.g., reducing retention times); • Water quality management (e.g., flushing schedules or dosing optimization); • Leakage management (e.g., active leakage control); • Pressure management

Source: Cherchi, C., M. Badruzzaman, J. Oppenheimer, C.M. Bros, and J.G. Jacangelo. 2015. Energy and Water Quality Management Systems for Drinking Water Utility's Operational Cost Reduction: A Review. *Journal of Environmental Management*, 153, 108-120. (Also adapted from Raucher et al., 2008; Leiby and Burke, 2011)
[1]Discouraged in Texas by State regulations (TCEQ)

3.3.4 Water Quality Management Strategies

Drinking water practices that use energy efficient programs must still comply with federal and state environmental water quality standards and achieve plant production requirements (Raucher et al., 2008). Thus, customized strategies that are part of a "multiple barrier" approach (Raucher et al., 2008) have to be integrated with the EWQMS in order to select and manage raw water supply sources and maintain statutory water quality standards within the distribution infrastructure.

3.3.4.1 Source Water Quality

Water supply management objectives for operational cost minimization must ensure that source water characteristics do not have significant impacts on water quality before final delivery to customers (Jentgen et al., 2003). Water sources are expected to fully satisfy the distribution demand profiles by feeding a pressurized distribution network.

Water source portfolios can include groundwater, surface water, desalinated and imported water supplies. Selection of raw water sources by EWQMS is contingent upon water rights and on the agreement that each district stipulates with water providers for provisions of the selected source portfolios. The availability and allocation of water from these sources are dependent upon seasonal and climatic conditions as well as raw water chemistry and quality and technologies available for treatment (e.g., in desalinated sources). This input leads the EWQMS optimization software towards the selection of water quality supplies within the constraints of

water quality and costs. Appropriate pump operation for raw water withdrawal from selected sources is scheduled to reduce costs and improve the level of water quality in downstream processes. Optimal management of sources and reservoirs is expected to yield higher water quality, particularly when it supports a water treatment plant production with a constant flow rate (Bakker et al., 2011). Main water quality improvements and reduced overall energy consumption are observed when the automation of reservoir control is based on model prediction rather than level based flow controls (Bakker et al., 2011). This guarantees minimal changes in production flow and up to 10–20 percent lower turbidity and particle counts by effectively setting upper and lower reservoir levels under the flow forecasted conditions.

The quality of raw water sources may influence the water treatment processes required. Advanced water treatment technologies (e.g., membranes, advanced oxidation, etc.) that are energy intensive are increasingly needed to meet treatment goals (e.g., removal of total dissolved solids [TDS], trace contaminants, etc.). The optimization of water treatment processes has not been directly integrated with EWQMS programs since treatment energy expenditure, with the exception of desalination and ultraviolet (UV) radiation, is usually small compared to pumping and transmission. Although the energy consumption of these processes is not currently included in EWQMS, the software can select water sources that require less energy for treatment (groundwater vs desalinated water).

3.3.4.2 Distribution System Water Quality

Distribution system operation and management must comply with specific criteria to avoid water quality degradation and loss of supply reliability during transmission. Low flow velocities in distribution systems may lead to water stagnation and failure of system flushing mechanisms. High retention times due to large storage volumes increase the risk of decreased turnover, with accompanying disinfection by-product (DBP) formation and biological re–growth. Thus, theoretical models consider factors such as residual disinfectant concentration, DBP formation potential, and taste and odors for distribution system optimization (Kurek and Ostfeld, 2013). Maintaining a minimum residual disinfectant concentration (e.g., chlorine) is also needed to limit bacterial re–growth at each node and storage tank in the distribution system.

Modeling distribution system water quality based on chlorine residuals and DBPs is not common practice due to monitoring constraints; instead water age is typically used as an indicator parameter of water quality and recommended as a key decision tool for water distribution system management (Kurek and Ostfeld, 2013). Modeling water age is relatively simple, since its calibration does not require additional parameters apart from those required for hydraulic calibration (Murphy et al., 2007). However, water age may not accurately reflect chlorine residual and DBP profiles if variability of chlorine decay rates exists in different segments of the distribution system, if multiple water sources are withdrawn and if waters of different ages are combined in tanks or pipe junctions (Murphy et al., 2007).

If not adequately managed, typical energy efficiency practices can increase or decrease water age in the system, particularly when storage tank refills are shifted to off–peak hours, when booster pumps are not adequately set to guarantee sufficient pressure (Raucher et al., 2008) or if

multi–pressure zones are not managed with properly configured pressure regulating valves. Storage issues, due to tank short circuiting and dead zones, can sometimes become too complex for hydraulic modeling software to simulate water age during normal extended period simulation runs, thereby adding to the computational requirements. In some instances, distributed processor simulations may overcome this limitation.

Current EWQMS programs incorporate solutions to minimize water age by improving water turnover in storage and minimizing the transfer of aged water between storage tanks in the same or adjacent pressure zones (Beyer et al., 2005). Schedules that follow deep cycling and pulse flow operation are also considered when reservoir storage is insufficient to cover the following 24 hour needs of a specific pressure zone (Beyer et al., 2005). When multi-day strategies were required to turn over water in storage tanks with working volume greater than a day's demand, a "target cycler" was created and first implemented at EBMUD. This sets different water target upper levels each day over an extended period, typically 7 or 14 days, with a period of gradual decline followed by a period of replenishment to force water to cycle in the storage tank. Before EWQMS implementation, EPWU and EBMUD targeted a conservative 50% of daily water turnover in tanks by running in deep cycling mode (Derceto and EPWU, 2008; Chan, 2013). The deep cycling worked well for storage that moves up and down every day, however, large reservoirs could not cycle in only one day especially during low water demand. At EPWU a 70 percent drawdown was considered a realistic and achievable operational target for a small number of reservoirs to preserve water quality (Derceto, 2013).

A second strategy used to preserve water quality at EBMUD is pumping in cascade where a chain of pump stations and floating in-zone storage exists for incrementally higher pressure zones. Running all pumps in a cascade simultaneously ensures that the freshest water is pumped directly to the higher elevation storage tanks from the bottom of the cascade (Chan, 2013).

Off-line water quality modeling (e.g., chlorine, DBPs and age of water) can be conducted within the hydraulic software. However, accurate chlorine and DPB predictions are only practicable following extensive field calibration in a detailed network model. Although age of water modeling is a common substitute for specific quality parameters, it is not routinely undertaken by water utilities (with the exception of LVVWD). The barriers to including age of water modeling in an EWQMS are:

- Need for a detailed hydraulic model embedded in the EWQMS;
- Need for extended periods of hydraulic and water quality data since water age is measured in days, not hours;
- Considerable increase in simulation times when running water quality simulations.

Some utilities reported water quality problems during EWQMS control. NWL reported some water quality issues when pumping from a larger reservoir that proved difficult to solve since NWL has strict constraints for the rate of change of the WTP flow (Dellow, 2013a). EMWD also experienced some water quality issues at the very early stage of EWQMS implementation

(Ghaderi, 2013). In both cases, the EWQMS solution was forced to follow constraints that were in direct conflict with water quality. Making sure constraints do not conflict with operational requirements is a common challenge in implementing an EWQMS.

3.3.5 Tradeoffs Between Energy, Water Quality and Operations Management

In EWQMS, best efficiency practices for energy and cost reduction are simultaneously implemented within constraints of water quality requirements and operating rules. Table 3.4 shows a conceptual illustration of the effect of various energy management strategies on energy cost, energy consumption, GHG emissions, water quality, and overall system reliability. The table indicates that the implementation of energy management practices that target the reduction of costs may positively or negatively impact the other operational improvement goals.

Because of the interdependency and conflicting relationships between energy cost, water quality objectives and risk management practices, the optimization is critical for effective operation. Predictions for system optimization in an EWQMS are attained using an array of algorithms that solve optimization problems for specific objective functions (e.g., goals) by imposing distinct constraints (Boulos et al., 2006). The use of complex algorithms within an extensive number of operational constraints may not guarantee an optimal solution and are prone to saturate hardware and software capabilities by generating time–intensive computations (Bunn, 2006; Raucher et al., 2008). The cost of energy, rather than energy consumption, is the objective function typically minimized for utilities in order to achieve lower operating costs. Figure 3.6 shows a conceptual illustration of some of the constraints that are considered as boundary conditions while generating a solution for a least energy cost operation. These constraints ensure compliance with water quality regulations, consumptive use permits and energy and mass conservation principles in the network system and at junction nodes (Boulos et al., 2006). Energy charges, energy efficient measures and asset management practices are other implicit and explicit boundaries typically applied.

Each utility operates with a set of specific constraints and an operation with unrealistic constraints may not produce a feasible solution in an EWQMS. A clear distinction is required between operator preferences and actual hard constraints. The number of constraints has to be prioritized and be minimal at the beginning of EWQMS implementation and, if required, the number of constraints can be increased gradually only if necessary to achieve operational requirements but must keep within the ability of the software to converge to a solution. Bunn (2006) discussed the major operational constraints of four U.S. water utilities by emphasizing the distinctive features of each optimized scenario. Some examples include deep cycling of water tanks to reduce average water age (e.g., EBMUD) (Chan, 2013), the use of gas reciprocating engine driven variable speed pumps (e.g., EMWD) (Ghaderi, 2013), and reservoir management to maximize limited storage system capacity (e.g., Washington Suburban Sanitary Commission, WaterOne).

Table 3.4: Effect of energy and water quality management strategies on overall water utility management objectives

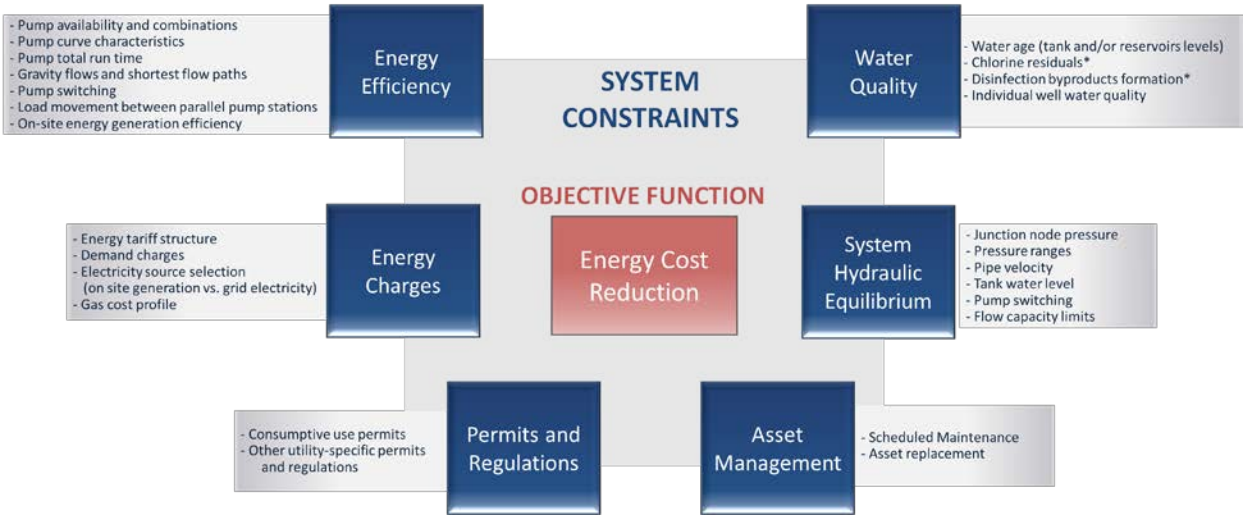
Strategies	Energy Cost	Energy Consumption	GHG Emissions	Water Quality	System Reliability
Shift pumping from peak to low cost tariff periods	Decrease	No Change	Unknown	Unknown	Decrease
Select natural gas driven engines during peak tariff periods	Decrease	Increase[1]	Decrease	No Change	Improve
Utilize renewable energy generation on–site	Increase	No Change	Decrease	No Change	Improve
Optimize pumping strategies and system operations *(e.g., pump combination selection, VFD installation, pumping in cascade, pumping at/near the BEP, etc.)*	Decrease	Decrease	Decrease	Improve	Improve
Reduce leakage in distribution systems *(e.g., pressure reduction strategies and infrastructure improvements, etc.)*	Decrease	Decrease	Decrease	No Change	Improve
Select high quality source water	Unknown	Unknown	Unknown	Improve	Unknown
Manage reservoir or storage tank *(e.g., new set–points for reservoir's operating levels, new water withdrawal management strategies such as deep cycling and pulse flow operation, etc.)*	Decrease	Unknown	Unknown	Improve	Improve

Source: Cherchi, C., M. Badruzzaman, J. Oppenheimer, C.M. Bros, and J.G. Jacangelo. 2015. Energy and Water Quality Management Systems for Drinking Water Utility's Operational Cost Reduction: A Review. *Journal of Environmental Management*, 153, 108-120. (Also adapted from Raucher et al., 2008)

Note: "Unknown" indicates that a positive or negative impact may occur depending on site specific constraints

[1]Subject to debate: while a large central power plant is more efficient than local gas engines, there are significant energy losses from the power plant to the electrical load.

Figure 3.6: Objective functions and typical operational constraints of an EWQMS



*Currently not included as an operational objective function or a constraint in full-scale EWQMS implementations
Source: Cherchi, C., M. Badruzzaman, J. Oppenheimer, C.M. Bros, and J.G. Jacangelo. 2015. Energy and Water Quality Management Systems for Drinking Water Utility's Operational Cost Reduction: A Review. *Journal of Environmental Management*, 153, 108-120.

3.4 Software and Optimization Techniques

3.4.1 Optimization Techniques for EWQMS

A number of mathematical methods have been successfully applied in water management to solve optimization problems (Bagirov et al., 2012). Deterministic techniques (e.g., linear, non–linear and dynamic programming) have commonly been applied due to their high robustness and low computational requirements (Jowitt and Germanopoulos, 1992; Nace et al., 2001). In linear programming, linear functions are used to describe the problem constraints and the objective functions, such as those used for minimizing satellite booster chlorination and pumping to a fixed free outfall (Boulos et al., 2006). However, the non–linear nature of the majority of optimization problems in drinking water practice limits the effective applicability of these linear approaches to non–linear systems of high complexity, particularly if based on non–linear hydraulic and water quality relationships. Typical EWQMS systems based on linear and non–linear approaches employ mixed integer programming to solve pump scheduling problems that are based on binary choices (e.g., on/off) (Derceto, 2013; Bagirov et al., 2012). In dynamic programming, the system is discretized into a series of stages within an allowable range and generates a discrete solution that may not correspond to the global solution of the initial problem. Dynamic programming is difficult to implement in complex networks of variable pressure and strict water quality constraints.

Recent efforts have introduced stochastic and metaheuristic approaches to solve large network optimization and combinatorial problems; however, their application for real–time control of water supply and distribution systems is still limited (Barán et al., 2005). Typical models include genetic algorithms, simulating annealing, and particle swarm optimization. These models are

mostly based on iterative search algorithms that attempt problem solving with two or more, often conflicting, objective functions. While simulating annealing locates a good approximation to the global optimum of a given function in a large search space after the evaluation of alternatives (McCormick and Powell, 2004), genetic algorithms and particle swarm optimization work by maintaining and evolving a population of Pareto–optimal solutions during the search. Other techniques have been tested by water supply optimization practitioners and include ant colony optimization (Ostfeld and Tubaltzev, 2008; López–Ibáñez et al., 2008), honey bee mating optimization (Mohan and Babu, 2009), harmony search (Geem, 2009), tabu search (Cunha and Ribeiro, 2004) and shuffled frog leaping optimization (Eusuff and Lansey, 2003). A critical review of these methods is presented by Sörensen (2013), which identifies slight differences in all evolution strategies that are based on the same underlying approach.

Lately, hybrid approaches that are based on linear programming and genetic algorithms have been proposed and are built on the advantages of both deterministic and heuristic methods (Cisty, 2010). In general, although considered ideal for optimizing energy and water quality management systems, the algorithms presented above have limited applications in real drinking water systems control. These techniques must oversimplify the network and the initial assumptions in order to overcome intrinsic challenges due to non–linear network hydraulics and the subsequent advanced mathematical complexity and extensive fine tuning of parameters interferes with real–time solutions.

3.4.2 Optimization Techniques for Water Demand Forecasting

Water utilities have traditionally employed consumption–following pumping operations in which wells and booster pumps are automatically controlled in response to reservoir levels and distribution pressures. In order to optimize pumping schedules, minimize energy or take advantage of energy supplier pricing schedules, a proactive rather than reactive system of operation is needed. Therefore, the water demand forecaster is a critical functional component for an EWQMS that allows the leveraging of multiple energy management strategies to reduce costs by accurately forecasting consumption for at least the next 24 hours at 15–60 minute intervals. For example, opportunities are identified to use storage to take advantage of TOU regimes, minimize simultaneous pumping operations and maximize operation of the most efficient pumps (Leiby and Burke, 2011; Jentgen et al. 2007). While the water industry utilizes long–term forecasting for infrastructure capital planning and short–term forecasting to set water rates, the extremely short–term daily or hourly forecasting utilized by the electricity and gas industry is a more suitable option for drinking water demand management and operations (Pacific Institute, 2013). Current EWQMS that are built on the basis of short-term demand forecasting do not have the capability to directly impact water demand and its management. Nevertheless, in conjunction with a robust hydraulic model, EWQMS may have the capability to identify some issues in the distribution system (e.g., leakage through pressure drops) that can be beneficial for water demand management and related strategies.

Water utility extremely short–term consumption forecasting includes modeling with conventional regression methods and time series analysis, artificial intelligence techniques of expert systems and artificial neural networks (ANN) (Jain and Ormsbee, 2002). Modeling

techniques such as heuristic models, ANN, and regression models often show similar performances from hour–to–hour forecasts and their accuracies depend upon the precision and repeatability of the SCADA data, as well as the sophistication, calibration and level of maintenance of software tools (Jentgen et al., 2007). Absolute relative errors ranging from 6.0% to 8.5% for the hourly heuristic prototype, 5.8% to 8.4% for the ANN prototype, and 5.7% to 5.9% for the linear regression prototype were reported; the accuracy generally lowers when switching from daily to hourly forecasts (Jentgen et al., 2007).

Recently, newer forecasting strategies have relied upon the implementation of ANN models, expert systems, and "fuzzy logic" deployed through commercial systems (e.g., Nostradamus). Table 3.5 summarizes the key features of this modeling for short–term forecasting and the utilities in which the given model has been implemented.

Table 3.5. Typical short–term consumptive forecast (STCF) models used by water utilities

Forecasting Technique	Forecasting Principle	Selected Utilities using these Techniques
Regression	Multi–variable linear equations are developed to relate inputs (e.g., yesterday's consumption, current day rainfall, current day maximum temperature, current day solar radiation, etc.) to outputs (e.g., today's forecasted consumption).	Method is used in conjunction with other methods presented below.
Similar Day	A forecast is made by searching from a historical database of consumption, weather data, etc. for the day that closely matches with the projected conditions of upcoming day.	Colorado Springs Utilities*
Time Series	The base consumption is overlaid with long–term trends for growth, seasonal consumption, regressive component that accounts for weather in order to make a water consumption forecast.	El Paso Water Utilities Dallas Water Utilities
Expert System (Rule Based)	The forecasting is generated from water system operator's heuristic knowledge of consumption behavior (e.g., change in water consumption relative to a threshold value) under different conditions (e.g., winter, summer, rainy periods).	Lexington Kentucky American Water Company
Artificial Neural Network (ANN)	The model is trained by presenting it with a historical data set of observed inputs and the resulting observed consumption and an interactive process is used to minimize the error between the model prediction and observed consumption.	Jacksonville Electric Authority* San Diego Water Department* Las Vegas Valley Water District*
Hybrid	A combination of two or more methodologies (regression, expert system, and ANN) into one larger application.	Toronto Water†[1] Washington Suburban Sanitary Commission†[1] Las Vegas Valley Water District †[1] East Bay Municipal Utility District †[2] Greater Vancouver Regional District†[2] Seattle Public Utilities†[2]

*Installed STCF operational system
†STCF prototypes
[1]Regression, ANN, Heuristic
[2]ANN, Heuristic

Source: Cherchi, C., M. Badruzzaman, J. Oppenheimer, C.M. Bros, and J.G. Jacangelo. 2015. Energy and Water Quality Management Systems for Drinking Water Utility's Operational Cost Reduction: A Review. *Journal of Environmental Management*, 153, 108-120. (Also adapted from Jentgen et al., 2007)

3.4.2.1 Commercial Solutions for EWQMS

Both commercial software and research–grade optimization techniques from various academic efforts have been developed over the years. Commercial software suppliers, such as Derceto's *Aquadapt*, have achieved some success with real, extended operational examples (Derceto, 2013). Derceto's *Aquadapt* is widely implemented and a detailed description of the *Aquadapt* software is presented in Section 3.1. This section only describes the feature solutions currently available besides *Aquadapt.* In addition to *Aquadapt*, Innovyze's IWLive (Innovyze, 2013), Schneider Electric's *Aquis* and Tynemarch's *MISER–PSL* (Fowler and Main, 2010; Woodward and Fowler, 2011) are other commercial software products that are marketed as EWQMS packages that typically interface with commercial hydraulic models. These commercial products use different programming options to optimize pump scheduling.

Innovyze's *IWLive* is a real time modeling software that links water network models to SCADA in order to produce predictions of system behavior over daily or weekly periods. The *IWLive* system acts as the central core for the Innovyze Smart Water Network (SWN) and can perform offline analyses and online network simulations that are continuously updated with real-time SCADA data. It equips the water utility control room with modeling tools that are both predictive and reactive. *BalanceNet*, an add-on module of *IWLive*, overcomes the problem of extensive search space faced by metaheuristic solvers by performing a two-stage optimization that includes a linear mass balance followed by a pump selection based on a genetic algorithm. The conceptual schematic of an IWLive framework is presented in Figure 3.7.

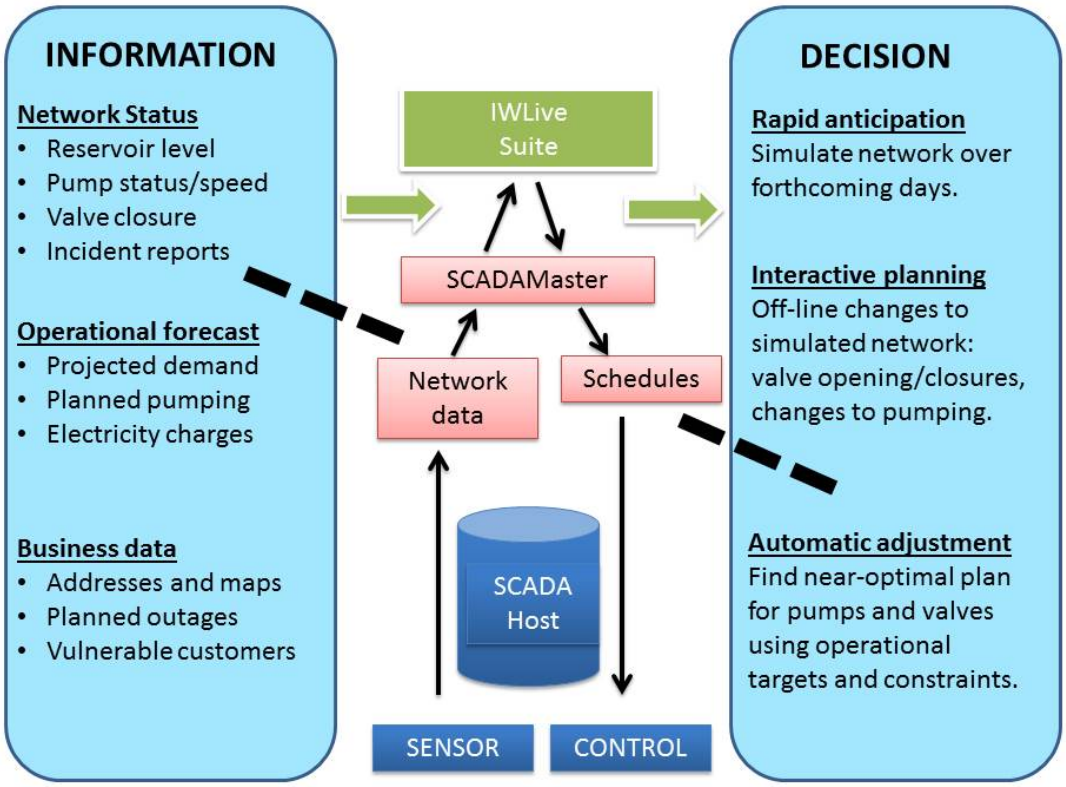
A real-time operations optimization software, *BalanceNet* extends the utility of SWN to help operators improve the efficiency of their networks and ensure more reliable operations at maximum cost (energy and chemical) savings. It automatically reads real-time field data, instantly updates the network model and determines the pump and treatment plant operation schedules that yield the lowest operating cost while satisfying desired system performance requirements (e.g., tank trajectory curves, minimum and maximum flows and velocities, total pump flows). *BalanceNet* combines an optimized mass balance storage model with the network model solver to quickly produce a set of near-optimal solutions for improving system operations. The network solver automatically defines the mass balance storage model, accounting for changes in demand, controls and other factors in each time step of the simulation period. The mass balance storage model is then optimized using Genetic Algorithms. Both electricity tariffs and pump switching costs are explicitly considered. The optimized pumping schedule can then be directly fed to the SCADA system for implementing the resulting network control policies.

Schneider Electric's *Aquis Operation*, a module of *Aquis Real-Time*, uses dynamic programming to optimize pump scheduling, reading data from SCADA systems and automatically sending a solution flow or pressure set point to the control system.

Tynemarch's *MISER–PSL* is a water resource planning tool for treated water production scheduling that utilizes linear programming to minimize total cost of production and transmission while meeting daily or weekly demand targets, and optimizes pump operation on short intervals (e.g. hourly) minimizing TOU cost while using predicted reservoir trajectory as a

constraint (Woodward and Fowler, 2011). The mass balance algorithm employed is based on user-defined rules for hydraulic transfer capability and pump operation, including average operating costs for treatment plant and pumping stations. The *MISER-PSL* software considers long and short term constraints such as water treatement plant 9WTP) flow limits, treatment chemical and electrical costs, maximum and minimum transfer rates, electricity tariff patterns, reservoir operation and demand patterns. Optimal pump schedules are generated by selecting more cost effective operating points within pumping stations, shifting pumping off-peak and utilizing cheaper water sources in the production plan. MISER is used by most UK water companies for long term and medium term offline production planning. In 2012, Wessex Water selected *MISER-PSL* (closed-loop) for optimization of production and pumping schedules in its supply area. Affinity Water (UK) also employs *MISER-PSL* for real time optimization of pump schedules in the Folkestone and Dover region.

Figure 3.7: *IWLive* conceptual framework (Innovyze, 2013)



In addition to commercial software, academic software applications have also been developed and applied for full-scale operation of major supply systems. Neptune (Savic et al., 2008), and POWADIMA (Salomons et al., 2007) are software applications principally developed by academics with government (e.g., European Union) and water industry funding. These academic trials have focused on developing suitable algorithms for management of real,

complex water supply systems by undertaking proof of concept studies using either off-line post processing or limited on-line real time control.

Project *Neptune* is a four-year collaboration project between a university and utility operators, for the development of a Decision Support System (DSS) for real time network operation. While *MISER-PSL*, *Aquis* and *Aquadapt* employ linear, mixed integer linear and dynamic programming respectively to control pump operations, Neptune pump optimization is formulated on Model Predictive Control (Skworcow et al., 2010; Fowler and Main, 2010; Derceto, 2013). Model Predictive Control is a technique employed to predict changes in dependent variables (e.g., system pressure, flow or reservoir level constraints) caused by setting independent variables (e.g., pump pressure, flow, valves, etc.). The procedure involves skeletonizing a hydraulic model, which is performed automatically during optimization and allows the primary hydraulic model to be modified in near real time in reaction to an event such as a burst, followed by re-optimization. The objective function is used to project possible solutions from the current baseline and minimize cost over a relatively short time horizon. Neptune was successfully tested on a medium sized water supply system in United Kingdom showing potential 30% energy cost savings (Skworcow et al., 2010). Neptune uses the EPANET hydraulic engine, GAMS modeling language and a non-linear solver CONOPT integrated with a commercial SCADA system. Neptune has been commercialized by ABB (Savic et al., 2008).

The EU funded the POtabale WAter Distribution Management (POWADIMA) software that employs an artificial neural network (ANN) predictor and genetic algorithm (GA) optimizer to introduce an optimal, real-time control of water distribution networks. The objective function is to meet the forecast demands at minimal operating pumping cost, subject to operational constraints such as statutory minimum pressure, minimum acceptable flow to avoid stagnation etc. POWADIMA was used to simulate storage tanks and pumping stations for networks within the cities of Haifa (Israel) and Valencia (Spain).

3.4.2.2 Research Approach for Evaluation of an EWQMS Modified with a GHG Module

Historically, the EWQMS framework was developed for simultaneous energy and water quality management to achieve operating cost reduction through real-time scheduling of pumping during off-peak tariff periods. However, little-to-no information is available on whether the existing framework could be utilized to achieve a water utility's energy consumption and GHG reduction goals. Too often, energy efficiency improvements remain uninvestigated due to concerns over constraints tied to water quality, production levels, and maintenance concerns.

One objective of this study was to develop and pilot test an integrated EWQMS modified with a GHG module to address the challenges of maintaining a proper relationship between cost reduction, energy minimization, GHG emissions reductions and water quality management. EBMUD and EMWD were selected as pilot test utilities. The functional specifications of the GHG module were appropriately developed and the module integrated into the existing EWQMS software product. Preliminary off-line simulations on specific portions of the distribution network in selected pilot areas were performed prior to piloting and reproduced the optimal pumping schedule to simulate and compare various optimization scenarios, which included financial costs savings, GHG emission reduction and efficient operation. Later, the tool

was validated through pilot testing in the selected sub-system based on the same optimization scenarios, and the results compared with the historical data (baseline) and those obtained with the offline evaluation. The conceptual schematic of the research approach used for this study is presented in Figure 3.1 and the description of the approach used is detailed in the following sections. The results of the offline simulations and pilot operations are presented in Chapter 4 and Chapter 5.

Figure 4.8: Research approach used in this study

3.5 Pilot Sites Selection

EBMUD and EMWD were the selected pilot utilities to test and validate the EWQMS modified with a GHG module. Both of these utilities currently have an EWQMS system utilizing *Aquadapt*. These two systems share many similarities but also have major differences. At the EMWD system, for example, some pumping stations include both electrical- and gas-driven pumps. Gas engines are used to avoid peak demand charges on the electric units. EMWD is in an area supplied by SCE, which relies on a mix of in-house power generation and power imported across the border from Nevada and they have higher GHG emissions per MWh than northern California energy suppliers. EBMUD has major water quality directives that limit operational flexibility; however, the impact this has on pump efficiency and GHG emissions has never been considered at this utility. Most of the EBMUD energy is supplied by Pacific Gas and Electric (PG&E), which has considerable hydro-electric power with zero GHG emissions, with additional imported power from thermal generation sources to meet peak demands.

Specific criteria developed to first shortlist and then select the pilot site at both EBMUD and EMWD included:

- Configuration (operations in a closed system);
- Ability to maintain full pump control;

- Ability to run the pump stations in series and parallel (EBMUD) or only in series (EMWD);
- Availability of mixed energy supplies consisting of natural gas and grid electricity (only at EMWD);
- Ability to utilize a mixture of flat rate and TOU tariff;
- Low operational and financial risk to the utility.

Based on these criteria, the pilot site at EBMUD was selected within the East of Hills operating area, which includes the Blackhawk, Blackhawk East and Acorn pumping stations. The East Valley region was selected as the site for pilot testing at EMWD and includes the Diamond 3, Mission Canyon 1 and Mission Canyon 2 pumping stations.

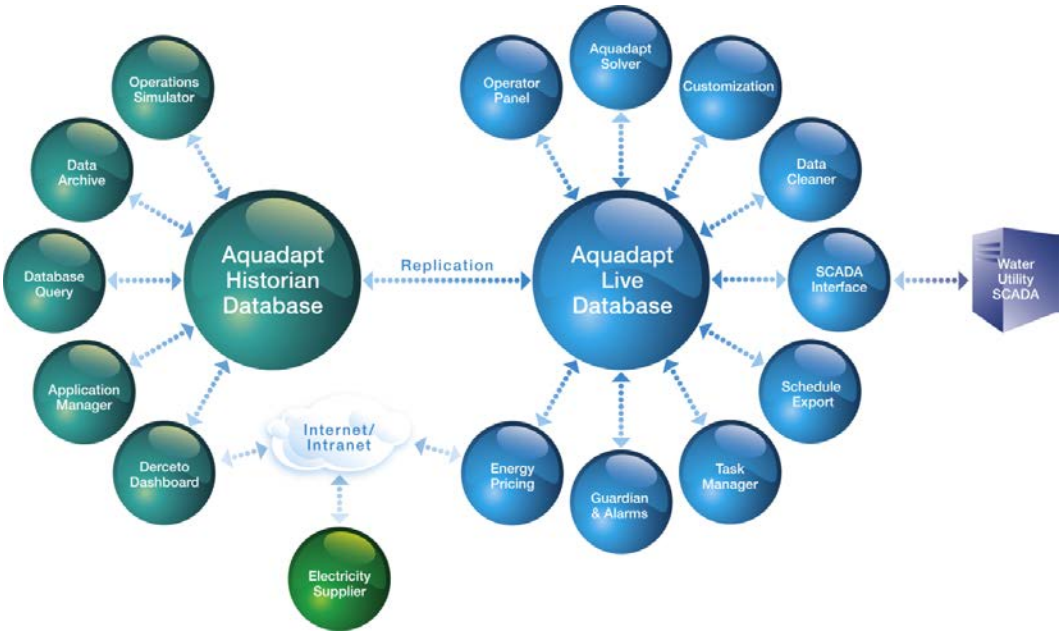
Detailed information on the pilot utilities and related pilot sites are presented in the following Chapter 4 for EBMUD and Chapter 5 for EMWD.

3.6 Development of GHG Module Functional Specifications

EMWD and EBMUD currently have an operational EWQMS system utilizing *Aquadapt*. The specific pump stations and assets identified in the pilot areas were integrated into the core product and reconfigured to use the GHG module in the optimization and decision making process.

The EWQMS system software is a modular real-time, on-line water distribution system optimization package that schedules pumps, flow control valves and production up to 48 hours in advance in large distribution systems. The system continuously adapts to refine its schedule in real-time in response to changing conditions including demand changes, equipment availability and treatment plant capacity. The software also improves water quality by seeking to increase turnover of storage and minimize production flow disturbances. Conceptual schematics of the software and related modules are presented in Figure 3.2.

Figure 4.9: Conceptual schematic of Derceto's *Aquadapt* (Derceto, 2013)



These modules were modified to include the new GHG emissions reduction component as the primary objective. A separate GHG optimizer module was created by the project team for the offline trials and consists of an Excel spreadsheet that runs a Visual Basic for Applications (VBA) program. The VBA program embedded in the spreadsheet calculates the optimal pumping schedule using a "greedy" algorithm typically used for an Optimization /Operation Research toolbox. A "greedy" algorithm is heuristic and makes a locally optimal decision at each stage of resolution in order to find the global optimum to the problem. The optimization criterion is based on minimization of the amount of GHGs released by the energy utilized to sustain pumping. The optimizer is capable of shifting as much pumping as possible to "greener" periods through analysis of the amount of GHGs released per unit of energy used at each period of the day. Figure 4.3 provides a schematic of the GHG module.

The GHG module requires the following inputs:

- Pump curves and efficiency curves. These curves are used to accurately calculate the historical and predicted energy usage of the pumps.
- GHG "tariff". It is a table of 48 values for 30 minutes period stored as a curve representing the amount of CO_2 released through the generation of one kWh of energy for a given day.
- Historical operational data. This information is required to calculate the historical CO_2 usage. This value is compared to the optimizer predictions and the historical water demand for the given day. Historical operational data include:
    - Pump flows. The user enters the 48 half hourly flows for each pump within the pump

station to be optimized.

- Outflows or pump outflows. It includes the amount of water that the pumps withdraw from a reservoir for each half hourly period.
- Tank level/volume for each half hourly period.
- Pump total dynamic head values. The pump head is used to calculate the energy usage.

The tool uses these data to calculate the historical water demand for that day and the historical CO_2 usage. When the optimization is being performed at the start of the day, a demand prediction profile can be entered to replace the historical data.

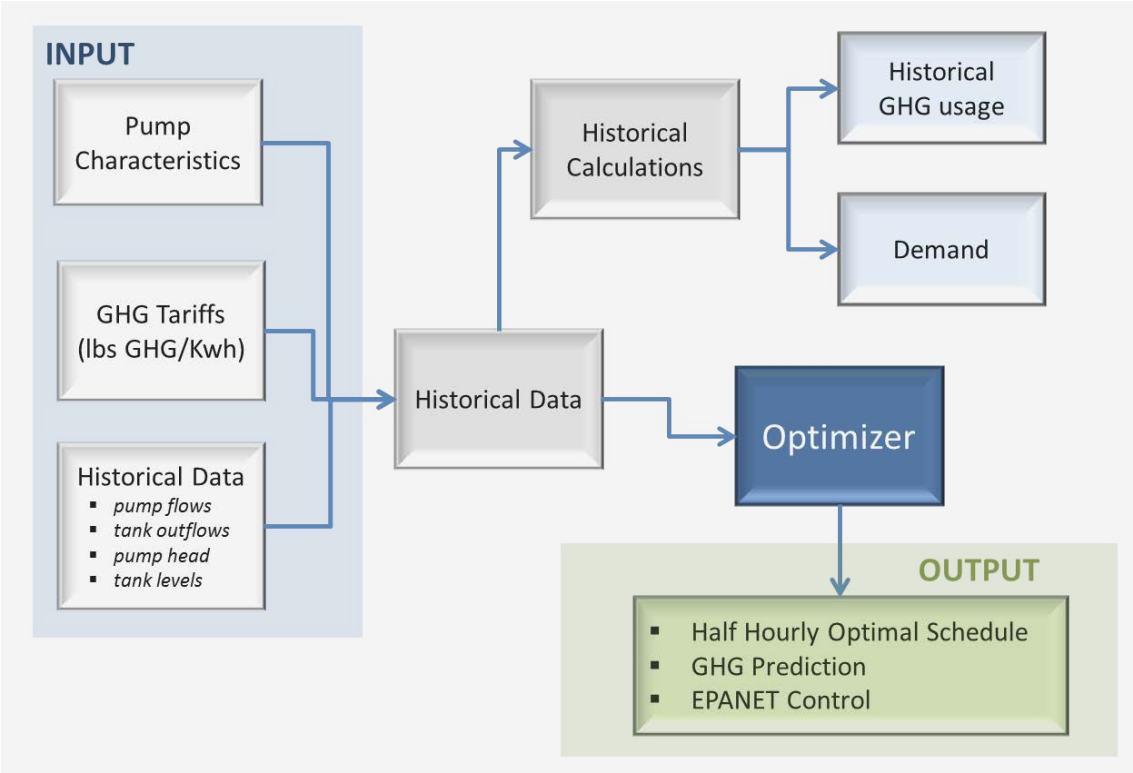
The module optimizes a pump station's schedule in half-hour periods for the upcoming 24 hour period. For each of the resulting 48-half-hour periods, the optimizer outputs the number of pumps to be used and the resulting tank volume. The optimizer then simulates the optimization software for that pump station. The pump schedule generated is then exported into EPANET format and allows the user to run a hydraulic simulation based on this schedule.

The optimizer relies on the greedy algorithm to find an optimal solution to the pump scheduling problem. The following steps illustrate the logic of the algorithm:

- Step 1: Obtain the initial level / volume of the reservoir;
- Step 2: Set the "start" period at the beginning of the day;
- Step 3: Use the demand profile to calculate the period of the day in which the minimum volume of the reservoir is breached, the "breach" period;
- Step 4: Rank by "tariff" (GHGs released per unit of water moved) and availability during all the periods between the "start" period and the "breach" period;
- Step 5: Turn on the lowest cost pumping period;
- Step 6: If adding pumping in this period causes the tank to breach maximum volume, set the new "start" period to be the subsequent period;
- Step 7: Recalculate all tank volumes and pumping costs for all the periods of the day between this period and the end of the day.
- Step 8: Repeat steps 3 to 7 until the demand is satisfied.

The steps described above are a simplification of the algorithm; additional fine-tuning of parameters and safety verifications were performed.

Figure 4.10: Conceptual schematic of the GHG module



3.7 Selection of Optimization Scenarios

Three different optimization scenarios were considered during the offline evaluations and pilot operations and their descriptions are provided in Table 4.1. The analysis compared historic manual (baseline) operation with the optimization objectives of cost reduction, kWh reduction or GHG reduction during the high demand summer season. During the offline simulations, the analysis was performed to predict system response for a week in winter, representing low water demand periods, for all optimization scenarios.

The cost reduction optimization scenario targets the lowest cost for pumping by scheduling the pumps at a lower tariff period and by minimizing energy consumption through operational pump efficiency improvements.

The optimization targeting kWh reduction limits the amount of energy used to move water, by moving it with the lowest hydraulic resistance and operating at the most efficient point on the pump curve. The kWh optimization scenario does not account for the energy source providing electricity (e.g., coal, hydropower, nuclear, wind, etc.), which results in different GHG emissions levels.

Table 4.6: Description of the offline simulation scenarios

Optimization Scenario		Description
Optimization Scenario	Baseline	**Primary principle:** System under no EWQMS operation (manual control by operators)
	Cost Optimization	**Primary principle:** Pump operated when the cost is minimum (selection order: off-peak, mid-peak, on-peak) **Secondary principle:** Pump operated at the lowest specific energy (kWh/MG pumped)
	kWh Optimization	**Primary principle:** Pump operated at the lowest specific energy (kWh/MG pumped) **Secondary principle:** Assumes flat tariff operations *Note: kWh optimization is the GHG optimization when flat GHG emission factors are used*
	GHG Optimization	**Primary principle:** Pump operated when the GHG emission factor (lbs-CO_2/MWh) is minimum **Secondary principle:** Pump operated at the lowest specific energy (kWh/MG pumped) *Note: Assumes that GHG emission factors vary depending on the energy sources*
Water Demand	Summer	Season characterized by high water demand
	Winter	Season characterized by low water demand

The GHG optimization scenario is the kWh optimization that includes accounting for the energy source. Typically, fixed emission rates of GHG (652 pounds [lbs] per MWh of electricity are assigned per kWh of electricity consumed in California, EPA eGrid, 2012) and using a flat rate emission factor is expected to produce an optimization strategy identical to the kWh optimization. However, in electricity markets, such as that in California, at times of high energy demand, power is imported from out-of-state coal fired power plants, while in lower demand periods the lower GHG hydropower, wind farm and nuclear sources within California provide the bulk of California's energy requirements. Thus, variable emission rates of GHG should be assigned per kWh of electricity consumed depending on the time of the day. As the real-time emission factors were not available for this study, the offline evaluation and pilot operations at EMWD and EBMUD were performed using the data obtained by the PLEXOS model (California Public Utilities Commission [CPUC], 2010). The PLEXOS model of the California energy market takes into account all of the generators supplying energy into the California market. The model

shows that there is a generalized linear relationship with a positive slope between market demand for power and the average GHG per MWh, indicating that as demand increases, less efficient generators enter the market, i.e., the last generators into the market generally have higher CO_2 emissions per MWh delivered (Figure 4.4). This slope function was then applied to actual total market demand for the weeks analyzed in July and February 2013. The market demand data was obtained directly from the California Independent System Operator (CAISO) database. While the range of values for CO_2 per MWh across the day was small, there was a noticeable pattern where higher demand periods, which are also the most expensive tariff periods aligned with higher CO_2 emissions, so optimizing for CO_2 also tended to avoid higher cost periods. An example of this trend for EMWD is shown in Figure 4.5 highlighting the similarity between the tariff profile during a summer week and the GHG emitted per MWh delivered.

Figure 4.11: Emission of CO_2 per MWh delivered based on the PLEXOS model of the California energy market

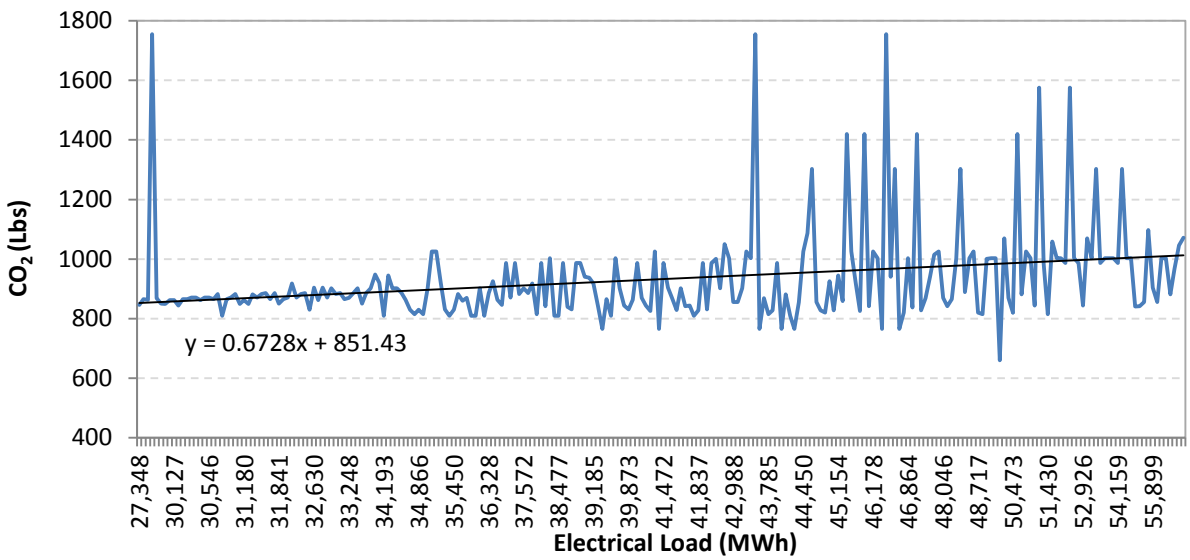
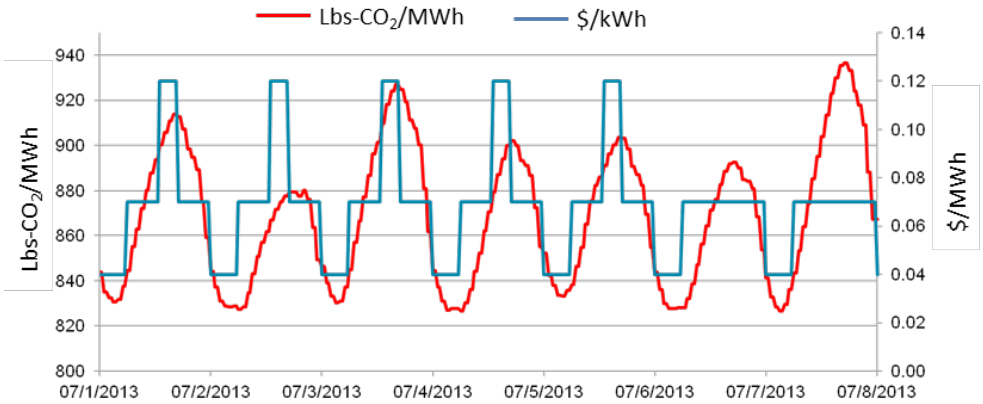


Figure 4.12: Comparison of energy tariffs and CO_2 emissions for MWh delivered



3.8 Offline Simulations of System Operation and Water Quality

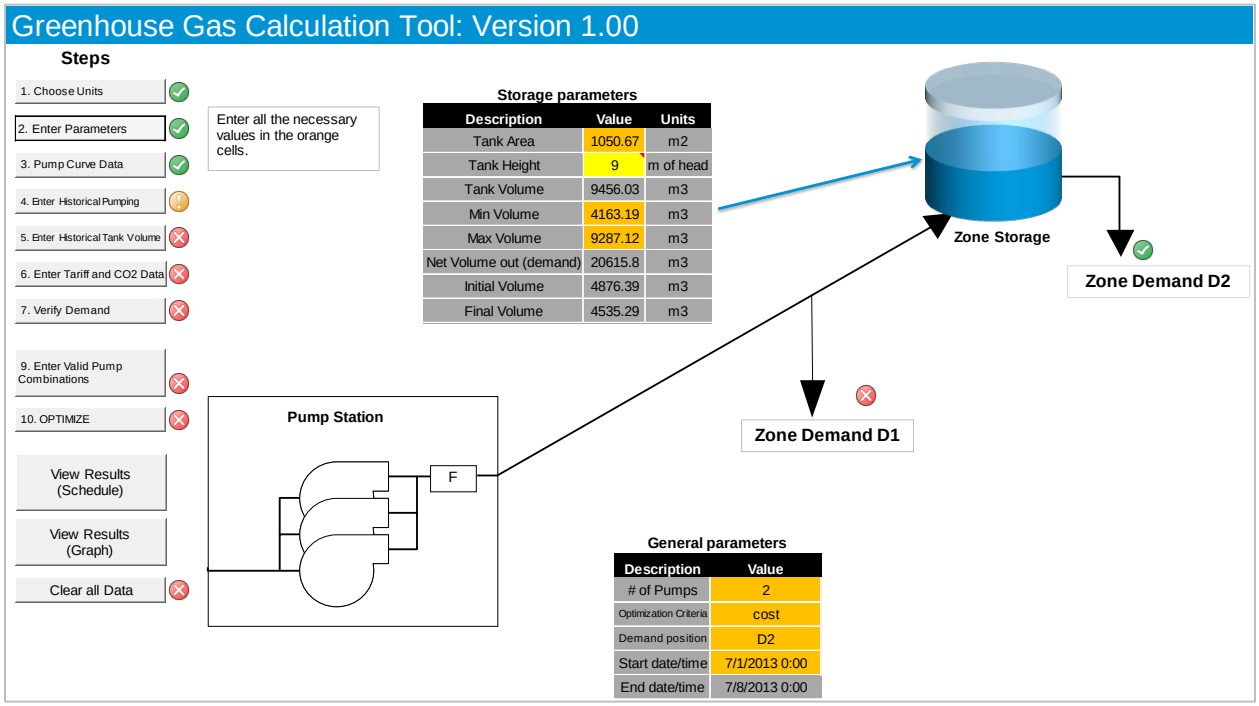
A series of offline trials were performed for different optimization strategies on the representative sub-system within the EBMUD and EMWD operating areas to predict system operations and water quality implications under different optimization scenarios. Details on the offline simulations approach are reported in the following sections and the related results presented in Chapter 4 (EBMUD) and Chapter 5 (EMWD).

3.8.1 Offline Simulations of System Operation

The offline simulations were performed using the Excel VBA-based simulator with logic previously described. Figure 3.6 shows the interface of the Excel-based offline simulator. The system predictions and operations are attained by the offline simulator using an array of algorithms that solve optimization problems for one pump station and one reservoir at a time for each optimization criteria. When the off-line GHG module is integrated into the EWQMS software, the production of GHG emissions becomes the objective function that is minimized during optimization. Five different strategies were identified as a means of achieving GHG emission reduction:

- *Running pumps in series*. This strategy enables pump stations in series to move water with a lower overall total dynamic head.
- Pumping into emptier tanks.
- *Pumping in low GHG periods*. The supply of energy into the California market, for example, comes from different sources. Hydroelectric and nuclear power have very low (zero) GHG emissions while high carbon footprints are associated with coal fired power. If the list of energy sources for the different times of the day (or average value for a small region at Eastern) is provided by the power suppliers, it may be possible to calculate the corresponding GHG emission factors in real-time.
- *Efficient pump selection*. The pump efficiency curves were used to select the pumps to run in a given station at a given period of time.
- *Electric versus gas-driven pump selection*. The selection of a gas-driven versus an electric pump is be made depending on the lowest GHG emissions that the two options produce in a given condition.

Figure 4.13: Interface of the Excel VBA-based offline simulator



3.8.2 Offline Evaluations of Water Quality

Calibrated hydraulic models were provided by EMWD and EBMUD for the offline simulations. Two versions of the calibrated hydraulic model for the Blackhawk system were approved by EMBUD for use in the off-line optimization. The models were previously acquired for the EWQMS establishment and operation, and comprise a recently simplified model (EBMUDrevised071217.inp) and a more detailed model dating from 2003 (SanRamon(BAT).inp). Both models were provided in EPANET format. The simplified model comprises 2,177 pipes and 2,018 junctions and represents all significant mains in the EBMUD San Ramon system; the larger model represents the same network in 2003 but also contains the smaller distribution pipes and a more accurate representation of customer demand. The average demand for the winter, spring and summer weekly periods investigated offline were 1.07 MGD, 3MGD and 3.70 MGD, respectively.

EMWD provided MWH with the calibrated hydraulic model for the East Valley system (EMWD_POTABLE_2164_10-1.mxd) in InfoWater format. The InfoWater model comprises some 3700 pipes and 3030 junctions and represents all significant mains in the EMWD East Valley system. The average demand for the two weekly periods investigated was observed to be 0.24 MGD in the winter week and 0.79 MGD in the summer week.

Model Validation. The simplified model was updated and validated before simulating operations of the off-line optimization scenarios by comparing against actual recorded flow and level at each pumping station and tank. This was conducted in order to demonstrate the applicability of

the model for subsequent water quality investigations. The hydraulic validation shows that the InfoWater model is capable of matching pump operation (flow and switching) and reservoir performance (levels) with an acceptable degree of accuracy. As only limited data were available to validate the model, it was not practicable to make adjustments to the basic model parameters to achieve a closer match. The model demand distribution and pipe velocities have been accepted as sufficient for the purposes of this study. Because each model utilizes the same parameters and assumptions, the outputs can be compared directly, without concern for small modeling inaccuracies introduced in the update process. Note that water age values cannot be measured in the field, and it is not possible to independently validate the model predictions.

Hydraulic Modeling. The models are used to compare the performance of the different operating strategies investigated in the off-line optimization. They are sufficient to identify any noticeable differences in water quality resulting from the selected pump schedules, using age of water as a surrogate for the actual chemical and physical characteristics of the water in the system.

Three optimization scenarios were modeled in the InfoWater model using pump switching derived from the off-line simulations minimizing cost, GHG and kWh. Basic demand and flow data for each scenario, and the actual operation were also developed. The prime purpose of hydraulic modeling in the offline evaluation was to identify whether changes in water quality could be expected during the pilot test under different optimization scenarios.

Water Quality Predictions. Water quality in the Blackhawk pilot zone (EBMUD) and Diamond 3 zone (EMWD) was modeled in InfoWater using the Age of Water quality option. The Age of Water simulation employs a number of assumptions, which include:

- Water entering the system at sources (treatment plant and wells) has zero age;
- Water quality at the start of simulations for each pipe, junction and tank in the system is initialized using results of prior extended period simulations until predictions stabilize;
- Water quality in tanks is modeled using Continuous Stirred Tank Reactor approach in which water entering the tank immediately mixes with water in the tank (i.e. completely mixed);
- Water age at dead end pipes with no demand applied (a model simplification) continue to age indefinitely and can be ignored.

The various sources for the primary pumping stations in each network are all some distance upstream of the pilot test zone. There are no direct sources within the zones (for example a borehole). Hence, the age of water entering the system is dependent on the performance of the entire upstream network. The operating schedule for each primary pumping station also affects the water age entering the downstream system. Both effects have been predicted in the model. Results have not been revalidated as part of this project and the output from upstream predictions has been taken as given. To ensure a representative initial water age in the entire network, the spring, summer and winter demand scenarios were run for 14 days of standard pump operation (on level control) prior to simulating actual or optimized off-line controls.

Water quality modeling results were used to determine whether planned on-line optimization scenarios could materially affect the quality of water being delivered to customers.

3.9 Real-Time System Operation and Water Quality

The EWQMS modified with GHG module was tested for real-time operation in the selected subsystems at EBMUD and EMWD. During the pilot, each optimization scenario (cost, kWh and GHG optimization) was scheduled to run for at least two weeks. Water quality measurements at the tanks in the system have been obtained and have been used to monitor actual performance and to corroborate the general predictions made offline.

A pre-pilot test plan was developed to instruct the utility on the modifications that the software developer made to the server, the database and the software in preparation for the pilot. A series of guidelines were also developed for operator training purposes, which include instructions on system operations, avoidance of overrides, etc. The elements of the pre-pilot test plan are included in Table 4.2.

During the real-time pilot operations the project team has:

- Reviewed the SCADA data and EWQMS schedules daily;
- Responded promptly to troubleshooting tickets issued by the utilities;
- Attended weekly online meetings with the pilot utilities to provide/receive progress updates on the pilot operation performance;
- Coordinated operator efforts for water quality sampling and energy data readings; and
- Conducted a site visit at EMWD and performed water quality sampling with the field operator.

Table 4.7: Elements of the pre-pilot test plan distributed to the utilities

Pre-Pilot Test Plan	
Operator's Training	▪ Install "short-cut" to open software interface; ▪ Training of Op/Net Engineer by software developer; ▪ Develop guidelines for operators to follow during the pilot (e.g., including instructions to reduce instances of overrides).
Server Upgrade and Operator Panel Changes	▪ The core software remained unchanged; ▪ The customized code has been adjusted with focus on the pilot sites; ▪ Deactivation of all non-pilot sites in the system and their removal from the operator panel.
Database Modifications	▪ Pilot sites split from rest of system with identification of boundary reservoirs; ▪ Updated pump curves with latest test data.
Software Modifications	▪ New executables to run specifically for the pilot site split.
Hydraulic Model	▪ Updated hydraulic model to reflect system split.
Economic Pump Control (EPC) software	▪ EPC to designate the software developer control ("energy schedule"); ▪ Change EPC pump priorities at each pump station.

A series of quality assurance and quality control (QA/QC) tasks were performed to ensure the precision, accuracy, completeness, comparability and representativeness of both qualitative and quantitative data throughout the pilot. The project was run under ISO 9001 Quality Management processes and each deliverable reviewed through a multistage quality assurance, signed off at each step and revision, and then issued along with a formal Document Transmittal notice to enhance traceability. Data accuracy was verified by calibrating the model used to predict GHG emissions and kWh's against recent historical data. The EWQMS system was fed recent information and produced predicted kWh values for each energy account. These were then compared against actual accounts received from the electricity supplier.

After the pilot installation, actual values of kWh were read from the electricity suppliers metering and used to calculate kWh per MG delivered. This value was then compared with kWh per MG for the same sites prior to the installation of the GHG module. This process used the water utilities water demand metering information and the electricity suppliers meter data and was therefore independently sourced. The statistical basis to be used in the data analysis, emission factors, data sources, statistical analysis was defined.

Water quality data was properly reviewed by the utility QA/QC team and the project team. The following elements were subjected to review: sampling procedures, sample chain of custody, development and strict adherence to principles of good laboratory practice (using qualified staff and reliable, well-maintained equipment), verified and specified analytical methods for

measurements (including sensitivity, selectivity, precision, and accuracy), and consistent use of standard instrument operation procedures (including calibration and standardization procedures, minimum reporting limits (MRLs) and/or method detection limits (MDLs), and frequency).

Details of the pilot test plans for each utility and results are reported in Chapter 4 (EBMUD) and Chapter 5 (EMWD).

CHAPTER 4:
Implementation of the EWQMS Modified with a GHG Module at East Bay Municipal Utility District

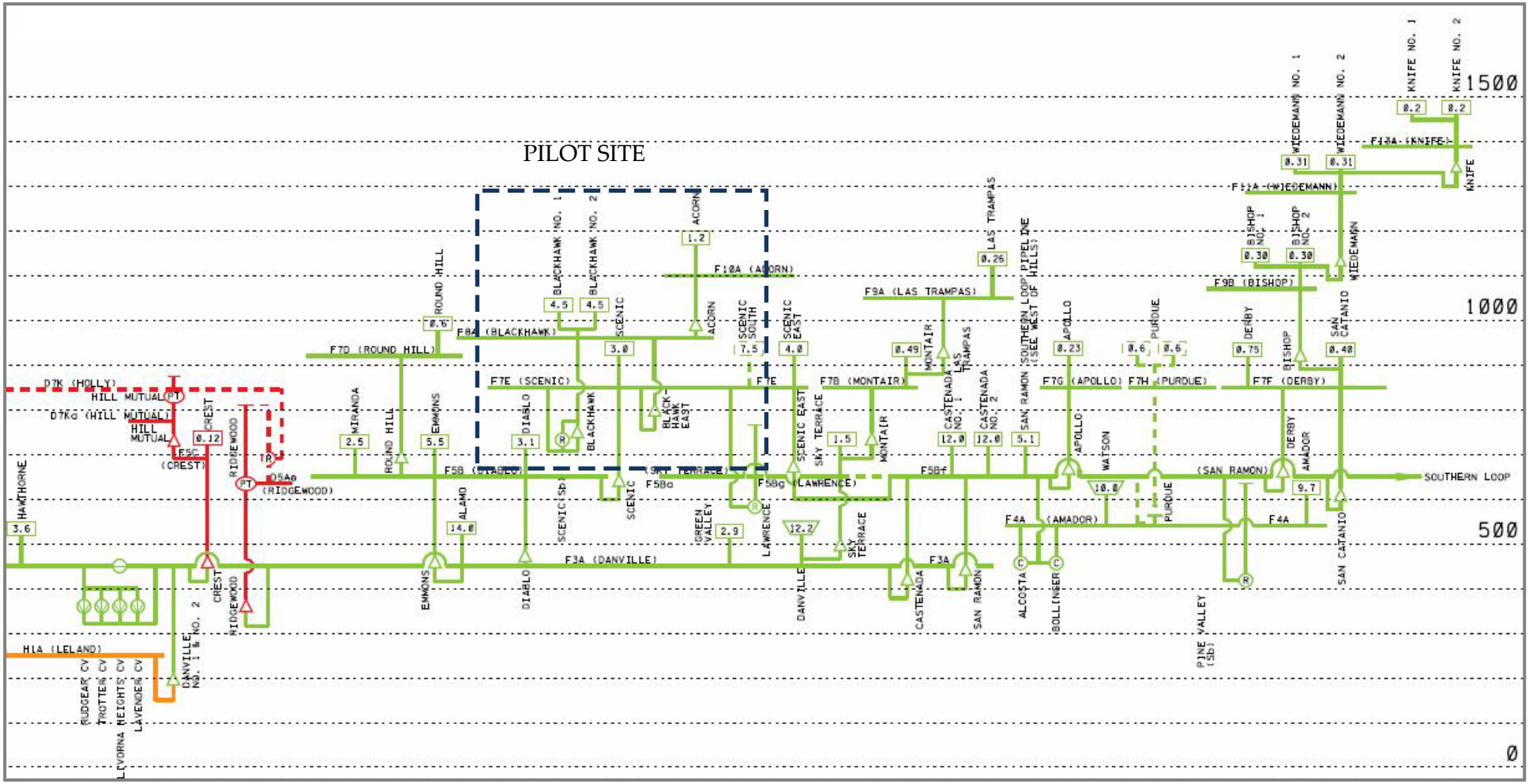
This chapter includes the findings of the offline simulations and of the real-time pilot operations of the EWQMS modified with the GHG module at EBMUD. This chapter also includes water quality predictions that foresee the potential impacts of energy optimization and GHG emissions reduction on the water quality in tanks and to customers and those resulting from real-time operations.

4.1 Pilot Site at EBMUD

EBMUD serves 1.3 million people in the Alameda and Contra Costa counties with approximately 375 MGD average peak daily demand. In 2004, EBMUD implemented the EWQMS system, in the San Ramon area, which accounts for about 30 percent of the total energy use and 20 percent of the total geographical area of the district and 33 percent of the total volume of water supplied. The annual energy bill for the optimized distribution network at EBMUD is $2.8 Million.

The pilot site area was selected within the East of Hills of the San Ramon area, which includes the Blackhawk, Blackhawk East and Acorn pumping stations (Figure 5.1). The schematic of the selected pilot area is presented in Figure 5.2. The pilot site is supplied by two reservoirs (out of three available reservoirs, one was out of service) and characterized by a large storage to supply demand ratio. The upstream storage of the Scenic and Scenic East Reservoirs was not considered as part of the offline simulation and pilot operation analysis. All pumping stations in the EBMUD pilot area have three electric pumps with a maximum of two pumps that can run simultaneously (Figure 5.3). The Blackhawk and Blackhawk East pump stations run in parallel and both are in series with the Acorn pump station. Running the Acorn Pump station simultaneously with either of the other pumping stations has a hydraulic benefit in that the first pump station increases significantly the suction pressure at the second pump station, thus the pump operates at a more desirable head/flow and efficiency/flow condition. The Blackhawk pump station has smaller pumps, running at lower flow rates than the Blackhawk East pump station, thus with lower hydraulic resistance and lower energy use per million gallon pumped.

Figure 5.1: A schematic of the EBMUD's East of Hills operating area.
(The outlined area is the pilotsite selected for this study)



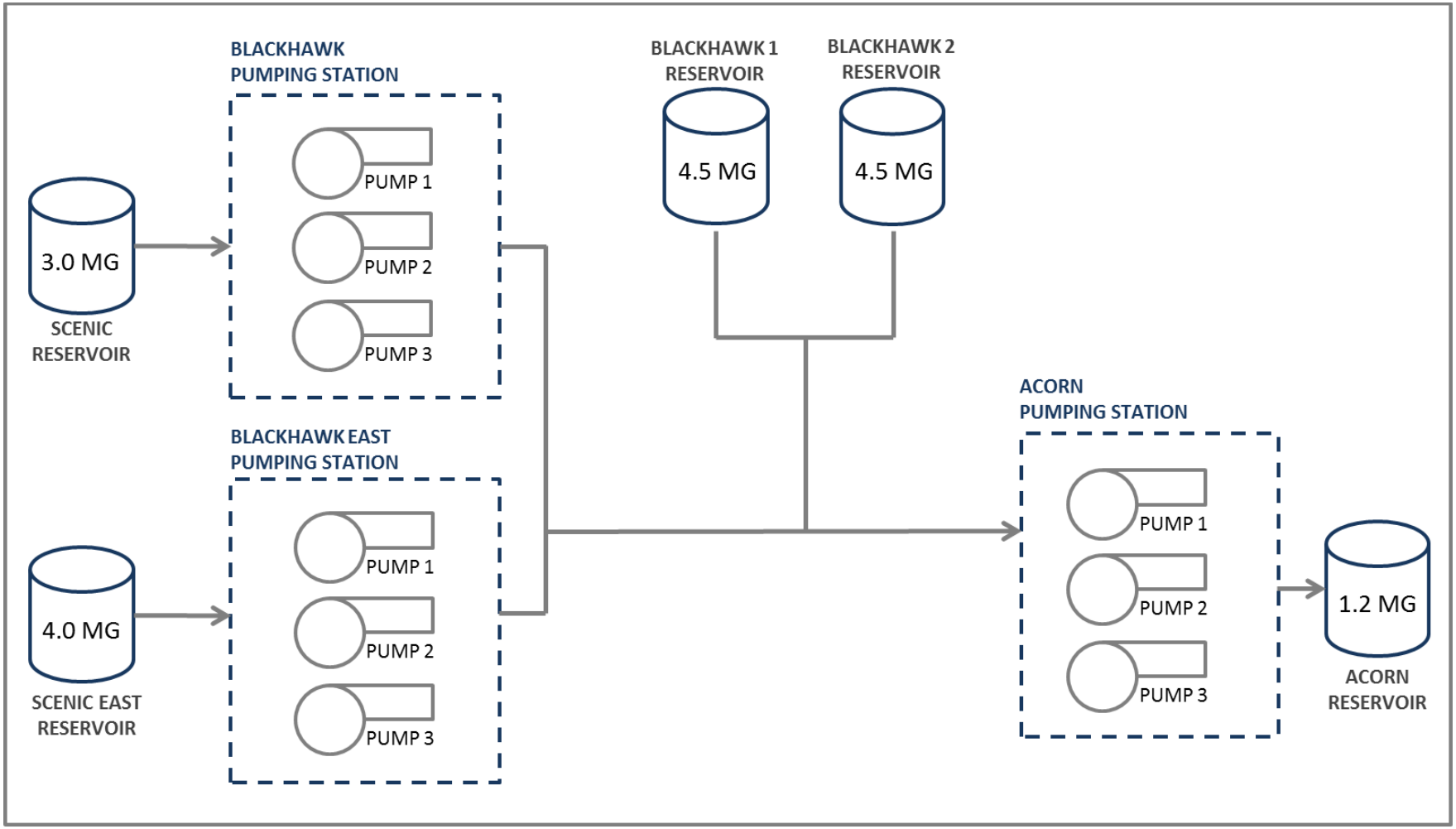

BLACKHAWK
PUMPING STATION
BLACKHAWK 1
RESERVOIR
BLACKHAWK 2
RESERVOIR
4.5 MG
4.5 MG
3.0 MG
SCENIC
RESERVOIR
PUMP 1
PUMP 2
PUMP 3
ACORN
PUMPING STATION
BLACKHAWK EAST
PUMPING STATION
PUMP 1
PUMP 2
PUMP 3
4.0 MG
SCENIC EAST
RESERVOIR
PUMP 1
PUMP 2
PUMP 3
1.2 MG
ACORN
RESERVOIR

Figure 5.3: Pumping stations and tanks in the pilot site at EBMUD

4.2 Offline Evaluation of EWQMS Modified with GHG Module

The offline trials used a simulator to determine the outcomes for different optimization strategies on the representative sub-system within the EBMUD operating area. Three different optimization scenarios were considered during the offline evaluations and their description is provided in Table 5.1. The analysis compared historic (baseline) operation with the optimization objectives of cost reduction, kWh reduction or GHG reduction for summer and winter scenarios, using historical data from July 1-7, 2013 and February 21-27, 2013, respectively.

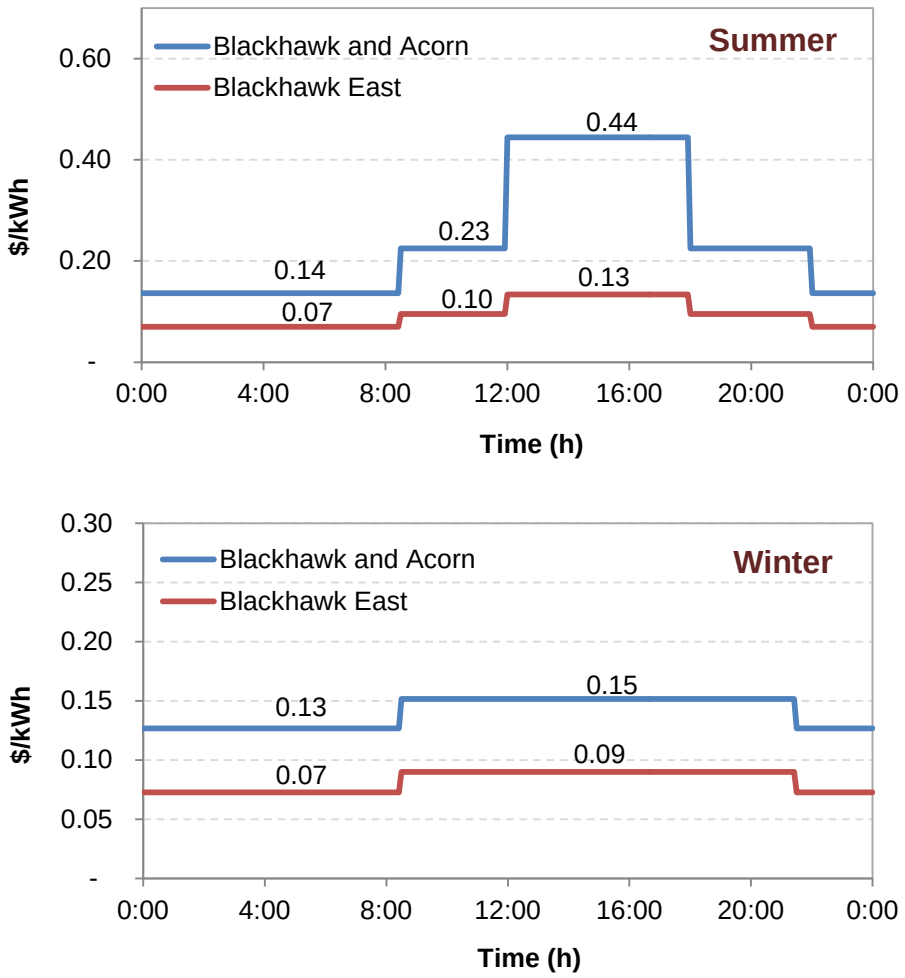
At EBMUD, all pump stations were subject to seasonal TOU tariffs by PG&E (e.g., summer and winter). The Blackhawk East tariff structure is characterized by lower rates than those applied to the Blackhawk and Acorn pump stations (Figure 5.4) and includes three peak period demand charges: a maximum-peak-period ($14.59/kW for summer and winter), a maximum-part-peak-period ($3.41/kW for summer and $0.21/kW for winter), and a maximum-demand charge ($11.85/kW only for summer). The maximum-peak-period-demand charge per kilowatt applies to the maximum demand during the month's peak hours, the maximum-part-peak-demand charge per kilowatt applies to the maximum demand during the month's part-peak hours, and the maximum-demand charge per kilowatt applies to the maximum demand at any time during the month.

Details on the offline analysis and related results are reported in the following sections.

Table 5.1: Description of the offline simulation scenarios

Optimization Scenario		Description
Optimization Scenario	Baseline	**Primary principle:** System under no EWQMS operation (manual control by operators)
	Cost Optimization	**Primary principle:** Pump operated when the cost is minimum (selection order: off-peak, mid-peak, on-peak)
	kWh Optimization	**Primary principle:** Pump operated at the lowest specific energy (kWh/MG pumped) *Note: kWh optimization is the GHG optimization when flat GHG emission factors are used*
	GHG Optimization	**Primary principle:** Pump operated when the GHG emission factor (lbs-CO_2/MWh) is minimum *Note: Assumes that GHG emission factors vary depending on the energy sources*
Water Demand	Summer *(High Demand)*	Scenario optimized in the week of July 1-7, 2013
	Winter *(Low Demand)*	Scenario optimized in the week of February 21-27, 2013

Figure 5.4: PG&E TOU tariffs applied at the Acorn, Blackhawk and Blackhawk East pumping stations during the offline simulations at EBMUD

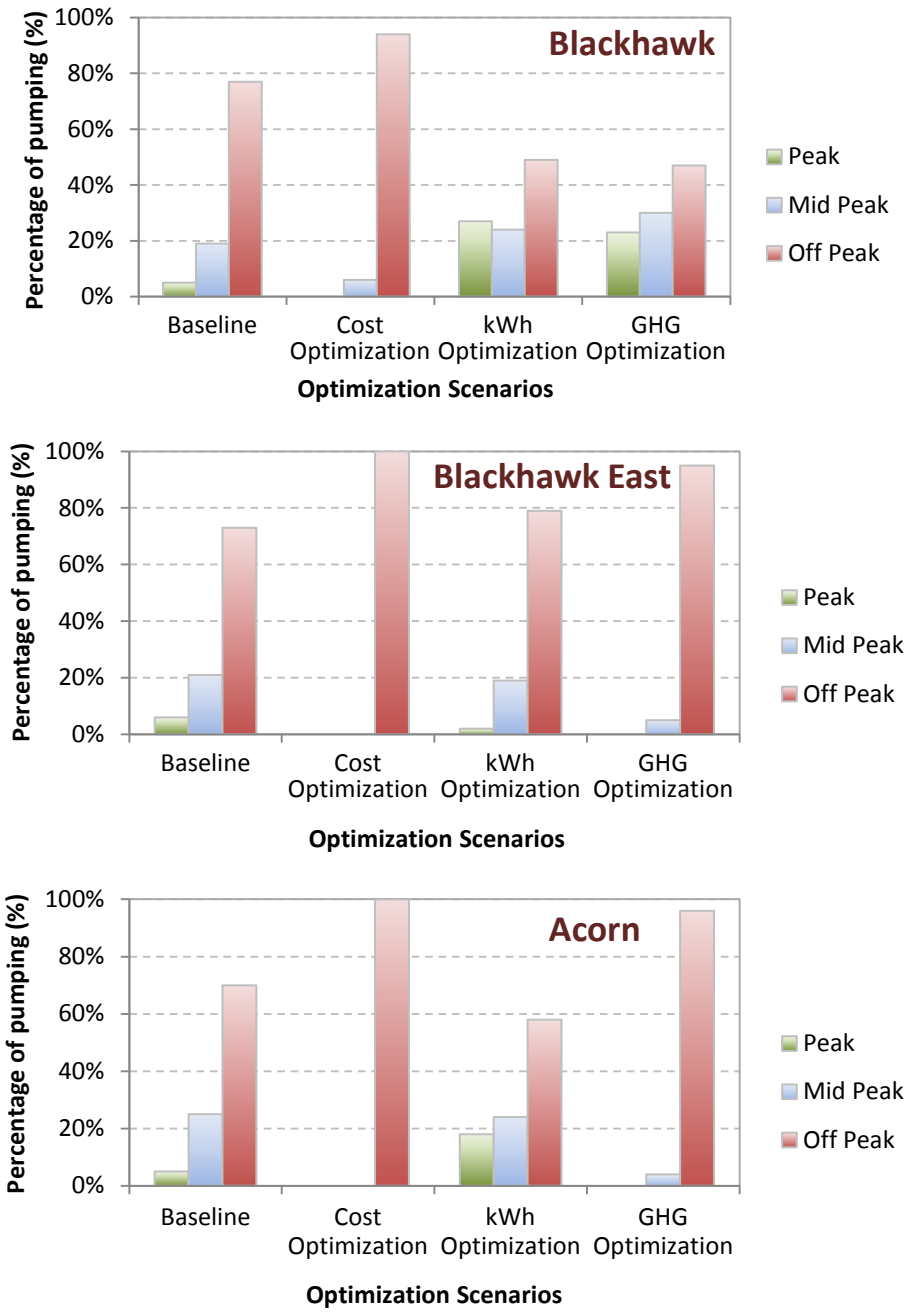


4.2.1 Summer Simulations Results

Figure 5.5 shows the percentage of pumping at Blackhawk, Blackhawk East and Acorn pump stations during different tariff periods and for different optimization scenarios. For all pump stations, the cost optimization scenario shifted the load (94 percent at Blackhawk and 100 percent at Blackhawk East and Acorn) to off-peak periods, with no pumping occurring during peak times. Due to the avoidance of pumping during the peak and mid-peak periods at Blackhawk and the peak period at Blackhawk East, the cost optimization simulation operated against a higher average head than any other scenario. At Blackhawk, when the system was optimized for GHG and kWh, 23 percent and 27 percent of the pumping, respectively, occurred during peak hours. The Blackhawk East and Acorn pumping stations, mostly avoided the peak and mid-peak periods under all the optimization scenarios except kWh minimization for Acorn, and significantly operated with cascade pumping, although this was mainly due to the high utilization of all pump stations. In general, under all the optimization scenarios, there was an increase in pumping by the Blackhawk pump station and a correspondent decrease in pumping

from the Blackhawk East pump station if compared to the historical values. It should be noted that pumping at Blackhawk required lower energy per unit of water pumped than the other stations, but this pumping station was under a more expensive tariff structure. The trade-off between kWh reduction and cost increase was considered in the optimization. In addition, during summer, when demand is much higher, there is less flexibility for pumping higher volume of water due to the increased demand (lower storage to demand ratio).

Figure 5.5: Percentage of pumping at different tariff periods under the baseline, cost, kWh and GHG optimization at Blackhawk (top), Blackhawk East (mid) and Acorn (top) pumping stations during summer



Figures 4.6, 4.7 and 4.8 summarize the results for the one-week simulations of cost reduction, kWh reduction and GHG reduction optimization scenarios for the summer period at EBMUD. The results are compared in terms of energy usage, cost incurred, and GHG production. The cost analysis includes the actual energy cost associated with pump operations and the demand charges applied to the Blackhawk East pumping station for the anytime maximum demand, maximum mid-peak demand and maximum peak demand. Both the kWh and the GHG minimization strategies were permitted to pump during peak tariff periods. The highest demand charges were obtained in the baseline and kWh scenario, mostly due to the pumping during on-peak periods.

Optimizing for cost reduces the cost associated with pumping ($1,924/week) when compared to the other scenarios analyzed (Figure 4.6). The cost optimization used 0.4 percent more energy (15,261 kWh/week), thus, produced higher GHG emissions than historical operation (15,204 kWh/week). The kWh optimization minimizes the energy use (14,282 kWh/week) but generates higher costs than the other optimization conditions ($3,149/week) as it required pumping during very expensive tariff periods. The pumping schedule generated by the GHG optimization is 1 percent and 35 percent more expensive than the baseline and the cost optimization condition, respectively. Although more expensive, the kWh and GHG optimization reduced energy consumption and GHG emissions compared to the baseline and cost optimization scenarios (Figures 4.7 and 4.8).

Figure 5.6: Weekly energy costs and demand charges associated with all pumping stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization during summer

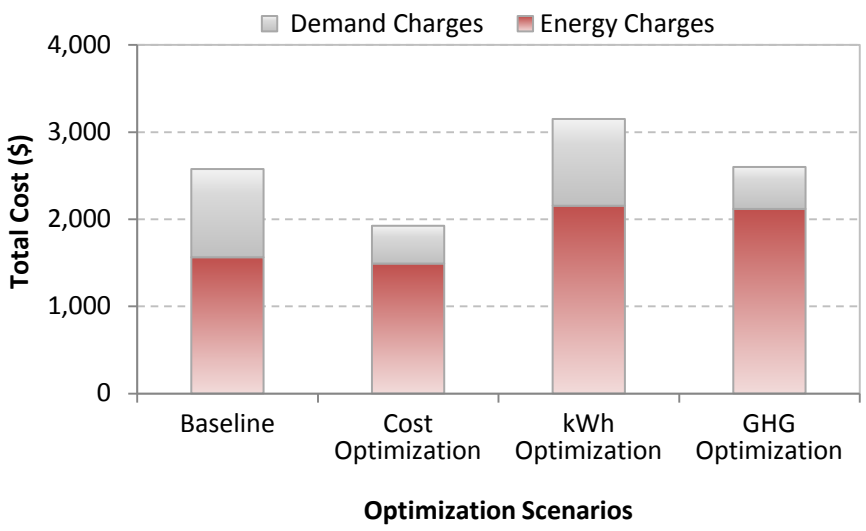


Figure 5.7: Weekly energy consumption associated with all pumping stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization during summer

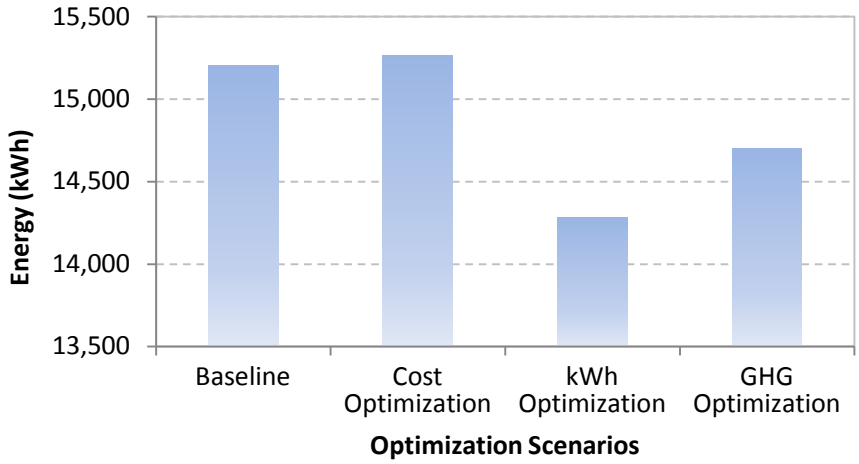
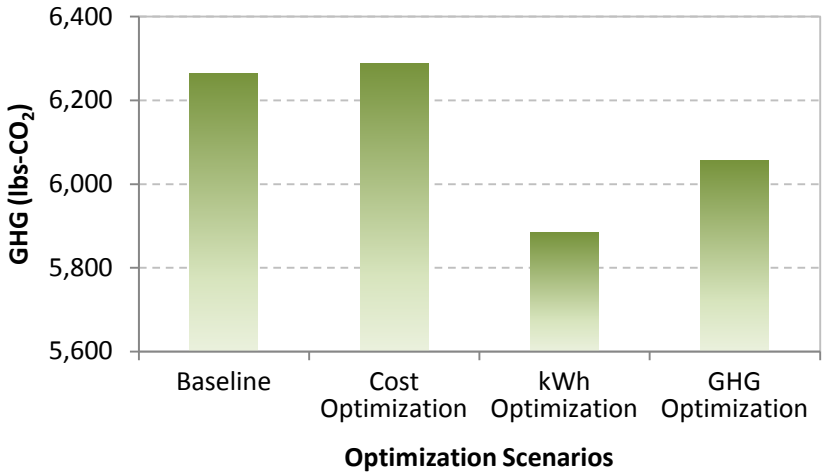


Figure 5.8: Weekly GHG emissions associated with all pumping stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization during summer



The above figure shows that the GHG optimization generates higher GHG emissions than the kWh optimization scenario. The explanation for this observation lies in the understanding of the optimization principles. The differences in optimization principles between various optimization scenarios are presented in Tables 3.1 and 4.1. The GHG optimization is based on the assumption that emission factors vary throughout the day depending on the energy supply portfolio of the electric utility (Figure 3.5). Under the GHG optimization, the operational goal was to run the pumps when the emission factors were minimal, regardless of the energy consumption. Thus, unlike kWh optimization, the GHG optimization was not the lowest energy operation and required more energy compared to the kWh optimization. Therefore, we observed that GHG optimization produced higher emissions compared to kWh optimization.

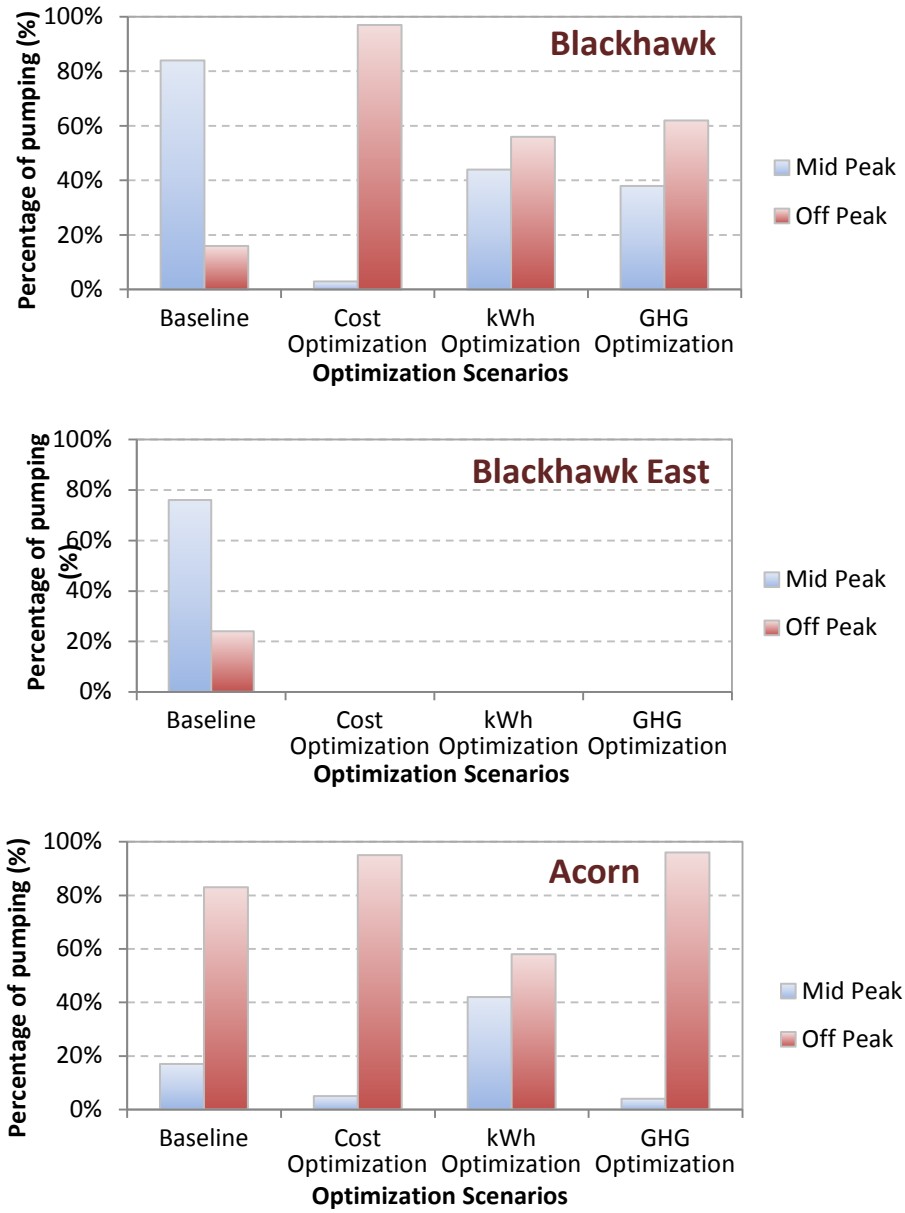
The data suggest that water utilities should just focus on kWh optimization to achieve the lowest GHG operation until the variability of GHG emission factors for given water utility are well established by the electric utilities.

In summary, the GHG optimization is based on a variable rate of GHG generation during the day, whereas the kWh and cost optimization is based on a constant GHG generation during the day. Due to this difference in emission assumptions, the cases are not directly comparable but do give an indication of the possible additional GHG emission reduction over a cost optimization scheme through kWh and GHG optimization.

4.2.2 Winter Simulations Results

In winter, the system is characterized by a very large storage to demand ratio so there is a greater pumping flexibility than that observed for summer. In addition, the tariff system in winter has lower differential than that of summer (Figure 5.4). As there was significantly less demand in winter all optimization scenarios were able to operate exclusively with the Blackhawk pump station (Figure 4.9) and, with the exclusion of the baseline period, no pumping occurred at Blackhawk East. The Acorn pumping station, mostly avoided the peak and nearly mid-peak periods (<5 percent) especially under the cost and GHG optimization scenario. The kWh optimization distributed approximately 44 percent and 42 percent of the pumping to mid peak periods at Blackhawk and Acorn pumping stations. The GHG optimization distributed 38 percent of the pumping to mid-peak and the remaining 62 percent to off-peak periods. The baseline operation did not use any concurrent pumping and this is reflected in the higher average head pumped against. The kWh optimization scenario had lower concurrent pumping percentage (data not shown) as there were times where it was not possible to pump concurrently as levels in the Acorn tank reached minimum level prior to Blackhawk pumping resuming.

Figure 5.9: Percentage of pumping at different tariff periods under the baseline, cost, kWh and GHG optimization at Blackhawk (top), Blackhawk East (mid) and Acorn (top) pumping stations during winter



Figures 4.10, 4.11 and 4.12 summarize the results for the one-week simulations of cost, energy and GHG optimization scenarios for the winter season at EBMUD. The results are compared in terms of energy usage, cost incurred, and GHG production using variable and flat rate evaluations. When compared to the historical operations, the three optimization scenarios significantly outperformed for all conditions analyzed. Demand charges were only applied to the baseline period ($461), as there was no pumping occurring during peak periods for the three optimization scenarios analyzed. Cost, kWh and GHG optimization resulted in similar

associated costs ($453, $454 and $458/week). Lower costs than those observed for the kWh and GHG optimization scenarios were expected when optimizing for cost, since almost all load was shifted to the off-peak window due to the high storage availability during low demand periods.

The kWh and GHG scenarios had little cost penalty but both gave reduction in kWh used (3,305 and 3,405 kWh/week) and GHG emissions (1,362 and 1,403 lbs/week).

Figure 5.10: Weekly energy costs and demand charges associated with all pumping stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization during winter

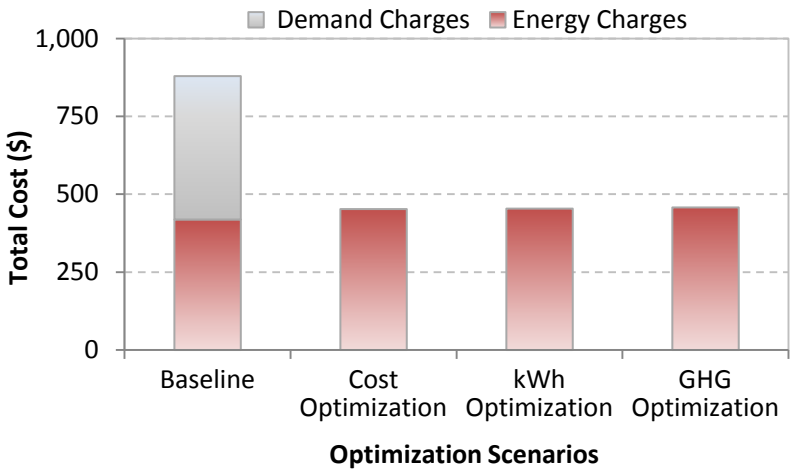


Figure 5.11: Weekly energy consumption associated with all pumping stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization during winter

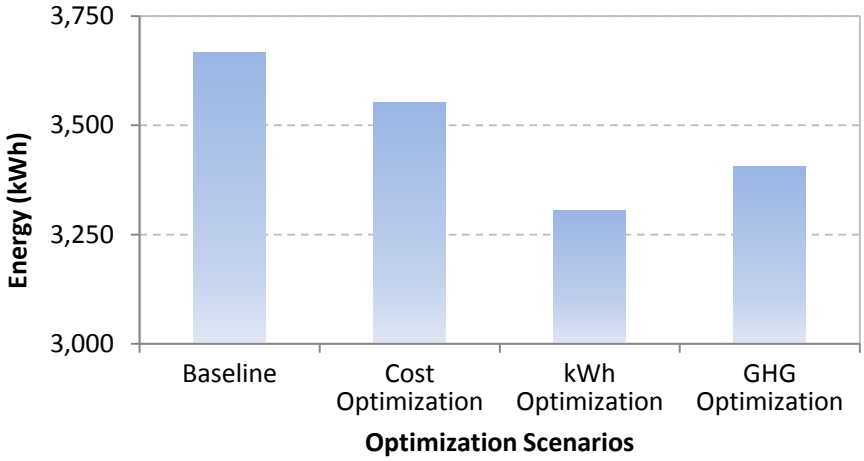
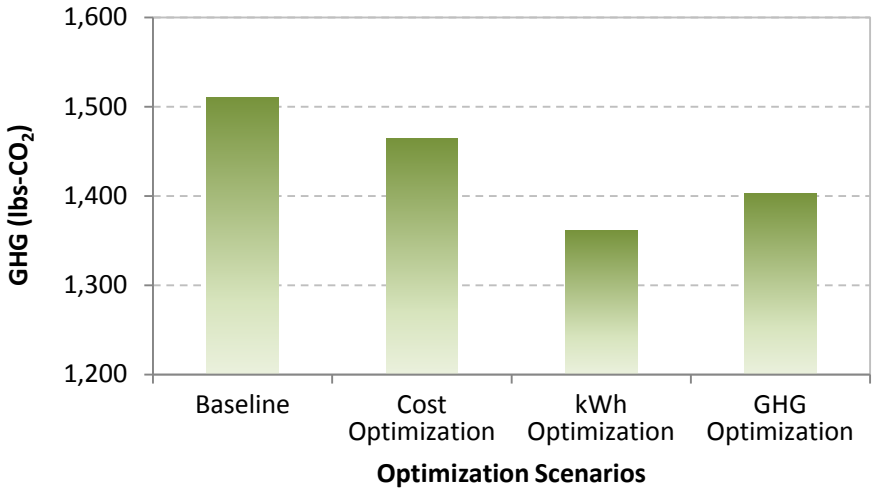


Figure 5.12: Weekly GHG emissions associated with all pumping stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization during winter



The above figure shows that the GHG optimization generates higher GHG emissions than the kWh optimization scenario. The same observation was made for the summer simulations and an explanation for this observation has been presented in the previous Section 4.2.1.

4.3 Real-Time Operation of EWQMS Modified with GHG Module

The EWQMS modified with GHG module was validated through real-time operation in the selected subsystems, Blackhawk, Blackhawk East and Acorn pumping stations, at EBMUD between June and August, 2014. During the pilot, each optimization scenario (cost, kWh and GHG optimization) was scheduled to run for at least two weeks, as presented in Table 5.2. Details of the pilot test plan and results are reported in the following sections.

Table 5.2: Pilot operation schedule and operational details at EBMUD

Optimization Scenario	Pilot Operation			Avg. Demand (MGD)
	Start	End	Days	
Baseline	June 2nd	June 15th	14	3.00
Cost Optimization	June 23rd	July 13th	21	2.96
kWh Optimization	July 14th	July 27th	14	2.89
GHG Optimization	July 28th	August 10th	14	3.07

4.3.1 Data Collection and Analysis

During the real-time pilot operations the following data were collected:

- *Electricity consumption*. Total electrical usage at regular intervals, including measurements on the first and last day of each optimization scenario. EBMUD uses

smart metering systems at the Blackhawk station to provide 15-minute interval power readings.

- *Telemetry/SCADA data from the EWQMS software.* Readings from SCADA and those calculated by the EWQMS software were recorded with a 10-minute frequency. The data collected included tank levels, pump status, pump suction pressure, pump discharge pressure, pump station flow, individual pump flow, where available, and the optimal pump schedule calculated and used for comparing planned vs. actual performance.
- *Water quality parameters*. Weekly grab samples from the Acorn and Blackhawk reservoirs were collected and analyzed for chlorine residual, pH and temperature during the pilot. Prior to the online trial, two weeks of weekly grabs were collected to establish a baseline operation condition. One grab was collected the week after the end of pilot operations to capture a post-pilot operation condition.

During the pilot, the SCADA data and EWQMS schedules were reviewed daily and responses to troubleshooting tickets issued by EBMUD were addressed promptly. A series of events occurred during the pilot operation, some of which triggered operator overrides and optimization software out of system control. In particular:

- On different days of the real-time optimization (on July 1, July 2, July 14, July 29 and August 1, 2014), EBMUD was subject to the Peak Demand Pricing Event by PG&E. Under the peak demand pricing event, EBMUD pays substantially higher prices, including surcharges, when PG&E is facing critical peak demands, and applies to electricity consumed between 2 and 6 p.m. However, during these events, EBMUD did not need to override the system since pumping was minimized as much as possible to avoid costs. The pilot operations of all three scenarios were completed on August 11, 2014.
- During the kWh optimization, all pumps were not operated between 12:00 and 6:00 p.m. to avoid peak period. Preventing pumping during the peak electricity tariff periods during the energy minimization scenario marginally reduced the opportunity to realize energy efficiency benefits but reduced the energy cost incurred and was therefore unpreventable. This led to significantly different results between the offline trial and the real-time pilot outcomes.
- Operation intervention was recorded in various instances during various optimization scenarios (Table 5.3). The interventions by the operators did not have a significant effect on overall operation, and these periods were excluded from the analysis. In most cases the intervention consisted of scheduling pumps off during certain periods of the day, even though the EWQMS solution had not planned on running the pumps at those times. In one instance the operators scheduled running two pumps at Blackhawk East during the off peak period for two hours. This override had a minimal impact on energy usage although it was less energy efficient, but this operator intervention led to significant costs in terms of PG&E Anytime Demand Charge at Blackhawk East,

increasing the monthly bill by $1,754. This example highlights how a small period of sub-optimal operation can incur very large costs.

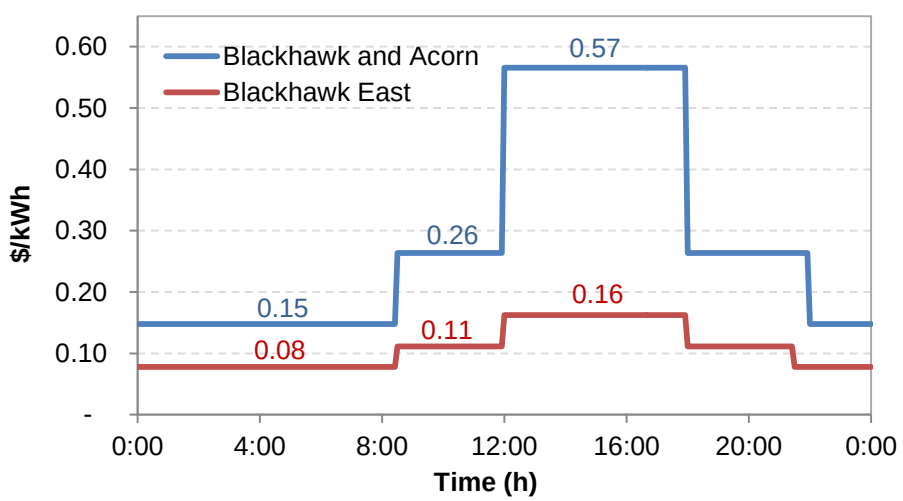
- The available storage at Blackhawk halved due to one tank out of service for scheduled maintenance. Under this condition, the EWQMS was limited by the reduced available storage and needed to shift pump operation to higher cost time periods, thus pumping during tariff shoulder periods was required, which would not have occurred if all normal storage volume had been available.

Table 5.3: EWQMS vs. manual control

Optimization Scenario	Time Pilot Operation (hours)	Time out of EWQMS Control (hours)	% Under EWQMS Control
Cost Optimization	504	17	97%
kWh Optimization	336	16.5	95%
GHG Optimization	336	13.5	96%

During the pilot, all pump stations were subject to the seasonal TOU tariffs by PG&E. The Blackhawk East tariff structure is characterized by lower rates than those applied to the Blackhawk and Acorn pump stations (Figure 5.13) and includes three peak period demand charges: a maximum-peak-period ($15.04/kW), a maximum-part-peak-period ($3.58/kW), and a maximum-demand charge ($11.85/kW).

Figure 5.13: PG&E TOU Tariffs applied at the Acorn and Blackhawk pumping stations during pilot operations



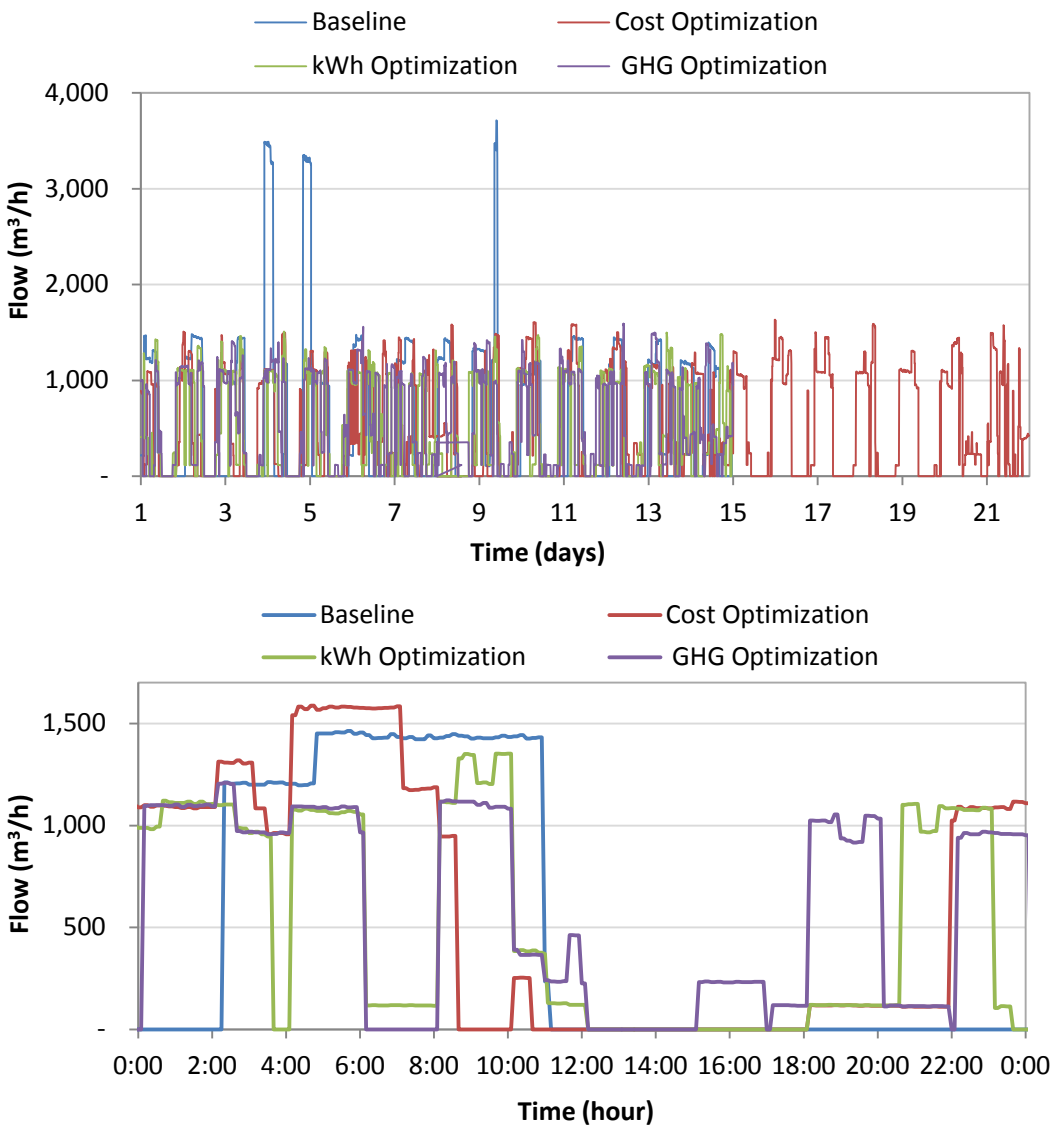
4.3.2 Real-Time Operation Results

This section summarizes the results for the cost reduction, kWh reduction and GHG reduction optimization scenarios obtained during the pilot operation at EBMUD. The results are compared with the baseline values in terms of energy usage and related cost, and the GHG

emissions production. Figure 4.14 shows typical flow profiles during the pilot for baseline operation and for various optimization conditions. During the baseline period, under operators' control, the operators were able to shift all the pumping to mid- and off-peak periods. Similarly, the EWQMS avoided peak tariff periods when operating under cost, kWh and GHG optimization scenarios.

Load shifting from peak and part peak tariff periods to off peak periods drove most of the savings in the offline simulation scenarios. However, due to the lower availability of storage for load shifting during the pilot (Blackhawk #2 storage tank under maintenance), less load shifting was possible, with the solver mostly focusing on increasing efficiency of operations. Thus, pumping during mid-peak periods occurred under all optimization scenarios, including that targeting cost reduction. Figure 5.15 shows the percentage of pumping during different tariff periods at the Blackhawk, Blackhawk East and Acorn stations. At Blackhawk, under cost optimization, 86 percent of the flow was diverted to off-peak periods, while the kWh optimization moved 46 percent of the pumping to mid-peak periods. At Blackhawk and Acorn, 4 percent and 10 percent of the pumping occurred during peak periods when optimizing for GHGs. By avoiding peak periods and related demand charges and by increasing pump efficiency, all optimization scenarios had lower total costs than the baseline (Figure 5.16). A 48 percent and 49 percent reduction in demand charges than the baseline was obtained at Blackhawk East under all optimization scenarios by avoiding running multiple pumps simultaneously.

Figure 5.14: Total flow profiles under the baseline, cost, kWh and GHG optimization scenarios during the duration of the pilot (top) and in a given day (bottom)



Optimizing for cost significantly reduces the cost associated with pumping ($5,820) compared to the other optimization scenarios analyzed, with an overall 23.7% cost reduction over the baseline (Figure 5.16). Under the same optimization a 4.8 percent decrease in energy consumption, thus also of GHG emissions, was observed compared to the baseline (Figure 4.17 and 4.18).

The kWh optimization generated the lowest demand charge cost due to a more efficient pump operation (i.e., using the lowest peak kW), which also translates into an overall 21.8 percent cost reduction compared to the baseline value. In addition, it achieved a 5.3 percent reduction in energy usage and GHG emissions.

The GHG optimization scenario reduced energy use and demand charges compared to the baseline, despite the costs associated with pumping during peak times. The GHG scenario experienced higher demand than all the other scenarios and therefore had to shift additional load to make improvements.

Figure 5.15: Percentage of pumping at different tariff periods under the baseline, cost, kWh and GHG optimization at Blackhawk (top), Blackhawk East (mid) and Acorn (top) pumping stations

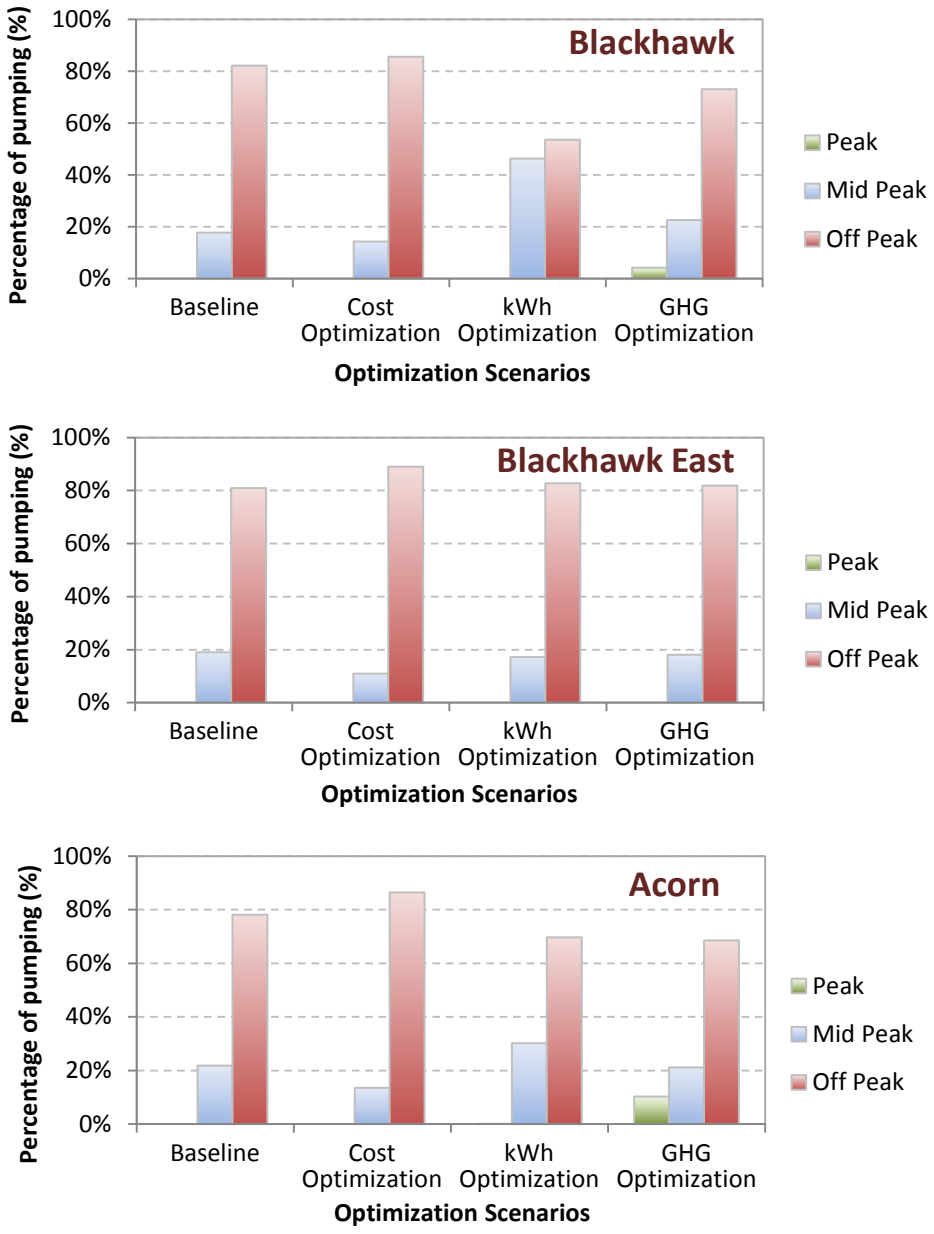


Figure 5.16: Energy costs and demand charges associated with all pump stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization

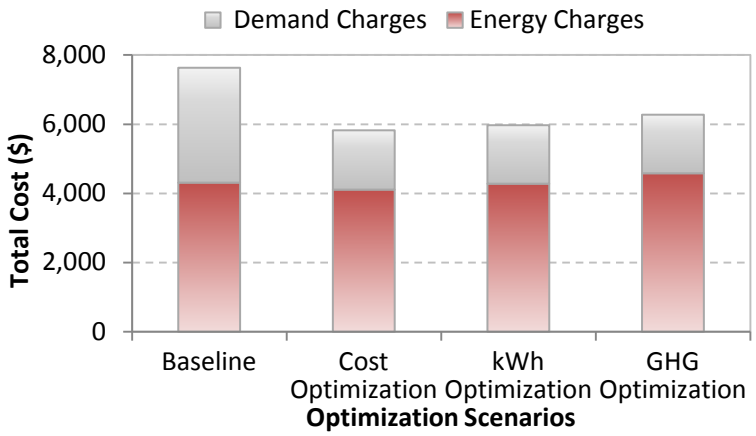


Figure 5.17: Energy consumption associated with all pump stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization

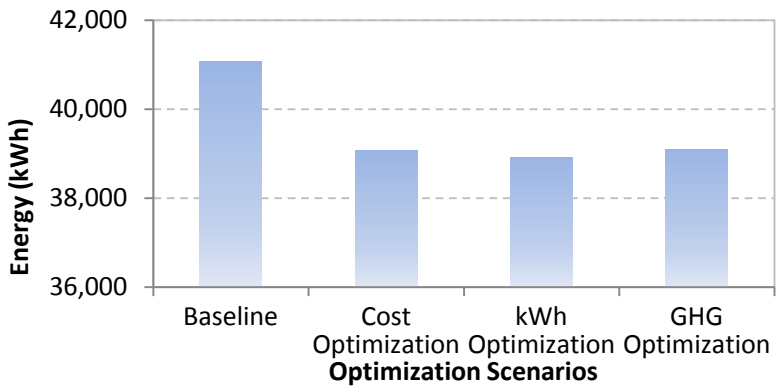
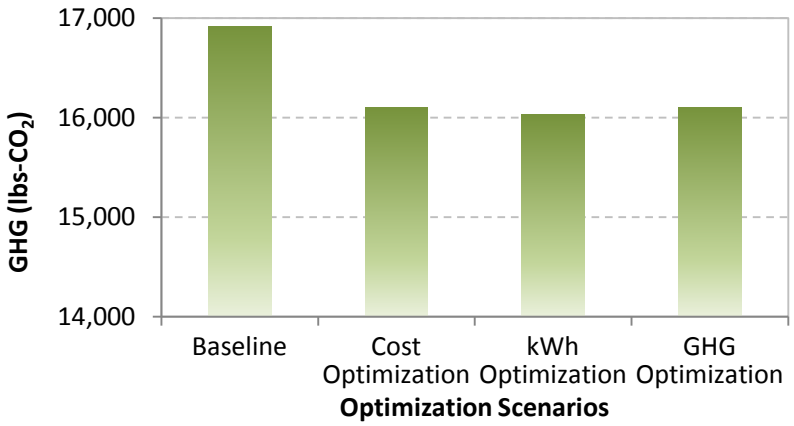


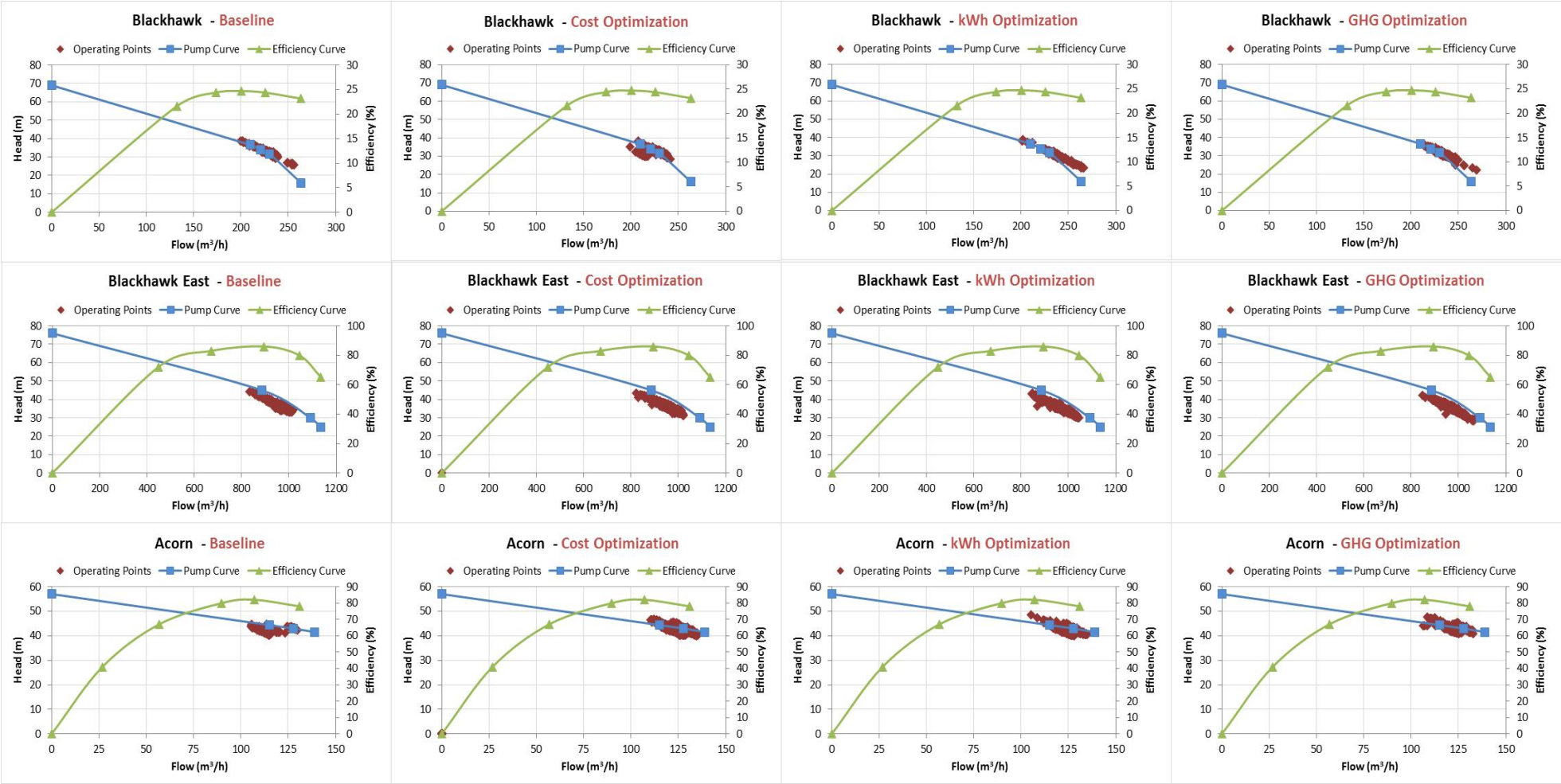
Figure 5.18: GHG emissions associated to all pump stations of the EBMUD pilot system optimized for cost, kWh and GHG minimization



The above figure shows that the GHG optimization generates slightly higher GHG emissions than the kWh optimization scenario. The same observation was made for the offline summer and winter simulations and an explanation for this observation has been presented in the previous Section 4.2.1.

Figure 4.19 shows Blackhawk, Blackhawk East and Acorn pump and efficiency curves, and related operating points during the pilot under different optimization scenarios. All optimization scenarios operated at a higher average flow than the corresponding baseline condition. As these are all fixed speed pumps this increased flow gives a corresponding efficiency benefit. For all pumping stations, both the cost and baseline scenarios operated over similar flow ranges (Figure 5.19). The kWh and GHG optimization scenarios operate over slightly higher flow ranges, due to the lower head to pump against. Although this lower average head pushes pump operation away from the BEP it still uses less energy as the efficiency reduction is offset by the lower hydraulic resistance.

Figure 5.19: Pump curves, efficiency curves and operating points at Blackhawk, Blackhawk East and Acorn pumping stations for different optimization scenarios



4.3.3 Comparison Between Offline Simulations and Pilot Operations Results

Table 5.4 shows the comparison of cost, energy and GHG emissions reduction between the baseline case and the offline predictions and the real-time operation results. Similar percentages of cost savings between the pilot (~24 percent) and the offline evaluation (~25 percent) were obtained when optimizing the system for cost minimization (Table 5.4). In contrast to the predictions, the real-time operations achieved high cost savings also when targeting kWh and GHG minimization. Avoidance of pumping operations during the peak tariff period for the kWh and the GHG optimization scenarios led to greater cost savings than those predicted by the offline simulations.

Real-time cost optimization generated a 4.8 percent decrease in energy consumption, thus also of GHG emissions, from the baseline, contrary to the slight increase predicted by the offline simulations (0.4 percent). Optimizing for kWh and GHG in real-time generated an overall improvement in energy and GHG emission reduction compared to the baseline (5.3 percent and 4.8 percent, respectively), similar to the 6.1 percent and 3.1 percent reductions predicted by the offline evaluation.

The offline scenario also predicted that the cost optimization would operate with a significantly higher head than the baseline at both Blackhawk and Blackhawk East sites, however, a decrease in head was observed during the pilot at both sites respectively. In contrast, an increase in head was observed at Acorn, and contradicts what the offline simulation predicted. This was a direct result of the optimizer picking a more efficient pumping operation at Acorn.

Table 5.4: Comparison between the baseline and the offline simulations and pilot operation results at EBMUD[1]

Optimization Scenario	Cost (% reduction)		Energy (% reduction)		GHG (% reduction)	
	Offline Simulations[2]	Pilot[3]	Offline Simulations[2]	Pilot[3]	Offline Simulations[2]	Pilot[3]
Cost Optimization	25.3%	23.7%	-0.4%	4.8%	-0.4%	4.8%
kWh Optimization	-22.3%	21.8%[4]	6.1%	5.3%	6.1%	5.3%
GHG Optimization	-0.9%	17.8%[4]	3.3%	4.8%	3.3%	4.8%

[1] "-"indicates increase in value relative to baseline

[2] Percentage based on the baseline selected for offline simulations

[3] Percentage based on the baseline selected for pilot operations

[4] High differences from offline simulation since pumps were not operated during the peak tariff period for the kWh and the GHG optimization scenarios

The difference in the costs incurred per pound of CO_2 emission reduction for the offline and pilot evaluations are presented in Table 4.5. The data indicate that the lowest cost for a pound of CO_2 reduction might be achieved in summer through kWh optimization ($1.9/lbs-$CO_2$), the lowest value also suggested with offline predictions for the summer season.

Table 5.5: Cost of carbon comparison between offline simulations and pilot operations at EBMUD

	Cost of GHG ($/lbs-$CO_2$)	
	Offline Simulations	Pilot
Change from Baseline to Cost Optimization	27.7	2.2
Change from Baseline to kWh Optimization	1.5	1.9
Change from Cost to kWh Optimization	3.0	2.1

4.3.4 Pump Prioritization Pilot Test Results

As an extension of the real-time operations performed at EBMUD, an additional set of trials was carried out to test the impact of efficient pump selection. Although not included in the initial scope of the project, this task was performed in response to the need for EBMUD to identify best practices for pump selection at the utility. Typically, EBMUD operates using a rotation strategy that evenly rotates the three pumps within a pumping station (Blackhawk, Blackhawk East and Acorn) based on the total run time. A pump prioritization test was performed at the EBMUD pilot site to determine if selecting the most efficient pumps within each pump station is a more beneficial strategy than the existing rotation approach.

The pump prioritization test approach is presented in Table 5.6. During the first three weeks the goal was to identify the pump with highest efficiency within each pumping station. The pumping stations were manually operated by running only one of the pumps at a time: "pump 1" was operated during the first week at all pumping stations, then "pump 2" and "pump 3" during the second and third week, respectively. In the following two weeks, the most efficient pumps were manually run at the three pumping sites with the best pump as determined from the first three weeks of trials set as the duty pump (Table 5.7). The last two weeks of operations were optimized for cost under EWQMS, where it could choose which individual pump to use rather than the enforced rotation policy.

Table 5.6: Pump prioritization test schedule

Objective	Operation	Days of Operation
Identification of the highest priority pumps	"Pump 1" in manual operation at all pumping stations	7
	"Pump 2" in manual operation at all pumping stations	7
	"Pump 3" in manual operation at all pumping stations	7
Operation with the highest priority pumps	System manually operated with the pump duty set in the most efficient priority order (see "Priority 1" in Table 4.7)	14
Operation under EWMQS	System operated under EWQMS optimized for cost	14

Table 5.7: Pump priority determined by the pump prioritization test

Pump Station	Priority #1	Priority #2	Priority #3
Blackhawk	Pump 3	Pump 2	Pump 1
Blackhawk East	Pump 3	Pump 1	Pump 2
Acorn	Pump 1	Pump 2	Pump 3

Due to small water demand variations throughout the testing, the results were normalized by the flow pumped during the week when the system was manually operated using the highest priority pumps at all pumping stations. Figures 4.20 and 4.21 show the results of the pump prioritization test for the different operating conditions identified in Table 5.6. Figure 5.20 shows that the operation using "pump 2" priority in all pumping stations is the unexpectedly less costly option tested in the first three weeks of operations compared with operations using "pump 3" at each pump station. When running the system with the best pump selection at each station this also generated higher costs than the operation using "pump 2" at all pumping stations. This was explained by noting that the operators on both occasions chose to run two pumps at Blackhawk East. By running two pumps, the efficiency was reduced as the pumps had to overcome a higher velocity head at the higher flow rate, thus leading to a higher kWh per MG delivered and higher peak kW demand.

EWQMS ran the Blackhawk pumping station more often than Blackhawk East, compared to previous weeks of operations as it is on a lower tariff. This incurred higher costs at Blackhawk, but saved greater costs at Blackhawk East. Acorn also required lower energy and achieved a reduction in cost from about $4,996 from the "highest priority" operation to $3,711 under EWQMS control. A 4.2 percent and a 25.7 percent cost reduction was obtained by the EWQMS compared to the "pump 2" (week 2) and to the "highest priority operation" (week 4-5), respectively. With its holistic optimization, EWQMS is selecting the most energy and cost efficient path (Blackhawk instead of Blackhawk East) and synchronizing pumping so that Acorn and Blackhawk operate simultaneously, with Acorn considerably benefiting from improved suction pressure. The efficiency benefits gained by using EWQMS are higher than those obtained by manually selecting the most efficient pump as they include the holistic benefits of running multiple pump stations in series, such as the suction pressure benefits at Acorn when either Blackhawk or Blackhawk East are pumping and the prioritization of Blackhawk over Blackhawk East when possible.

The results of our analysis indicate that there is a benefit of 1.8 percent (i.e., based on the average cost in week 1, week 2 and week 3) in terms of reduced cost available to EBMUD if pumps were set in priority order based on efficiency rather than the run-hours leveling rotation policy at the Blackhawk, Blackhawk East and Acorn sites. It would be reasonable to assume that similar savings would also be available to EBMUD if pump priority orders were updated at all stations. Extrapolating the results to all pump stations in East of Hills region a cost savings of $50,400 on an annual bill of $2.8 Million could be expected. When the EWQMS was allowed to select which pump to operate it also improved efficiency by 1.8 percent taking it from the 4.8

percent improvement achieved shown in Table 5.4 to the new total of 6.6 percent. This analysis demonstrates that there is potential for improvement. The savings associated with the efficiency-based pump selection may not appear to be substantial; however, this finding provides an indication that in-depth analysis of the importance of efficiency-based pump selection is warranted during the implementation of an EWQMS. Additional research should be performed to confirm whether such cost savings can be observed in other pumping stations. The impact of other factors such as reliability (having all pumps in similar condition), maintenance cost (including pump refurbishment) to keep pumps efficient should be incorporated in more detailed cost-benefit analysis of pump selection.

Figure 5.20: Cost and demand charges associated with various operating conditions during the pump prioritization test at EBMUD

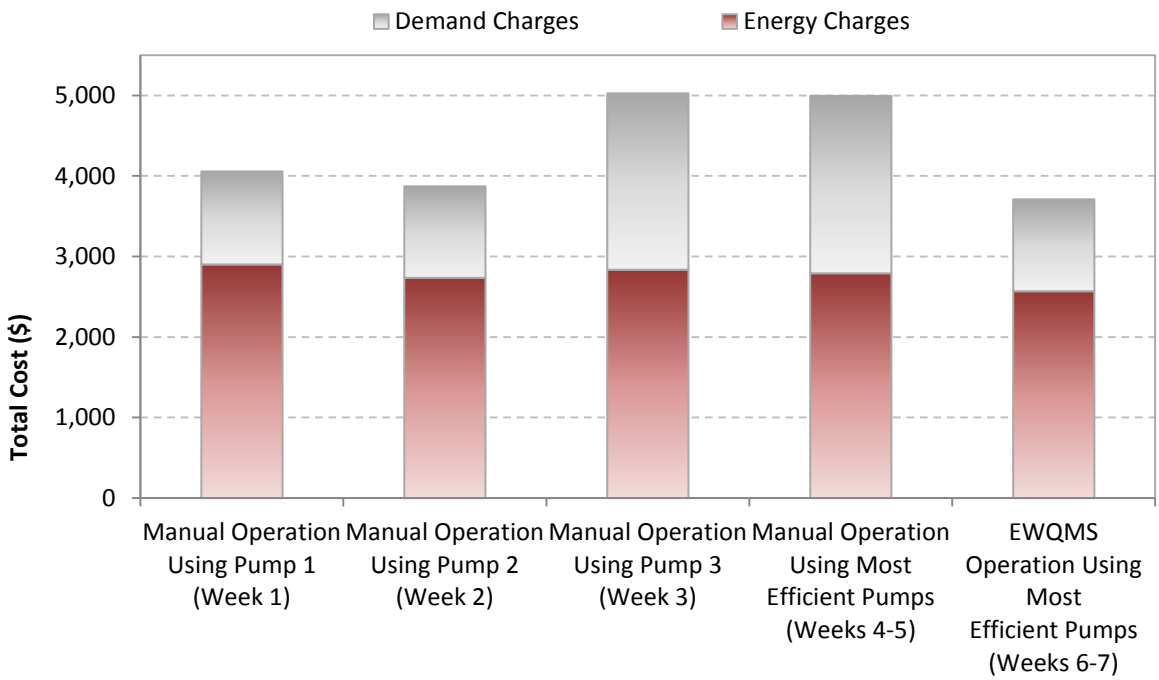
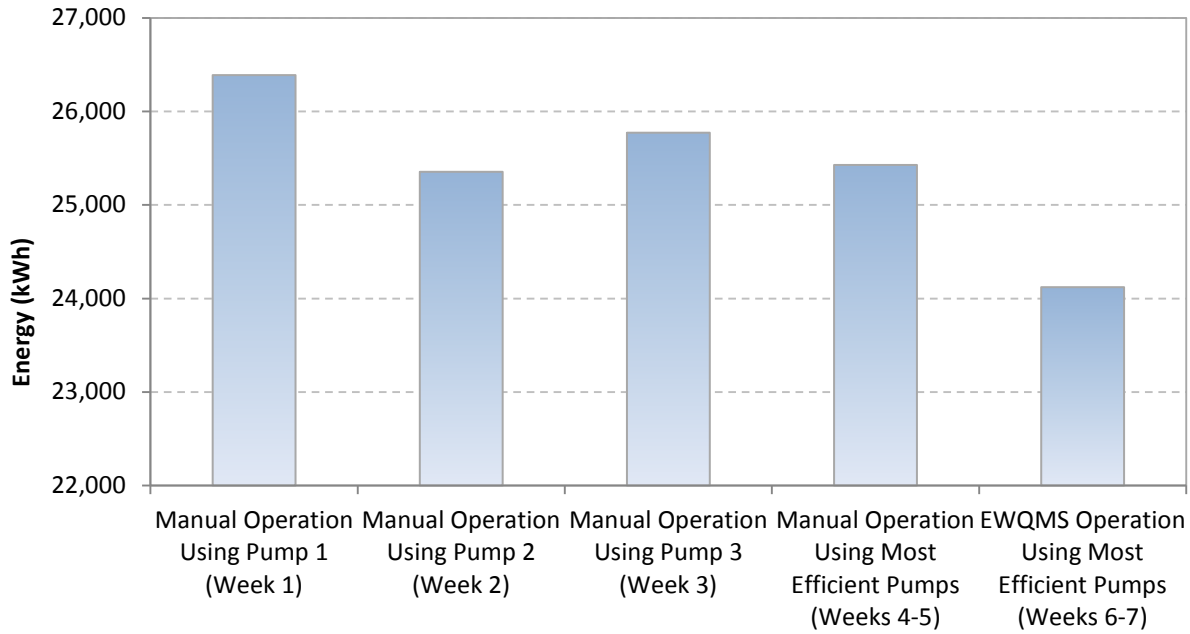


Figure 5.21: Energy consumption associated with various operating conditions during the pump prioritization test at EBMUD pilot



Note: The energy consumption during operation under rotation policy was calculated as an average of Week 1, Week 2 and Week 3 (25,838 kWh). This value was used for comparison with the operation based on efficiency priority order and with the EWQMS operations.

4.4 Impact of Optimization Scenarios on Water Quality

This section includes water quality predictions that foresee the potential impacts of cost, energy optimization and GHG emissions reduction on the water quality in tanks and to customers and those resulting from real-time operations.

4.4.1 Results from Offline Simulations on Water Quality

The optimized system hydraulic performance, individual scenario pump scheduling and contrasting level variation under each control regime obtained with offline water quality simulations at the EBMUD pilot zone were analyzed. In the InfoWater model, water enters the system at Scenic pressure zone at approximately 55 hours age. Due to long travel times in the network, and low turnover, the water age within Blackhawk 1 and 2 Tanks is predicted to be between 190 and 240 hours over the seven days modeled in summer 2013. Acorn Tank water age is predicted to be between 160 and 200 hours. Both tanks cycle over the seven day period providing approximately the same water age at the beginning and end of the historic operation simulation. Winter demand is significantly lower than in summer, and the maximum modeled water age is 230-240 hours in all of the system.

Predicted water age in tanks is listed in Table 5.8 and Table 5.9 for the summer and winter scenarios, respectively. Turnover is expressed as the percentage of active tank volume that is refreshed each day over the weekly off-line study period. The average age of water in the tanks

is similar in all cases, revealing no clear optimal strategy for managing water quality in tanks through pump optimization. This result is interesting as there are large differences in the tank levels cycle during the actual and optimized scenarios. Greater use of tank operational volumes and increased cycling in the actual operation should lead to improved water age. Similarly, optimization scenarios that tend to keep the tanks full should provide longer retention and greater aging. However, due to low demand on the system and very rapid refill rates, this is does not significantly affect the water age in the Blackhawk tanks.

Table 5.8: Predicted water age and turnover in tanks for the summer scenario at EBMUD

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Mean Age (hr.)				
Acorn Tank	186	217	199	224
Blackhawk #1 and #2 Tanks	213	216	235	235
Turnover[1] (%/day)				
Acorn Tank	13%	11%	12%	11%
Blackhawk #1 and #2 Tanks	11%	11%	10%	10%

[1] Turnover = 1/Age of Water (days) x 100%

Table 5.9: Predicted water age and turnover in tanks for the winter scenario at EBMUD

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Mean Age (hr.)				
Acorn Tank	335	288	303	288
Blackhawk #1 and #2 Tanks	278	286	288	293
Turnover[1] (%/day)				
Acorn Tank	7%	8%	8%	8%
Blackhawk #1 and #2 Tanks	9%	8%	8%	8%

[1] Turnover = 1/Age of Water (days) x 100%

Water quality in tanks is important as it strongly influences compliance with water quality standards. However, it is not necessarily representative of the water being delivered to customers across the network. In this section model prediction results were used to calculate the variation in water age reaching customers. In particular, the effect on customers is examined by comparing the quality of water in pipes within the distribution system. Figure 5.22 through Figure 5.25 show the maximum age of water modeled for each optimization case. While the maximum water age is not experienced for the entire seven day period, it is indicative of the worst quality of water that customers could receive under each operating regime. This is different from reporting water age in the tanks, as it considers the quality of water being drawn from the system at customer connections.

Figure 5.22: Representation of maximum modeled water age for baseline operations in summer and winter at EBMUD

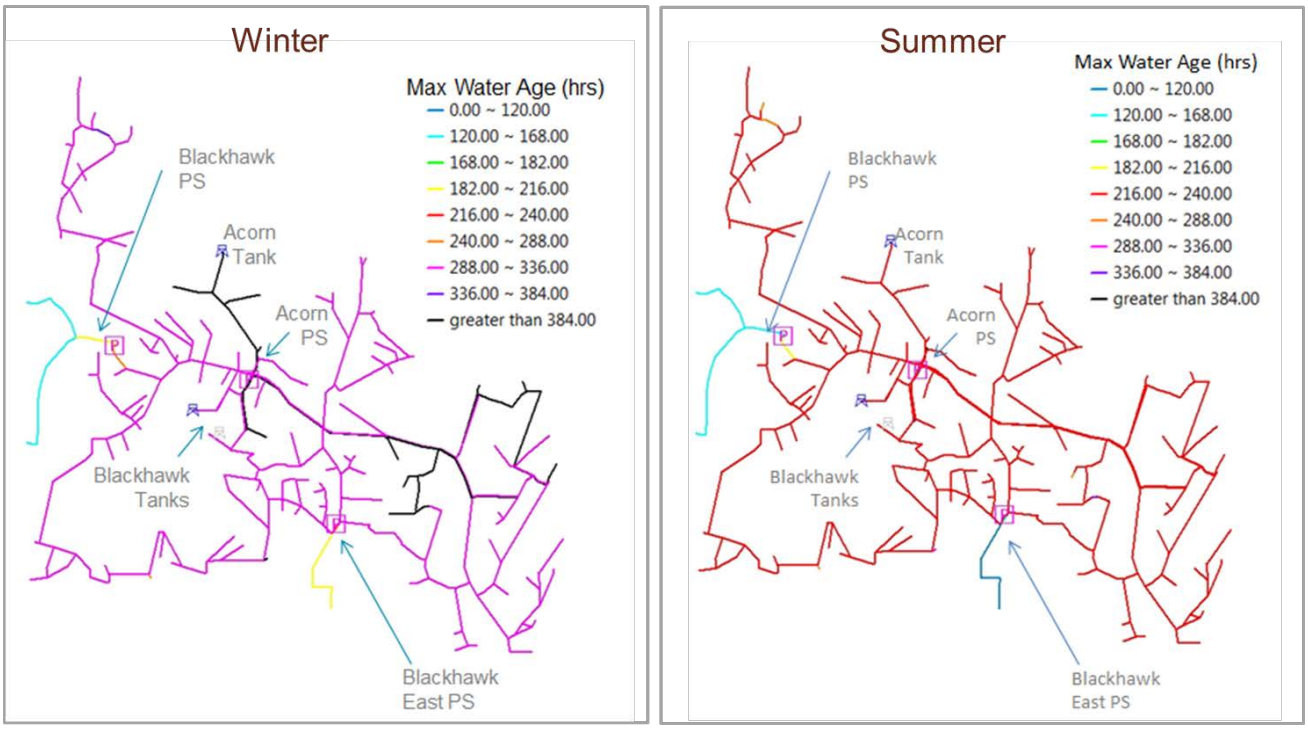


Figure 5.23: Representation of maximum modeled water age for cost optimization in summer and winter at EBMUD

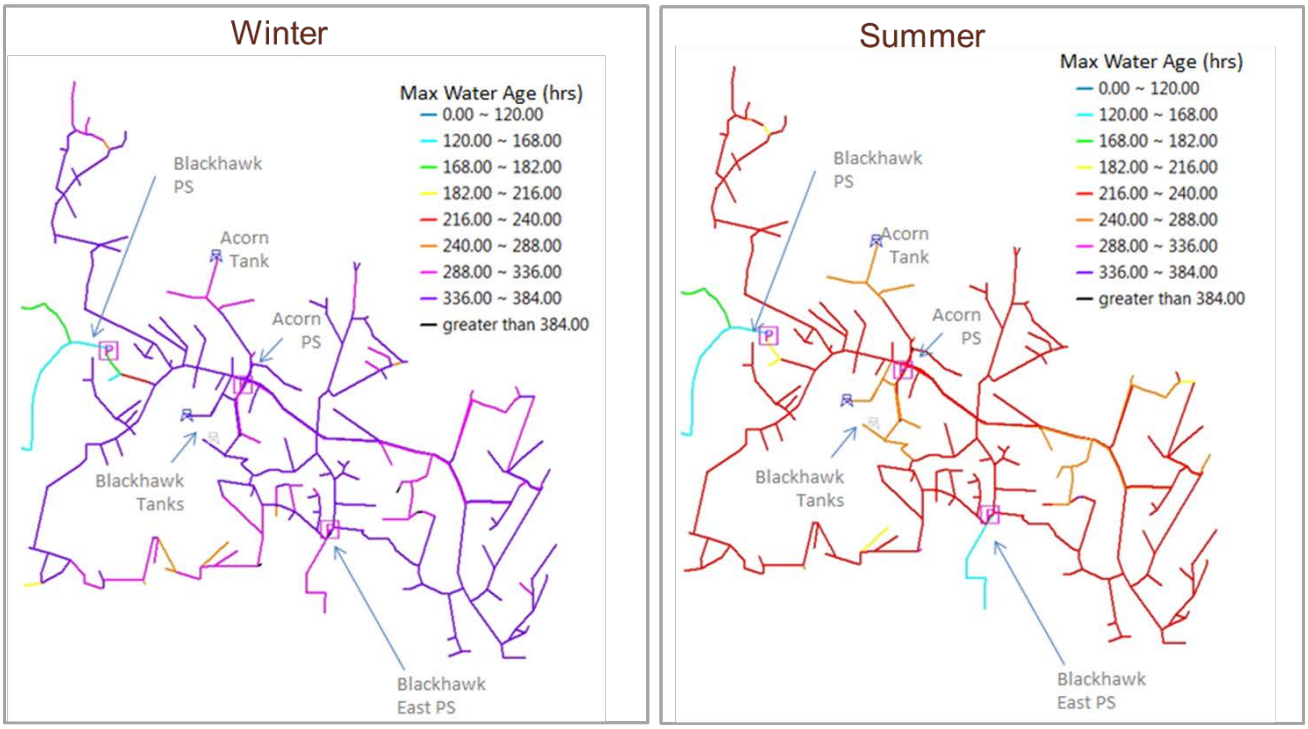


Figure 5.24: Representation of maximum modeled water age for energy optimization in summer and winter at EBMUD

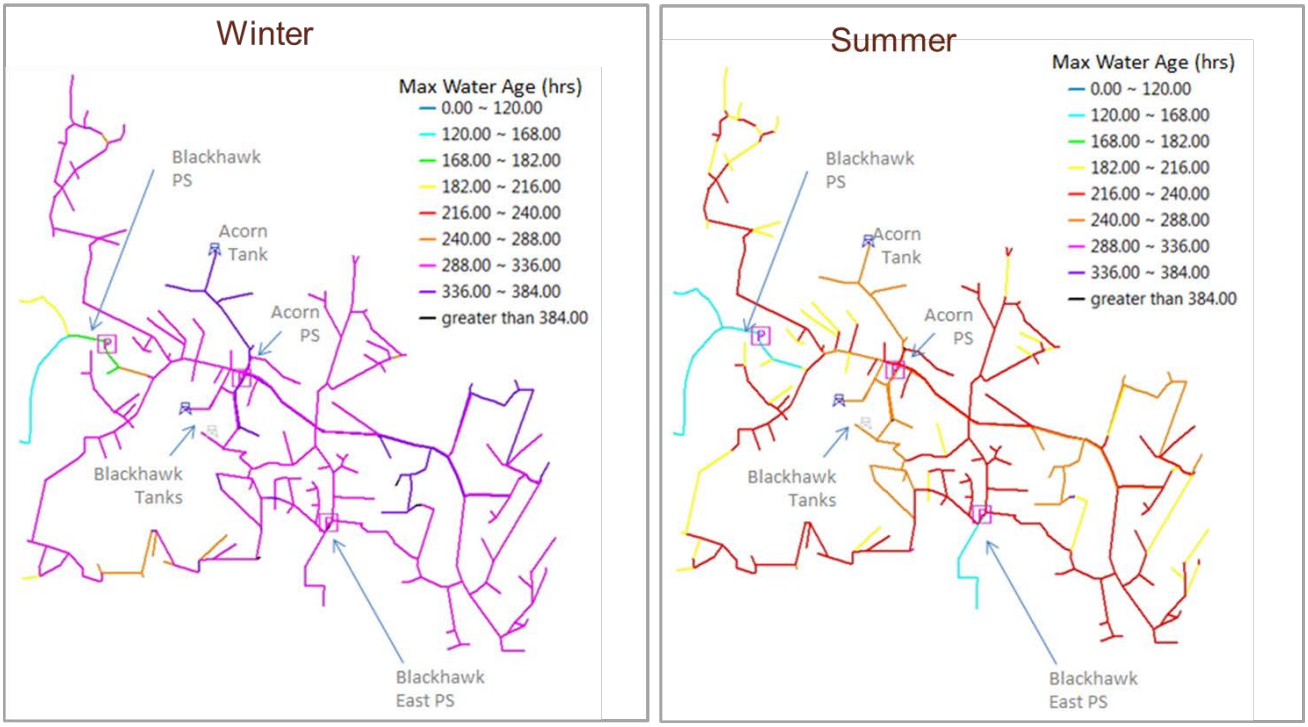
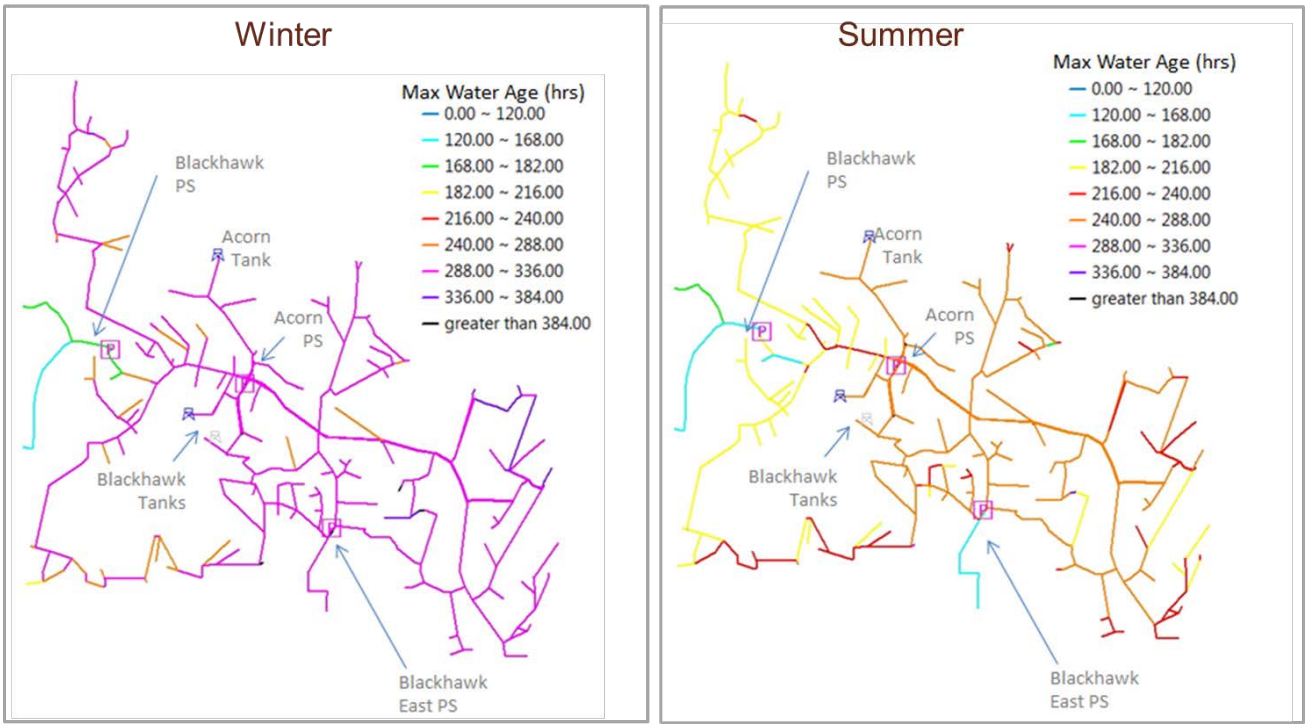


Figure 5.25: Representation of maximum modeled water age for GHG optimization in summer and winter at EBMUD



To highlight any spatial differences in water quality across the zones, results have been provided for three regions in the Blackhawk supply system and for Acorn (Table 5.10 and Table 5.11). Customers in the west of Blackhawk 1 and 2 tanks have been nominally assigned to the western sector, with the remaining customers taken to reside in the eastern zone.

In summer the mean age of water received by customers is approximately uniform, and between 130 and 152 hours, with the oldest water being delivered in Acorn zone. A similarly uniform quality distribution is given by the cost optimized scenario. However, the energy and GHG alternative operating strategies, the age of water received by customers varies spatially, due to continuous pumping into supply at Blackhawk or Blackhawk East Pumping Stations. This also has the effect of favoring customers closer to the pumping stations, at the expense of those further away. However, the effects are small in terms of average age of water delivered.

In winter, due to the reduced demand, all customers receive older water than in summer. The mean age of water varies from 240 to 329 hours. All optimization strategies tend to provide improved water quality compared to the actual case. This is due to the optimizer selecting more frequent pump operation at lower flow rates, which improves turnover within the network.

Table 5.10: Predicted water quality in distribution system for the summer scenario at EBMUD

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Mean Age - Blackhawk and Acorn Zone (hrs.)	136	123	108	108
Mean Age - Acorn Zone (hrs.)	152	120	165	147
Mean Age - Western Blackhawk Zone (hrs.)	141	124	95	89
Mean Age - Eastern Blackhawk Zone (hrs.)	130	124	104	112

Table 5.11: Predicted water quality in distribution system for the winter scenario at EBMUD

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Mean Age - Blackhawk and Acorn Zone (hrs.)	251	170	164	156
Mean Age - Acorn Zone (hrs.)	329	260	278	253
Mean Age - Western Blackhawk Zone (hrs.)	242	141	128	126
Mean Age - Eastern Blackhawk Zone (hrs.)	240	170	164	157

In summer, the water quality investigations have revealed that there is little clear difference in water quality impact of the four operating modes investigated in the off-line studies for the EBMUD's Blackhawk system. Detailed inspection of model predictions has shown that strategies that run all three pumping stations simultaneously provide, on average, a more uniform and equitable water age to customers across the system. Strategies that utilize continuous pumping into the network lead to unbalanced water quality distribution, with

customers located closer to the source receiving younger water at the expense of customers residing further into the network.

In winter conditions, the low system demand and large pump capacity results in optimized but less repeatable operation of the pumps. In this situation, it is not possible to find a clear differentiation between operating strategies tested off-line. Interestingly, all strategies do provide better water quality than the baseline. This can be explained by the historic operation of Acorn pumping station independently of Blackhawk and Blackhawk East pumping stations. In the actual case, Acorn pumping station was started before fresh supplies entered the zone, leading to previously stored water being pumped and giving noticeably older water to customers in Acorn pressure zone.

The overriding impact on water quality (age of water as surrogate measure) in the Blackhawk system is the low demand and large retention times in Acorn and Blackhawk Tanks, combined with the distance of the system from primary sources. Methods of reducing retention in the network and in tanks are not considered in the EWQMS study. However, general approaches could include:

- Reducing the maximum operating level in tanks in winter;
- Removing tanks from operation in low demand periods;
- Increasing frequency of pumping into system.

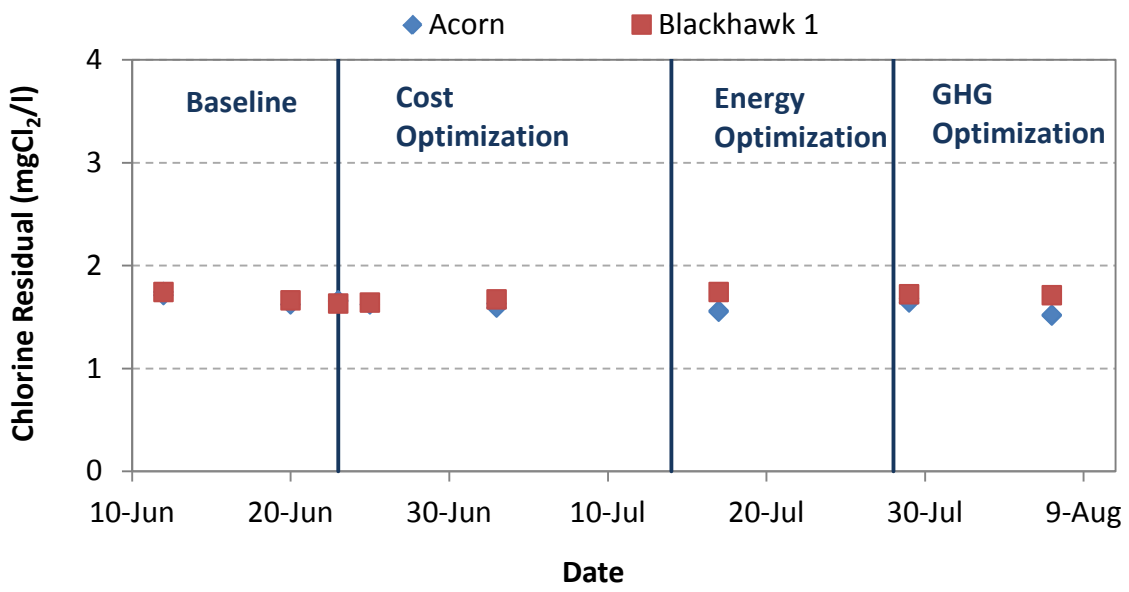
Disinfectant residual concentrations are not directly compared in the off-line studies. This is due to the lack of time series information and the complications of modeling chlorine decay in networks (ideally conducted using a calibrated water quality model). It is worth noting that, subject to compliance with disinfection byproduct rules, chlorine boosting could also improve the quality of water delivered to customers.

4.4.2 Results from Real-time Operations on Water Quality

Water quality samples were collected weekly during the real-time operations at Blackhawk #1 and Acorn reservoirs for chlorine residual, pH and temperature. Samples were also collected prior to the pilot period to establish baseline conditions for water quality. At Acorn, water samples were collected from two out of the four sample points, each located approximately seven feet apart along the height of the reservoir. At Blackhawk #1 reservoir sampling was performed at the 1,024 foot elevation tap (opposite the inlet and half way up) considered the most representative of well mixed conditions in the tank based on a previous study by the American Water Works Association (AWWA) (Grayman et al., 2000). Blackhawk #2 reservoir was out of service during the real-time operations.

EBMUD utilizes chlorination for final disinfection in tanks. Figure 5.26 shows the chlorine residual (mg/L as Cl_2) at Blackhawk and Acorn reservoirs overlaid with the different operation scenarios.

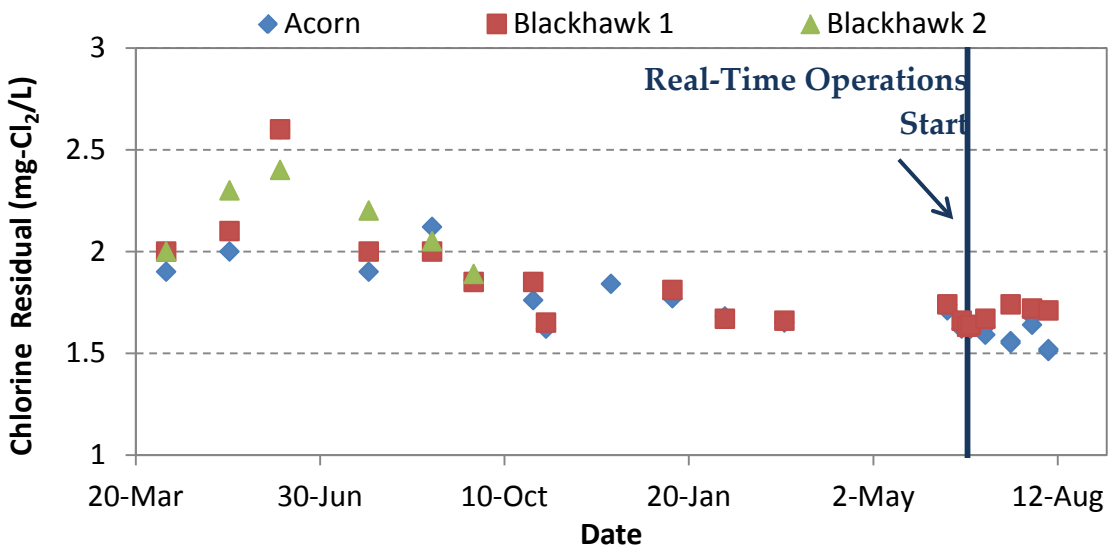
Figure 5.26: Chlorine residual at Acorn and Blackhawk reservoirs for different optimization scenarios



In Figure 5.27, the same chlorine residual results are contrasted with regular sampling data from Blackhawk and Acorn tanks for the period 2013-14. During 2013 there was a general trend for chlorine residuals in Acorn Reservoir to be equal to or marginally lower than in Blackhawk #1 tank. Figure 5.27 shows that this trend continues for the non-optimized baseline period and early cost optimization. However, the quality in the Acorn Reservoir begins to diverge from that in Blackhawk #1 reservoir under the three optimization scenarios.

The offline modeling under 2013 summer demands showed that continuous pumping results in lower turnover and increased aging of water in Acorn reservoir. This is due to a greater proportion of demand that is met directly from pump output rather than under gravity from the tank, in contrast to normal fill and draw operations. In summer 2014, during the baseline operating period, EBMUD generally ran both Acorn pumps simultaneously. When running EWQMS, all the optimization scenarios tended to select only a single duty pump at Acorn pumping station. This results in longer pump running hours at Acorn pumping station, and potentially leads to the water aging scenario seen in the off-line modeling exercise. A sustained infusion to the Acorn zone during the optimized cases causes the regions close to the pumping station to experience fresher water, whereas customers closer to the tank tend to receive stored water. In general, the measured differences in chlorine residual are small (approximately 0.1-0.2 mg/L) and it is tempting to conclude that the results are showing agreement with earlier hydraulic model age of water predictions. However, there are many other factors that could affect the results of grab samples in this zone, and it is not possible to draw firm conclusions from four data points.

Figure 5.27: Historic residuals and pilot sampling data for Acorn and Blackhawk tanks



Temperature and pH results for Acorn and Blackhawk do not show any significant variation over the optimization period. The pH varies from 9.0 to 9.7 in both Blackhawk and Acorn tanks. Temperature recorded at Blackhawk varies from 19.5 to 21.7 degrees Celsius. Acorn reservoir temperature is typically 1-2 degrees higher, ranging from 20.4 to 23.9 degrees Celsius. Temperatures increased over the test period, which is in line with ambient temperature rises. EBMUD experienced temperature stratifications at Acorn reservoir in the past. Based on the few available data points, there is some possible evidence of stratification in Acorn Reservoir in the final two weeks of the pilot period, and the temperature gradient is small. It is not possible to relate these changes to the optimization strategies, as it is most likely due to ambient temperature changes and measurements of reservoir mixing was not an objective for this study.

In general, the water quality samples show that there is no marked change in chlorine residual during any of the optimization regimes. This substantiates the earlier predictions from the offline simulations, which indicated there were no water quality concerns when running the on-line operations.

CHAPTER 5:
Implementation of the EWQMS Modified with a GHG Module at Eastern Municipal Water District

This chapter includes the findings of the offline simulations and of the real-time pilot operations of the EWQMS modified with the GHG module at EMWD. This chapter also includes water quality predictions that foresee the potential impacts of energy optimization and GHG emissions reduction on the water quality in tanks and to customers and those resulting from real-time operations.

5.1 Pilot Site

EMWD serves 630,000 people in Riverside County, CA with approximately 120 MGD average peak daily demand. The EMWD service area has three operational subsystems fully under *Aquadapt* control: Moreno Valley, Perris & Sun City, and East Valley. The pilot site area was selected within the East Valley region of the EMWD network, which includes the Diamond 3, Mission Canyon 1 and Mission Canyon 2 pumping stations (Figure 6.1, Figure 6.2 and Figure 5.3). The Diamond 3 pump station has two gas pumps and one electric pump operated on a time-of-use schedule. The Mission Canyon 1 and Mission Canyon 2 pumping stations only have electric pumps. These sites are characterized by a large storage volume to demand ratio throughout the year, with available upstream storage (22 MG) and very low demand (<1 MGD). The large available storage permits significant pumping flexibility as pumping can be moved to different times of the day or night without impacting the system's ability to supply water to users. The Diamond 3, Mission Canyon 1 and Mission Canyon 2 sites are in a cascade and they run in series when there is a hydraulic benefit from running them simultaneously. The first pump station significantly increases the suction pressure at the second pump station, making the pump operate at more desirable head/flow and efficiency/flow conditions.

Figure 6.1: A schematic of the EMWD pilot area

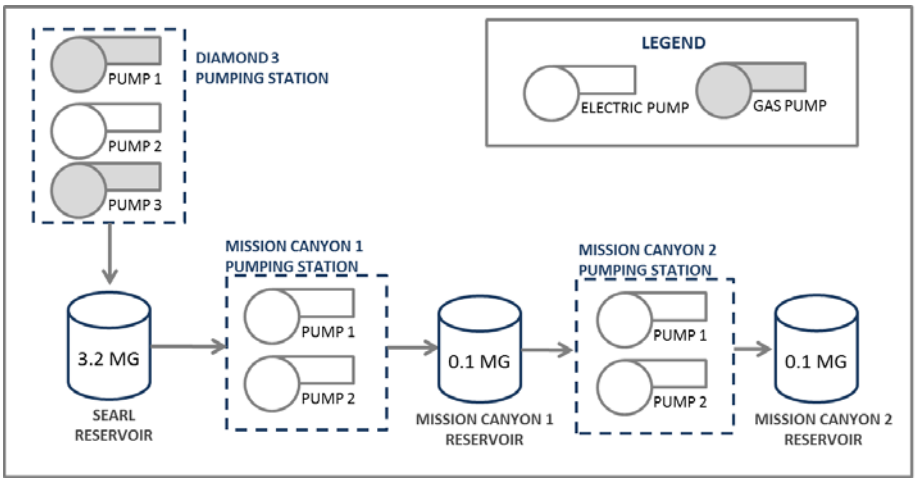


Figure 6.2: A schematic of the EMWD's East Valley operating area.
(The area outlined is the pilot site selected for this study)

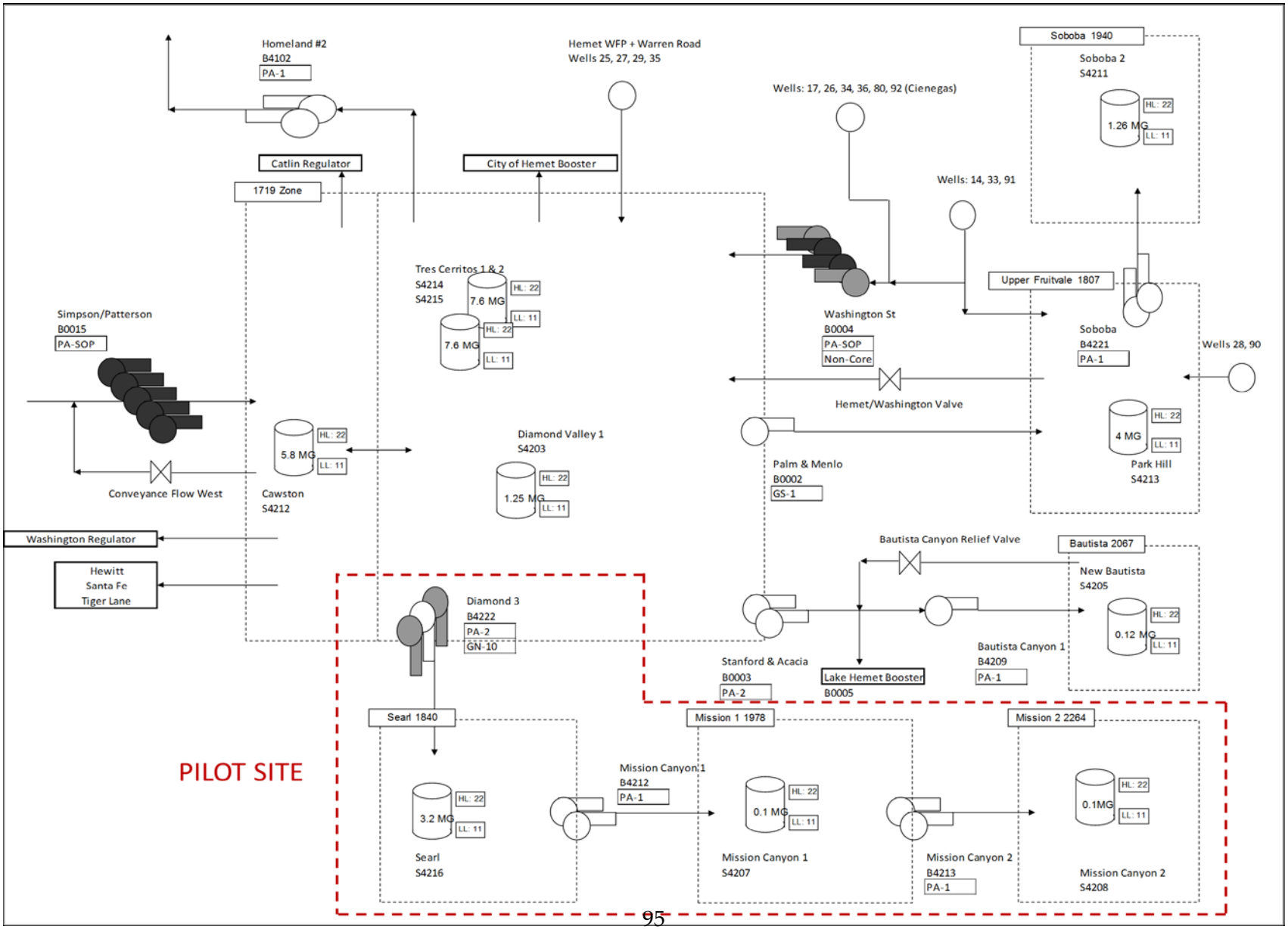


Figure 6.3: Pumping stations and tanks in the pilot site at EMWD

5.2 Offline Evaluation of EWQMS Modified with GHG Module

The offline trials used the simulator to determine the outcomes for different optimization strategies on the representative sub-system within EMWD's East Valley operating area. Three different optimization scenarios were considered during the offline evaluations and their description is provided in Table 6.1. The analysis compared historic (baseline) operation with the optimization objectives of cost reduction, kWh reduction or GHG reduction for summer and winter scenarios, using historical data from July 1-7, 2013 and February 2-8, 2013, respectively.

Table 6.1: Description of the offline simulation scenarios

Optimization Scenario		Description
Optimization Scenario	Baseline[1]	**Primary principle:** System under no EWQMS operation (manual control by operators)
	Cost Optimization	**Primary principle:** Pump operated when the cost is minimum (selection order: off-peak, mid-peak, on-peak)
	kWh Optimization	**Primary principle:** Pump operated at the lowest specific energy (kWh/MG pumped) *Note: kWh optimization is the GHG optimization when flat GHG emission factors are used*
	GHG Optimization	**Primary principle:** Pump operated when the GHG emission factor (lbs-CO_2/MWh) is minimum *Note: Assumes that GHG emission factors vary depending on the energy sources*
Water Demand	Summer *(High Demand)*	Scenario optimized in the week of July 1-7, 2013
	Winter *(Low Demand)*	Scenario optimized in the week of February 2-8, 2013

[1]For the purposes of a meaningful comparison the cost of gas pump usage were calculated as if it were electrical pump operation. An extremely high gas cost would have overwhelmed all the other data and made the results meaningless.

Pump stations at EMWD comprise an electric pump in parallel with two gas reciprocating engine driven pumps. EMWD operated the gas powered pumps during these weeks of offline simulations. Under the baseline operation any pumping during the peak tariff period was performed by the utility using the gas-engine driven pump. However, our analysis has indicated that, in recent years, the use of the gas pumps incurs much higher energy costs and at least five times the GHG per MG delivered than using the electric pumps (Table 6.2). For this study, the determination of the historical costs when using gas pumps was challenging, thus the energy consumption of the gas pumps were excluded from the calculations. Rather than using actual GHG and cost from the gas driven pumps, electric pumps were substituted for gas pump operation in these actual weeks using average expected operational kWh consumption and costs. This provides a better comparison between the three optimization strategies and the historical behavior, which would not have truly reflected the aims of this project. In addition, the presence of gas pumps and this combination of high storage to demand are not necessarily representative of the vast majority of water supply systems in the U.S.

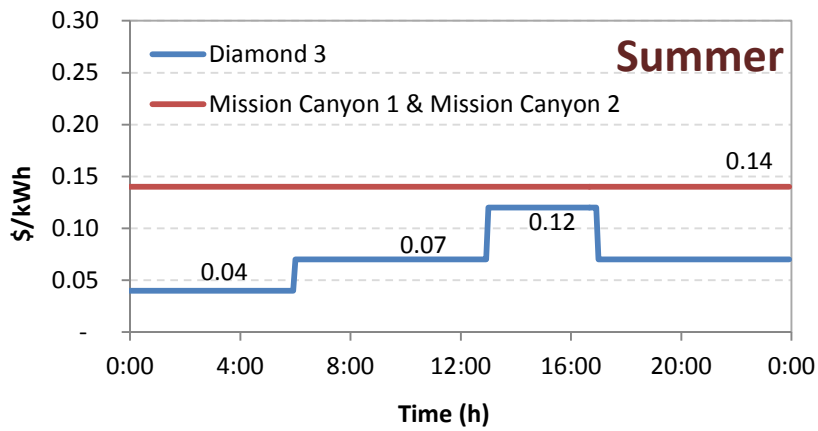
Table 6.2: Comparison of electric vs. gas-driven pumping

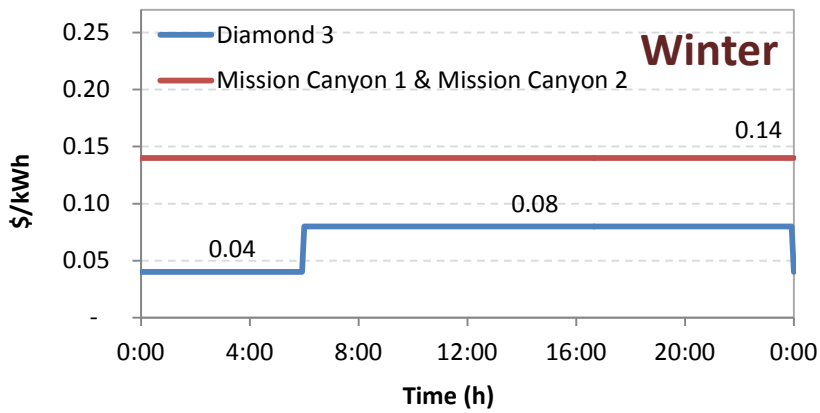
		Year 2010		Year 2013	
		Gas	**Electric**	**Gas**	**Electric**
Flow	MG	145	29	145	29
Energy Consumption	kWh/MG	2368	523	2368	523
GHG Emissions	lbs/kWh	0.46	0.52	0.46	0.52
Cost	cents/kWh	2.21	23.4	2.34	4.55
	$/MG	52.36	122.41	55.38	23.78

At EMWD, the Diamond 3 pump station was subjected to seasonal TOU tariffs by Southern California Edison (SCE) for summer and winter. Mission Canyon 1 and Mission Canyon 2 pump stations were under flat tariffs throughout the year. The Diamond 3 tariff structure is characterized by lower rates than those applied to Mission Canyon 1 and Mission Canyon 2 pump stations (Figure 5.4) and includes two peak period demand charges: a maximum-peak-period ($23/kW for summer and winter), and a maximum-demand charge ($8.55/kW only for summer). The maximum-peak-period-demand charge per kilowatt applies to the maximum demand during the month's peak hours, the maximum-part-peak-demand charge per kilowatt applies to the maximum demand during the month's part-peak hours, and the maximum-demand charge per kilowatt applies to the maximum demand at any time during the month.

Details on the offline analysis and related results are reported in the following sections.

Figure 6.4: SCE Tariffs applied to the Diamond 3, Mission Canyon 1 and Mission Canyon 2 pumping stations during the offline simulations





5.2.1 Summer Simulations Results

Figure 6.5 shows the percentage of pumping at Diamond 3 pumping station during different tariff periods and for different optimization scenarios during the week-long simulation period. As shown, high tariff periods were avoided during the historical operation due to the significant availability of storage and the use of gas-engine driven pump combinations. Under the cost optimization scenario, the pumping was mostly performed during off peak periods (97 percent) and never during peak hours. On the other hand, pumping of the kWh scenario occurs during all tariff rate periods and, therefore, incurs a higher cost, particularly due to the diversion of 8 percent of the flow to peak periods. In fact, during the kWh optimization, pumps are operated based on the least energy use strategy, regardless of the tariff structure applied (cost/kWh). Therefore, some of the energy efficient operations occurred during the peak period. The GHG optimization similarly allocated 44 percent of the flow to the mid-peak tariff period and the remaining 56 percent to off-peak times. During the GHG optimization, pumps are operated based on the lowest emission factor regardless of the tariff structure applied (cost/kWh). Therefore, some of the least GHG emission operations occurred during the mid-peak period.

Figure 6.6 shows a high level of concurrent pumping between Mission Canyon 1 and Mission Canyon 2 for all scenarios, to be expected with a hydraulic benefit of 8.6 meters of elevation head. The same result was not observed for concurrent pumping of the combination Diamond 3 and Mission Canyon 1, due to a hydraulic benefit of only 1.7 meters.

Figure 6.5: Percentage of pumping at different tariff periods under the baseline, cost, kWh and GHG optimization at Diamond 3 pumping stations during summer

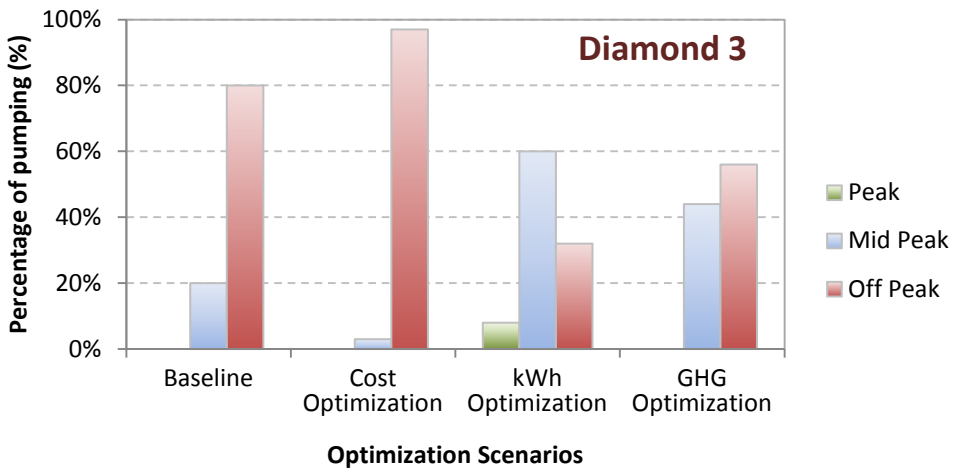
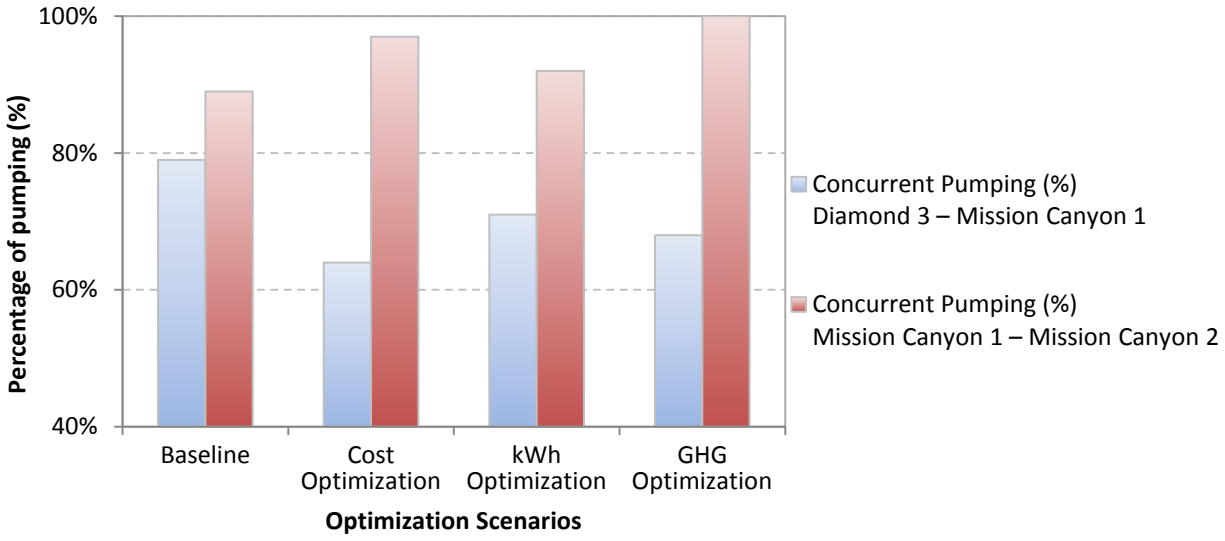


Figure 6.6: Percentage of concurrent pumping for the pump station combinations Diamond 3 – Mission Canyon 1 and Mission Canyon 1 – Mission Canyon 2 obtained under cost, kWh and GHG optimization scenarios during summer conditions at EMWD



Figures 5.7, 5.8 and 5.9 summarize the results for the one-week simulations of cost reduction, kWh reduction and GHG reduction optimization scenarios during the week-long summer

simulation at EMWD. The results are compared in terms of energy usage, cost incurred, and GHG production. Optimizing for cost reduces the cost associated with pumping ($471/week) compared to the kWh and GHG optimization scenarios analyzed. The kWh optimization minimizes the energy use but generates significantly higher costs than the other optimization conditions ($1,339/week). The kWh optimization was characterized by higher demand charges compared to the other scenarios ($1100, due to pumping occurring during peak tariff periods. Pumping schedules generated by the GHG optimization is more expensive than the baseline condition ($499/week vs. $455/week). The results show that, during summer, all optimization scenarios have lower energy requirements and produce less GHGs than the historical operations. Since the kWh schedule was characterized by higher average flows, lower hydraulic resistance on the fixed speed pump and, therefore, greater efficiency (lower kWh) was observed than the cost optimization schedule. The kWh and GHG optimization scenarios ran pumps against a lower average discharge head, thus moving water more efficiently through the network.

Figure 6.7: Weekly energy costs and demand charges associated with all pumping stations of the EMWD pilot system optimized for cost, kWh and GHG minimization during summer

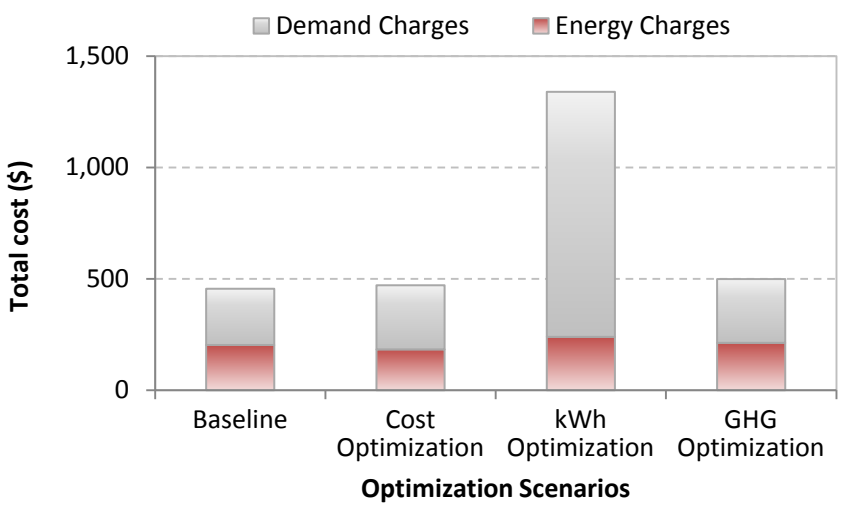


Figure 6.8: Weekly energy consumption associated with all pumping stations of the EMWD pilot system optimized for cost, kWh and GHG minimization during summer

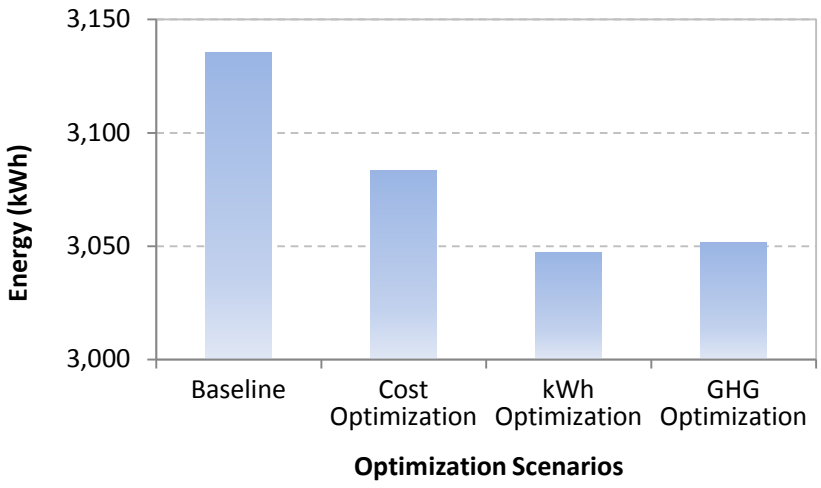


Figure 6.9: Weekly GHG emissions associated with all pumping stations of the EMWD pilot system optimized for cost, kWh and GHG minimization during summer

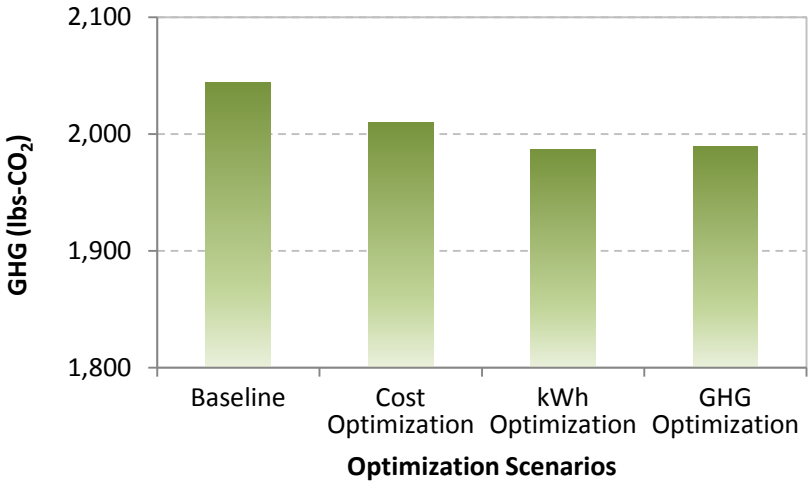


Figure 5.9 shows that the GHG optimization generated slightly higher GHG emissions than the kWh optimization scenario. The explanation for this observation lies on the understanding of the optimization principles. The difference in optimization principles between various optimization scenarios are presented in Tables 3.1 and 5.1. The GHG optimization is based on the assumption that emission factors vary throughout the day depending on the energy supply portfolio of the electric utility (Figure 3.5). Under the GHG optimization, the operational goal was to run the pumps when the emission factors are minimal, regardless of the energy consumption. Thus, unlike kWh optimization, the GHG optimization was not the lowest energy operation and required more energy compared to the kWh optimization. Therefore, we

observed that GHG optimization produced higher emissions compared to kWh optimization. Based on these results, the data suggest that water utilities should just focus on kWh optimization to achieve the lowest GHG operation until the variability of GHG emission factors for given water utility are well established by the electric utilities.

In summary, the GHG optimization is based on a variable rate of GHG generation during the day, whereas the kWh and cost optimization is based on a constant GHG generation during the day. Due to this difference in emission assumptions, the cases are not directly comparable but do give an indication of the possible additional GHG emission reduction over a cost optimization scheme through kWh and GHG optimization.

5.2.2 Winter Simulations Results

In winter, the system is characterized by a lower demand and lower differential tariffs than those of summer. The lower demand (high storage to demand ratio) allows EWQMS operations to move water in such a way that overall efficiency can be increased; however, the lower tariff differential during winter reduces the cost saving potential. Figure 6.10 shows the allocation of flows at Diamond 3 at different tariff periods and for the different optimization scenarios analyzed. The Diamond 3 pumping station, avoided the mid-peak completely under cost optimization and nearly completely when targeting GHG reduction (<5 percent). The kWh optimization was characterized by the lowest head to pump against but had the highest use of the mid peak tariff period (70 percent).

As observed for the summer scenario, the three optimization scenarios had a high level of concurrent pumping between Mission Canyon 1 and Mission Canyon 2 however, it was limited between Diamond 3 and Mission Canyon 1 (Figure 5.11). Since Diamond 3 had a very large storage to demand ratio, in many instances Mission Canyon 1 had to pump during times not optimal for Diamond 3.

Figure 6.10: Percentage of pumping at different tariff periods under the baseline, cost, kWh and GHG optimization at Diamond 3 pumping stations during winter

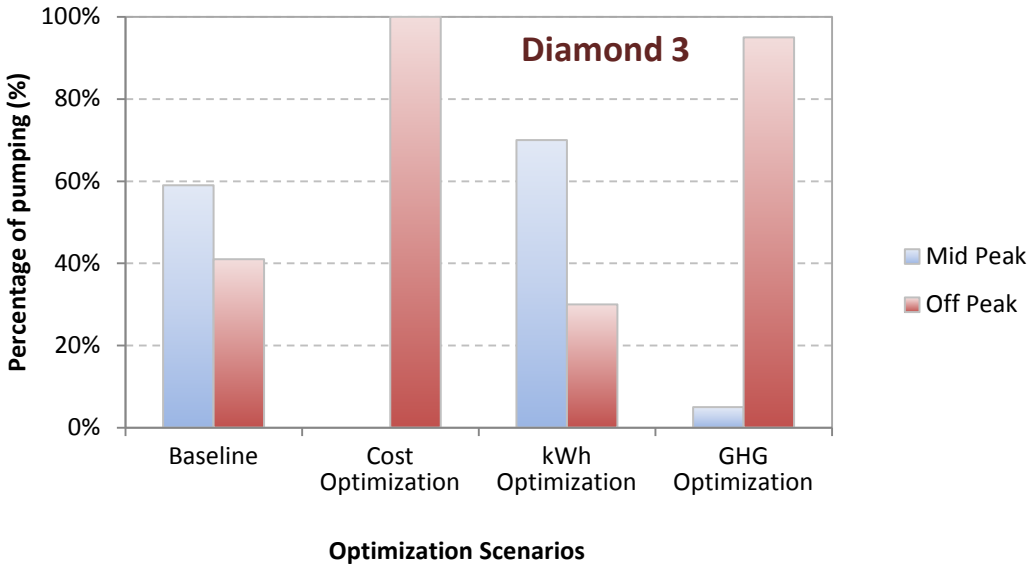
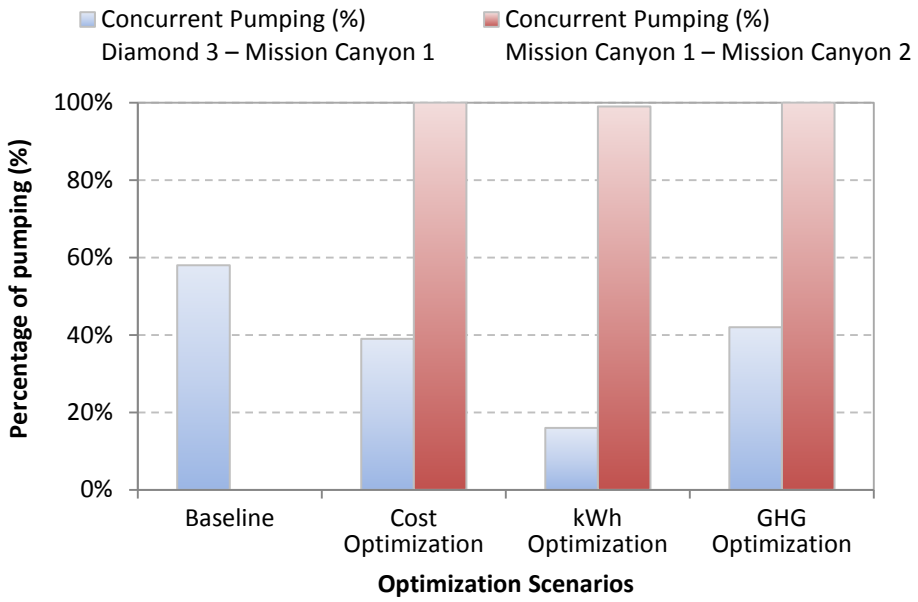


Figure 6.11: Percentage of concurrent pumping for the pump station combinations Diamond 3 – Mission Canyon 1 and Mission Canyon 1 – Mission Canyon 2 obtained under cost, kWh and GHG optimization scenarios during winter conditions at EMWD



Figures 5.12, 5.13 and 5.14 summarize the results for the one-week simulations of cost reduction, kWh reduction and GHG reduction optimization scenarios during winter at EMWD. The results

are compared in terms of energy usage, cost incurred, and GHG production. Optimizing for cost reduces the cost associated with pumping ($324/week) by 6 percent and 7 percent compared to the baseline and the kWh scenario, respectively, and is similar to that obtained when targeting GHG reduction ($326/week). The cost profile under TOU tariff and GHG emission profile appear to have similar trends. The kWh optimization minimizes the energy use (1,246 kWh/week) but generates higher costs than the other optimization conditions ($350/week). The same anytime demand charges were applied regardless of the target of the optimization ($247), due to pumping occurring at Diamond 3. The results show that, during winter, all optimization scenarios have lower energy requirements and produce less GHGs than the historical operation. During winter it was possible to reduce the energy consumption through efficiency gains more than in summer; however, due to the decreased tariff differential the cost savings achieved in winter are lower than those observed during summer.

Figure 6.12: Weekly energy costs and demand charges associated with all pumping stations of the EMWD pilot system optimized for cost, kWh and GHG minimization during winter

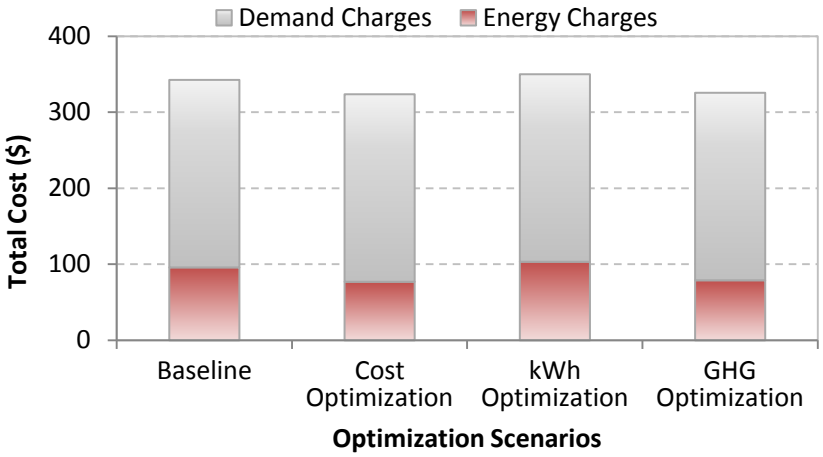


Figure 6.13: Weekly energy consumption associated with all pumping stations of the EMWD pilot system optimized for cost, kWh and GHG minimization during winter

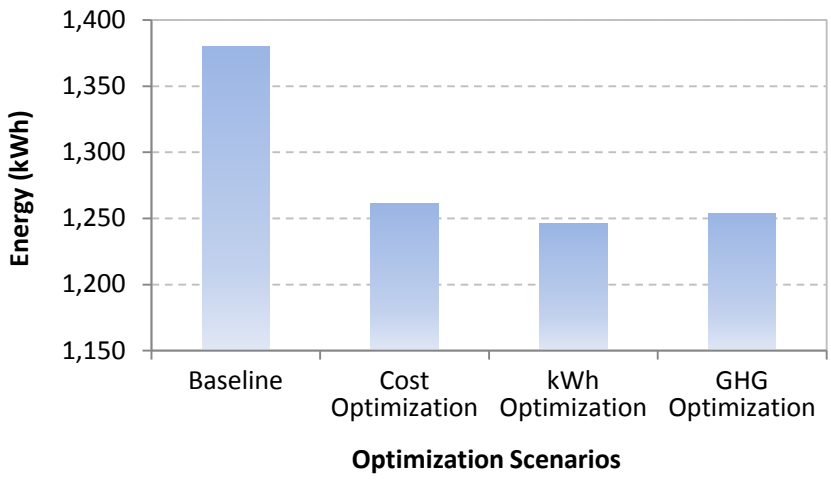
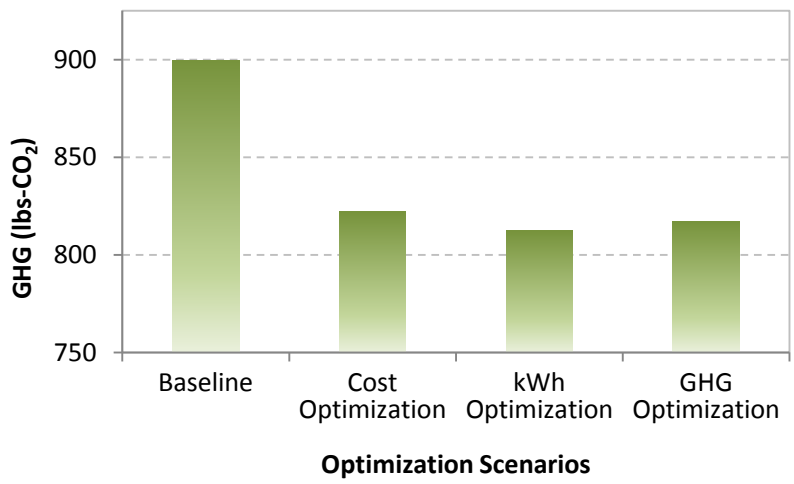


Figure 6.14: Weekly GHG emissions associated with all pumping stations of the EMWD pilot system optimized for cost, kWh and GHG minimization during winter



The above figure shows that the GHG optimization generates slightly higher GHG emissions than the kWh optimization scenario. The same observation was made for the offline summer and winter simulations and an explanation for this observation has been presented in the previous Section 5.2.1.

5.3 Real-Time Operation of EWQMS Modified with GHG Module

The EWQMS modified with the GHG module was validated through real-time operation in the selected subsystems, Diamond 3, Mission Canyon 1 and Mission Canyon 2 pumping stations, at EMWD between June and August, 2014. During the pilot, each optimization scenario (cost, kWh and GHG optimization) was scheduled to run for at least two weeks, as presented in Table 5.3. Details of the pilot test plan and results are reported in the following sections.

Table 6.3: Pilot plant schedule and operational details at EMWD

Optimization Scenario	Pilot Operation			Avg. Demand (MGD)
	Start	End	Days	
Baseline	April 14th	April 23rd	10	0.4
GHG Optimization	July 1st	July 13th	13	0.7
kWh Optimization	July 14th	July 27th	14	0.6
Cost Optimization	July 28th	August 10th	14	0.6

5.3.1 Data Collection and Analysis

During the real-time pilot operations the following data were collected:

- *Electricity consumption*. Total electrical usage was collected three times per week by an EMWD operator and the time of collection was recorded, including measurements on the first and last day of each optimization scenario.
- *Telemetry/SCADA data from EWQMS*. Readings from SCADA and those calculated by EWQMS were recorded with a 10-minute frequency. The data collected include tank levels, pump status, pump suction pressure, pump discharge pressure, pump station flow, individual pump flow, where available, and the optimal pump schedule calculated by EWQMS and used for comparing planned vs. actual performance.
- *Water quality parameters*. At EMWD, various sampling locations were identified in tanks (Searl, Mission Canyon 1 and Mission Canyon 2) within the pilot area. Samples were collected five times per week and analyzed for chlorine residual and temperature. The operators recorded tank levels during sampling and pump on/off mode at the sampling time. Prior to the online trial, two weeks of data were collected daily to establish a pre-pilot operation condition. Water samples were collected for a week after the end of pilot operations to capture post-pilot conditions. During the pilot testing at EMWD, water supply was changed on June 6, 2014 and July 17, 2014. However, no effects in water quality were observed due to source water changes.

During the real-time pilot operations the SCADA data and EWQMS schedules were reviewed daily and responses to troubleshooting tickets issued by EMWD were addressed promptly. A series of events occurred during the pilot operation, some of which triggered operator overrides and EWQMS out of system control. In particular:

- Mission Canyon 2 was switched from a flat tariff to a TOU tariff. The new tariff was incorporated into the on-line pilot.
- Between the months of July and August, Diamond 3 pumping station was subject to the TOU-PA-SOP (Super Off-Peak) by SCE. Energy charges under this tariff structure are based on the time of day and the season (on-peak, off-peak, and super off-peak). Energy- and time-related demand rates during the super-off-peak period are lower than the rates

during the off-peak period and substantially lower than the rates during the on-peak period. During the pilot, pumping at Diamond 3 was not allowed during the peak tariff window of the SOP tariff (1:00 PM to 5:00 PM). Preventing the kWh and GHG scenarios from pumping during the peak period greatly reduced the cost incurred but also reduced the opportunity to realize efficiency benefits.

- The online and offline simulations were conducted during the summer months (July-August) and characterized by similar water demands (0.6-0.7 MGD for the pilot vs. 0.8 MGD during the offline simulations). However, the baseline period considered for the pilot operations (within the month of April) had only 0.4 MGD of water demand. April was the most recent period when the system was under operator control and was selected as a baseline. It should be noted that the data was analyzed based on the normalized flow.
- Operation intervention was recorded during various optimization scenarios (Table 6.4). The interventions by the operators did not have a significant effect on overall operation, in terms of tank volume, and these periods were excluded from the overall analysis because they were manually controlled without any optimization. In most cases the interventions were a reaction to high pressure readings caused by a faulty meter and the need to run the gas pumps at Diamond 3 pumping station.
- During all optimization scenarios a throttled valve at Diamond 3 impacted pump station discharge pressure readings and the ability of the system, to shift electric load. In fact, due to the throttled pump in the system, frequent pump outages occurred from erroneous high pressure alarms. The high pressure alarms would trigger if the Searl tank level was high and also more likely when water demand was low. When water demand was low at night the excess pressure caused the pump to trip, which significantly reduced night pumping at lowest cost. The pumps were sometimes not reset into operation until the next morning and this forced more pumping to occur during the mid-peak tariff period. Since this occurrence was not detected or corrected until after the pilot was completed, the cost savings achieved were lower than those predicted offline.

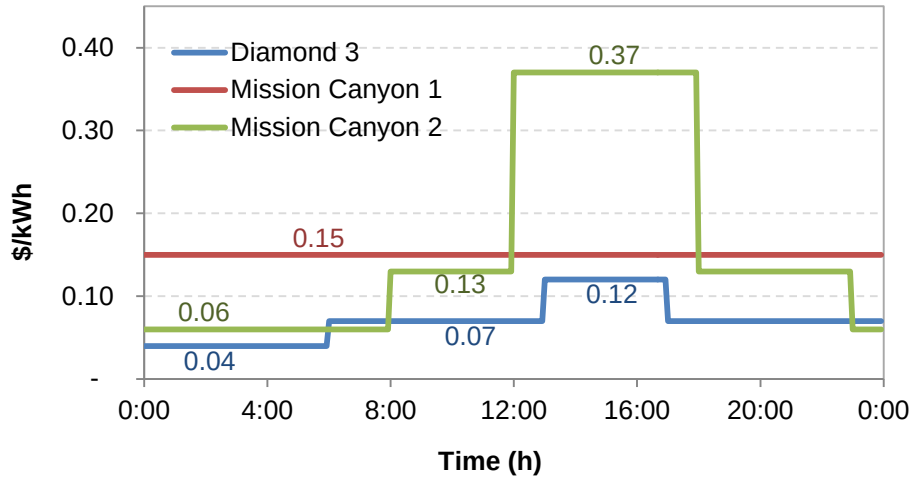
Table 6.4: EWQMS vs. manual control

Optimization Scenario	Pilot Operation Duration (hours)	Time Under Manual Operation (hours)	% Under EWQMS Control
Cost Optimization	335	1	100%
kWh Optimization	333	3	99%
GHG Optimization	332	4	99%

During the pilot, Diamond 3 and Mission Canyon 2 pump stations were subject to TOU tariffs by SCE, while Mission Canyon 1 was under a flat rate tariff. The Diamond 3 tariff structure is characterized by lower rates than those applied to Mission Canyon 1 and Mission Canyon 2

pump stations (Figure 6.15) and includes two peak period demand charges: a maximum-peak-period demand charge ($25.29/kW) and a maximum-demand charge ($8.55/kW). The maximum-peak-period-demand charge per kilowatt applies to the maximum demand during the month's peak hours, and the maximum-demand charge per kilowatt applies to the maximum demand at any time during the month.

Figure 6.15: SCE TOU tariffs applied at the Diamond 3, Mission Canyon 1 and Mission Canyon 2 pumping stations during pilot operations at EMWD



5.3.2 Real-time Pilot Operation Results

This section summarizes the results for the cost reduction, kWh reduction and GHG reduction optimization scenarios obtained during the pilot operation at EMWD. The results are compared with the baseline values in terms of energy usage, cost, and the GHG emissions.

The baseline selection at EMWD was challenging as extended periods of manual operations were not found in the historical dataset of recent periods with similar water demand. The selected baseline period from April 14th to April 23rd was characterized by lower water demand than in other optimization scenarios and by operation with solely gas pumps. The gas pumps are significantly less efficient than electric pumps. Typically gas pumps operate at 17 percent efficiency, which is lower than the 65 percent wire-to-water efficiency of electric powered pump operations. However, gas prices can be 1/5th of electric prices per kWh and are not charged with peak kW demand charges.

As a general rule, when average daily water demand is above 0.31 MGD, electric pumping appears to be the lowest cost choice. When average daily water demand is below 0.31 MGD, gas pumping is the lower cost choice because the electric demand charge impact makes the per kWh electricity effective cost higher than the equivalent gas cost. In all scenarios, electric pumps have a lower GHG output than gas pump usage. The GHG emissions per MG for gas engine driven pumps can be five times higher than electric pumps, using statewide values for GHG per kWh.

Because the GHG emissions for gas pumps is approximately five times greater than electric pumps, a meaningful comparison is not possible if a baseline using gas pumping is considered. Thus, an "electric baseline" was calculated, by substituting an amount of kWh as demanded by electric pumps delivering the same volume and flow rates as the gas pumps. The electric pumps produce only slightly more flow capacity than the gas pumps and if used during the baseline period, the associated operational cost would have been high due to the peak electric tariff period and related demand charges. Thus, it was assumed that the electric pumps would not be used during peak periods and instead the volume of water supplied by the gas pump was spread over the non-peak priced period in the same ratio as gas pumps were used in those no-peak periods. So, for example if under gas pump operations, the peak, mid-peak and off-peak electric tariff periods account for 20 percent, 40 percent, and 40 percent pumping, respectively, these percentages are converted to 0 percent, 50 percent, and 50 percent under electric operation.

Figure 6.16 shows typical flow profiles during the pilot for baseline operation and for various optimization conditions. During the baseline period, under operators' control, the operators were able to shift all the pumping to mid- and off-peak periods. Similarly, EWQMS avoided peak tariff periods when operating under cost, kWh and GHG optimization scenarios.
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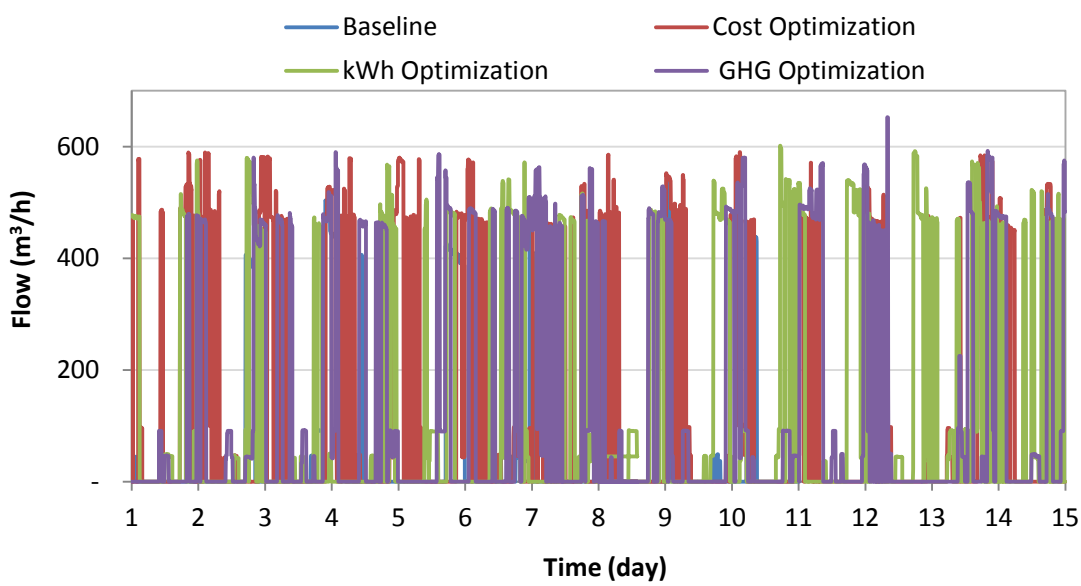
Figure 6.16: Total flow profiles under the baseline, cost, kWh and GHG optimization scenarios during the duration of the pilot (top) and in a given day (bottom)



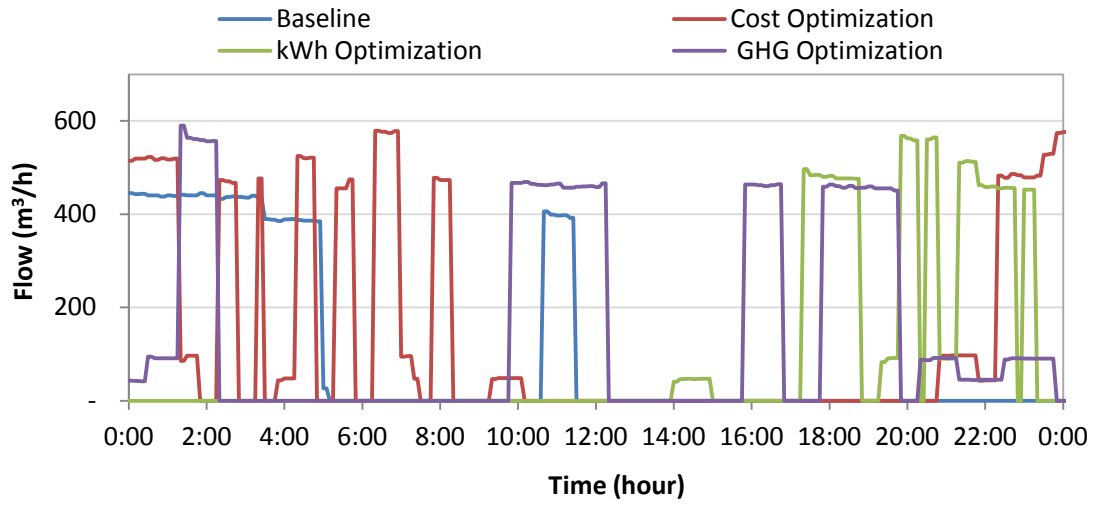
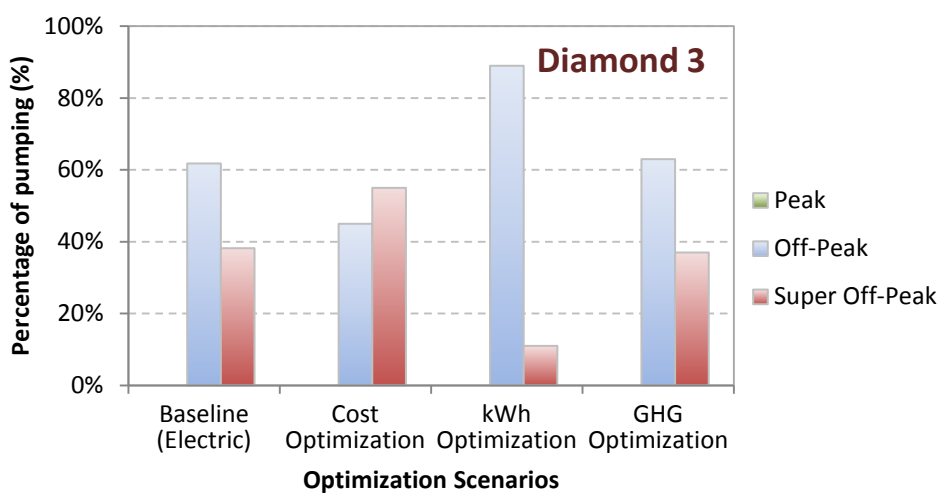
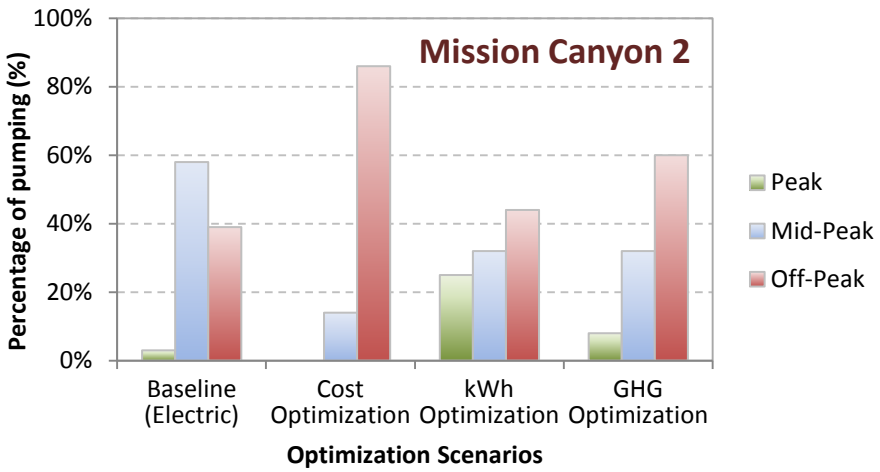


Figure 6.17 shows the percentage of pumping during different tariff periods at the Diamond 3 and Mission Canyon 2, both under TOU tariffs. Load shifting was not considered at Mission Canyon 1, since the pump station is under a flat rate tariff. At Diamond 3, under cost optimization, 55 percent of the flow was diverted to super off-peak periods, while the kWh and GHG optimization moved 11 percent and 37 percent of the pumping to the same tariff window, respectively. In general, at Diamond 3, pumping during off-peak was increased in all optimization scenarios due to high pressure alarms caused by the throttled valve at the station. At Mission Canyon 2, 25 percent of the pumping occurred during peak periods when optimizing for kWh and slightly less (8 percent) when targeting GHG. In both cases, the allocation percentage of the flow during peak periods was higher than that observed during baseline operations (3 percent).

Figure 6.17: Percentage of pumping at different tariff periods under the baseline, cost, kWh and GHG optimization at Diamond 3 (top) and Mission Canyon 2 (bottom) pumping stations





By avoiding peak periods and related demand charges, the cost optimization scenario had lower total costs than the baseline and the other optimization scenarios (Figure 6.18). The total demand charges at Diamond 3 and Mission Canyon 2 for all optimization scenarios were within 1.5 percent of those applied during the baseline period (Figure 6.18). Optimizing for cost reduces the cost associated with pumping ($693) compared to the other optimization scenarios analyzed, with an overall 7.8 percent cost reduction over the baseline. Under the cost optimization scenario, a 2.9 percent decrease in energy consumption, thus also of GHGs emissions, was observed compared to the baseline (Figure 5.19 and Figure 5.20).

The kWh optimization generated the lowest demand charge cost due to a more efficient pump operation (i.e., using the lowest peak kW), however generated an overall 5.6 percent cost increase compared to the baseline value. Similar to the cost optimization scenario, the kWh optimization scenario achieved a 2.9 percent reduction in energy usage and GHG emissions from the baseline. The kWh scenario and GHG scenario utilized both pumps at Mission Canyon 1 to increase efficiency based upon hydraulic conditions, which led to a higher average head but a lower overall energy use.

The GHG scenario experienced higher water demand (0.7 MGD) compared to all the other scenarios (0.6 MGD as shown in Table 5.3) and therefore had to shift additional load to make improvements. A 1.7 percent cost reduction was observed under this optimization condition compared to the baseline, with a 2.9 percent reduction in energy consumption and GHG emissions comparable to those obtained with cost and GHG reduction goals.

Figure 6.18: Energy costs and demand charges associated with all pump stations of the EMWD pilot system optimized for cost, kWh and GHG minimization

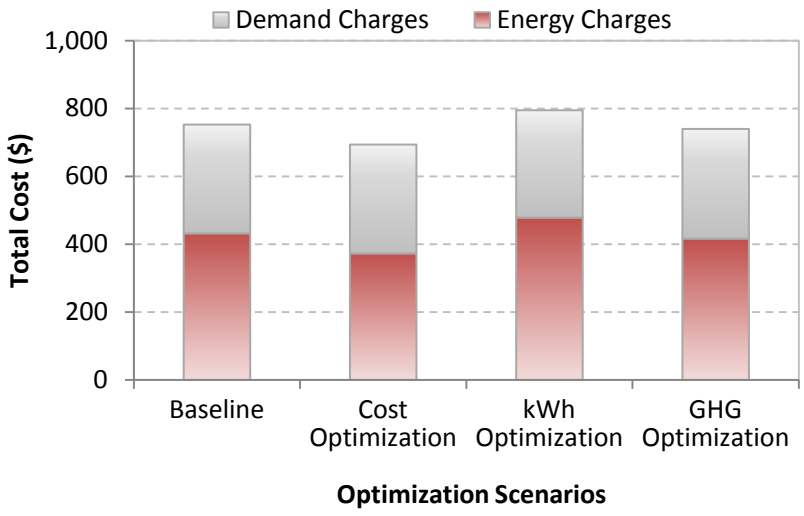


Figure 6.19: Energy consumption associated with all pump stations of the EMWD pilot system optimized for cost, kWh and GHG minimization

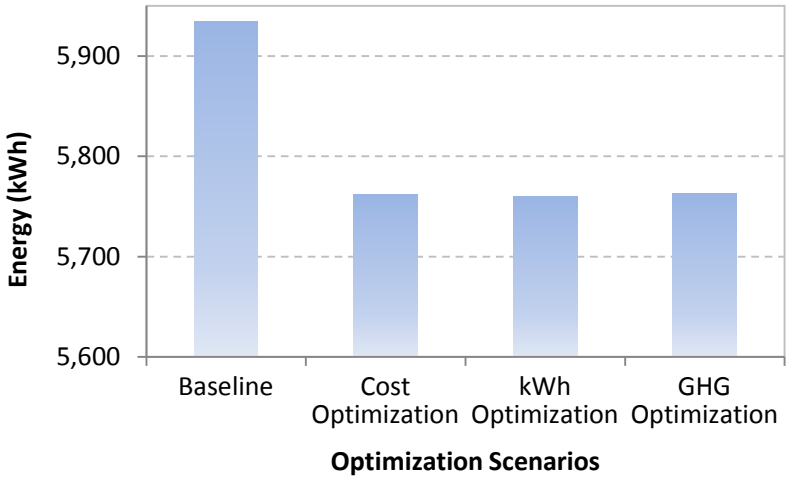
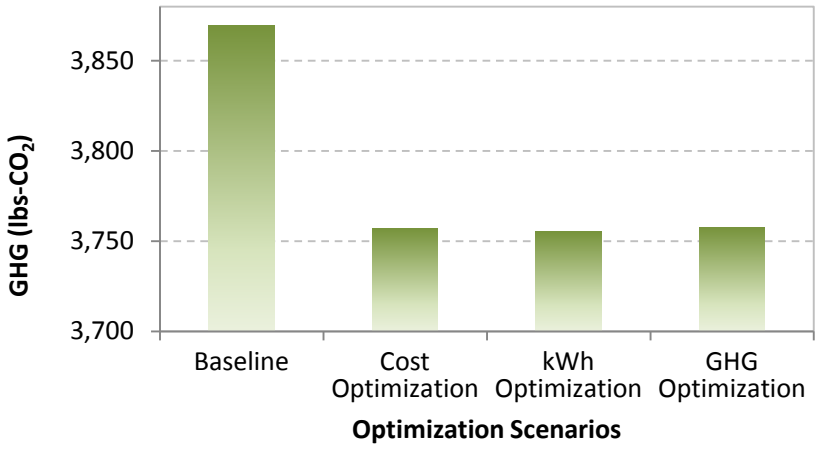


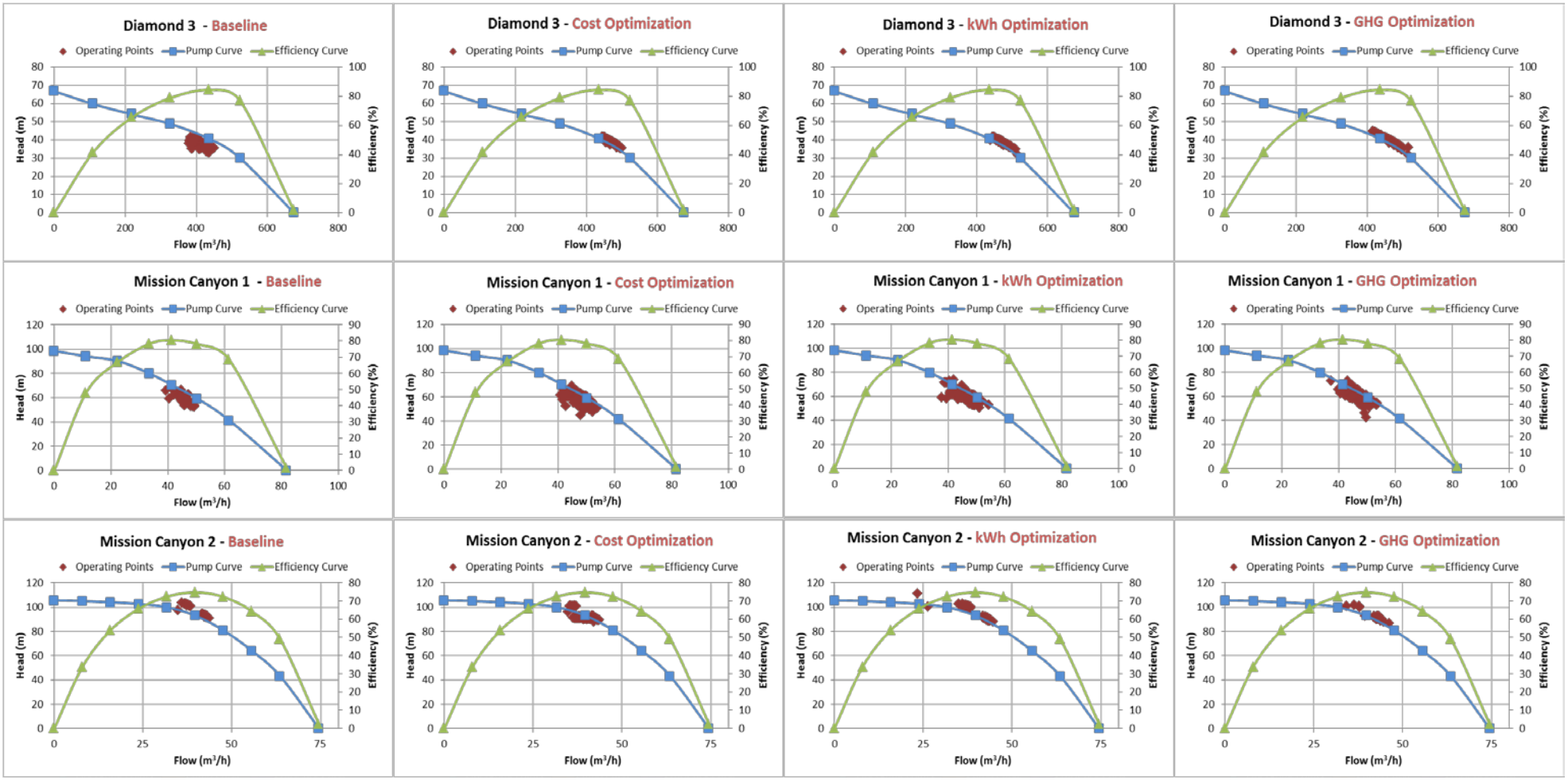
Figure 6.20: GHG emissions associated with all pump stations of the EMWD pilot system optimized for cost, kWh and GHG minimization



The above figure shows that the GHG optimization generates slightly higher GHG emissions than the kWh optimization scenario. The same observation was made for the offline summer and winter simulations and an explanation for this observation has been presented in the previous Section 5.2.1.

Figure 6.21 shows the pump curves and operating points for all pump stations and all optimization scenarios analyzed. As observed for EBMUD, all pump stations operated at higher average flow rates and therefore have improved efficiency compared to the baseline.

Figure 6.21: Pump curves, efficiency curves and operating points at Diamond 3, Mission Canyon 1 and Mission Canyon 2 pumping stations for different optimization scenarios



5.3.3 Comparison Between Offline Simulations and Pilot Operations Results

Table 6.5 shows the comparison of cost, energy and GHG emissions reduction between the offline predictions and the real-time operation results compared to the baseline.

Opposite trends of cost reduction were obtained between the pilot (7.8 percent cost reduction) and the offline simulation (3.4 percent cost increase) relative to the baseline when optimizing the system for cost (Table 6.5). In contrast to the predictions, the real-time operations also achieved a 1.7 percent cost reduction when targeting GHG minimization. Both real-time operations and predictions resulted in higher costs when targeting kWh.

Real-time cost optimization generated a 2.9 percent decrease in energy consumption and GHG emissions relative to the baseline, greater than the 1.7 percent predicted by the offline simulations. Optimizing for kWh and GHG in real-time generated an overall increase in energy and GHG emission reduction compared to the baseline (2.9 percent), similar to the 2.8 percent and 2.7 percent increase predicted by the offline evaluation, respectively.

Table 6.5: Comparison between the baseline and the offline simulations and pilot operation results at EMWD

Optimization Scenario	Cost (% reduction)		Energy (% reduction)		GHG (% reduction)	
	Offline Simulations[1]	Pilot[2]	Offline Simulations[1]	Pilot[2]	Offline Simulations[1]	Pilot[2]
Cost Optimization	-3.4%	7.8%	1.7%	2.9%	1.7%	2.9%
kWh Optimization	-194.1%	-5.6%	2.8%	2.9%	2.8%	2.9%
GHG Optimization	-9.5%	1.7%	2.7%	2.9%	2.7%	2.9%

[1]Percentage based on the baseline selected for offline simulations

[2]Percentage based on the baseline selected for pilot operations

The difference in the costs incurred per pound of CO_2 emission reduction for the offline simulations and pilots are presented in Table 6.6. The data indicate that the lowest cost for a pound of CO_2 reduction might be achieved in summer through kWh optimization ($0.4/lbs-$CO_2$), lower than that predicted offline ($15.4/lbs-$CO_2$).

Table 6.6: Cost of carbon comparison between offline simulations and pilot operations at EMWD

	Cost of GHG ($/lbs-$CO_2$)	
	Offline Simulations	Pilot
Baseline to Cost	-0.5	0.5
Baseline to kWh	15.4	0.4
Cost to kWh	37.0	66.3

5.4 Impact of Optimization Scenarios on Water Quality

This section includes the offline water quality predictions and online water quality observations that resulted from the three optimization scenarios of cost, energy, and GHG emissions.

5.4.1 Results from Offline Simulations on Water Quality

The optimized system hydraulic performance, individual scenario pump scheduling and contrasting level variation under each control regime obtained with offline water quality simulations at EMWD were analyzed. Predicted water age in the tanks is listed in Table 6.7 and Table 6.8 for the summer and winter scenarios, respectively. Turnover is expressed as the percentage of active tank volume that is refreshed each day over the weekly off-line study period. The average age of water in the tanks is similar in all cases, revealing no clear optimal strategy for managing water quality through pump optimization. The results show large differences in the maximum and minimum tank levels generated during the actual and optimized scenarios, particularly for Mission Canyon 1 and 2 Tanks. Greater use of tank operational volumes and increased cycling should lead to improved water age. However, due to low demand on the system and very rapid refill rates, this might not affect the water age reaching customers.

Table 6.7: Predicted water age and turnover in tanks for the summer scenario at EMWD

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Mean Age (hr.)				
Searl Tank	190	192	197	192
Mission Canyon 1	103	119	127	111
Mission Canyon 2	152	163	157	150
Turnover[1] (%/day)				
Searl Tank	13%	13%	12%	12%
Mission Canyon 1	23%	20%	19%	22%
Mission Canyon 2	16%	15%	15%	16%

Table 6.8: Predicted water age and turnover in tanks for the winter scenario at EMWD

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Mean Age (hr.)				
Searl Tank	275	284	301	287
Mission Canyon 1	215	210	228	220
Mission Canyon 2	306	284	288	280
Turnover[1] (%/day)				
Searl Tank	9%	8%	8%	8%
Mission Canyon 1	11%	11%	11%	11%
Mission Canyon 2	8%	8%	8%	9%

Model prediction results can be used to calculate the variation in water age reaching customers. This is different from reporting water age in the network, as it only considers water being drawn from the system at customer connections. Figure 5.22 through 5.25 show the predicted maximum age of water in the EMWD network for different optimization scenarios during summer and winter with actual demands and pump switching.

Figure 6.22: Representation of maximum modeled water age for baseline operations in summer and winter at EMWD

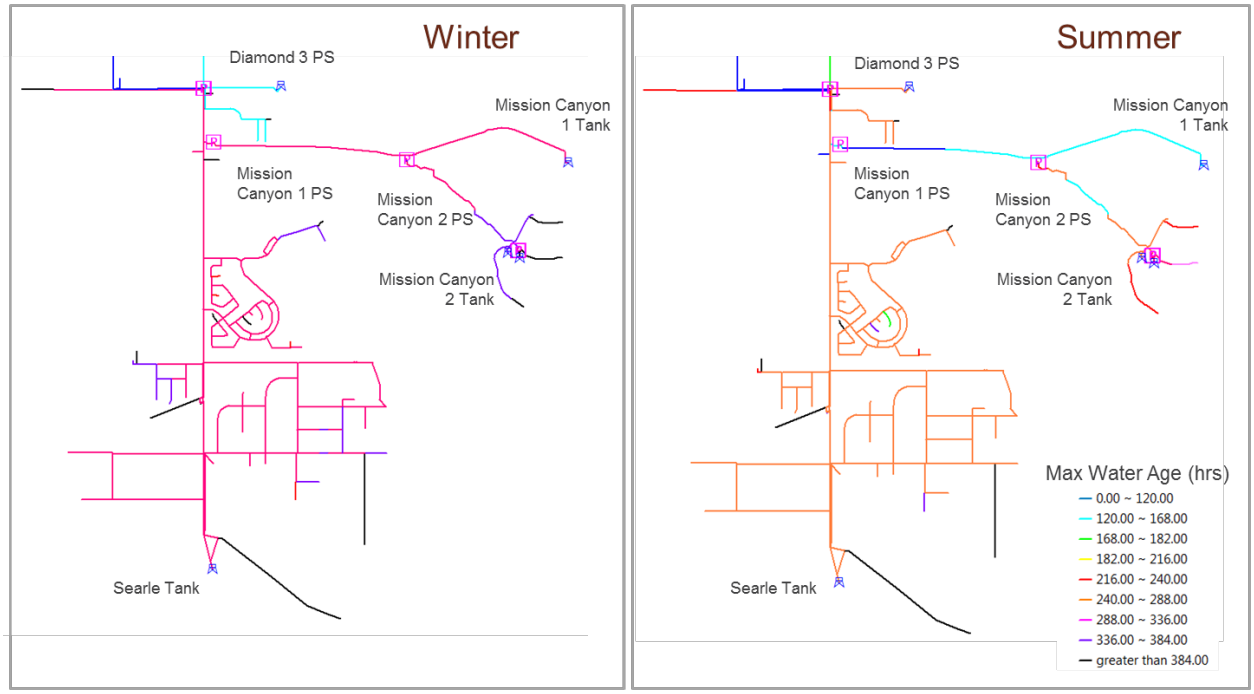


Figure 6.23: Representation of maximum modeled water age for cost optimization in summer and winter at EMWD

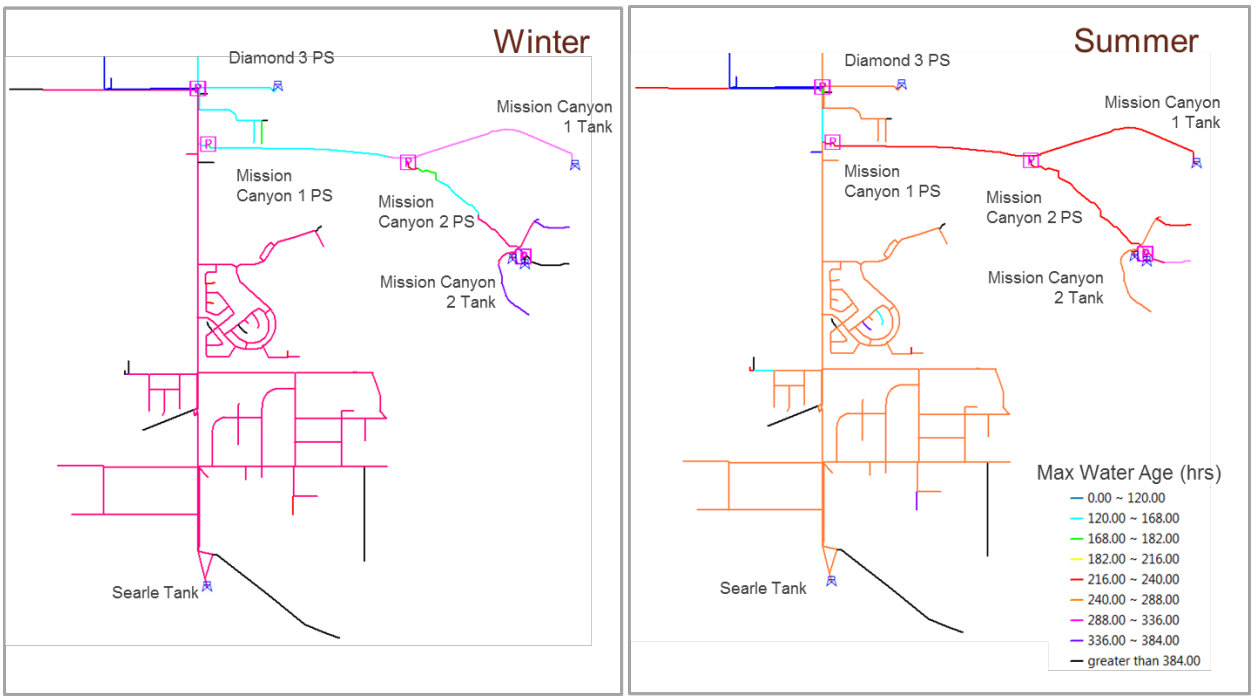


Figure 6.24: Representation of maximum modeled water age for energy optimization in summer and winter at EMWD

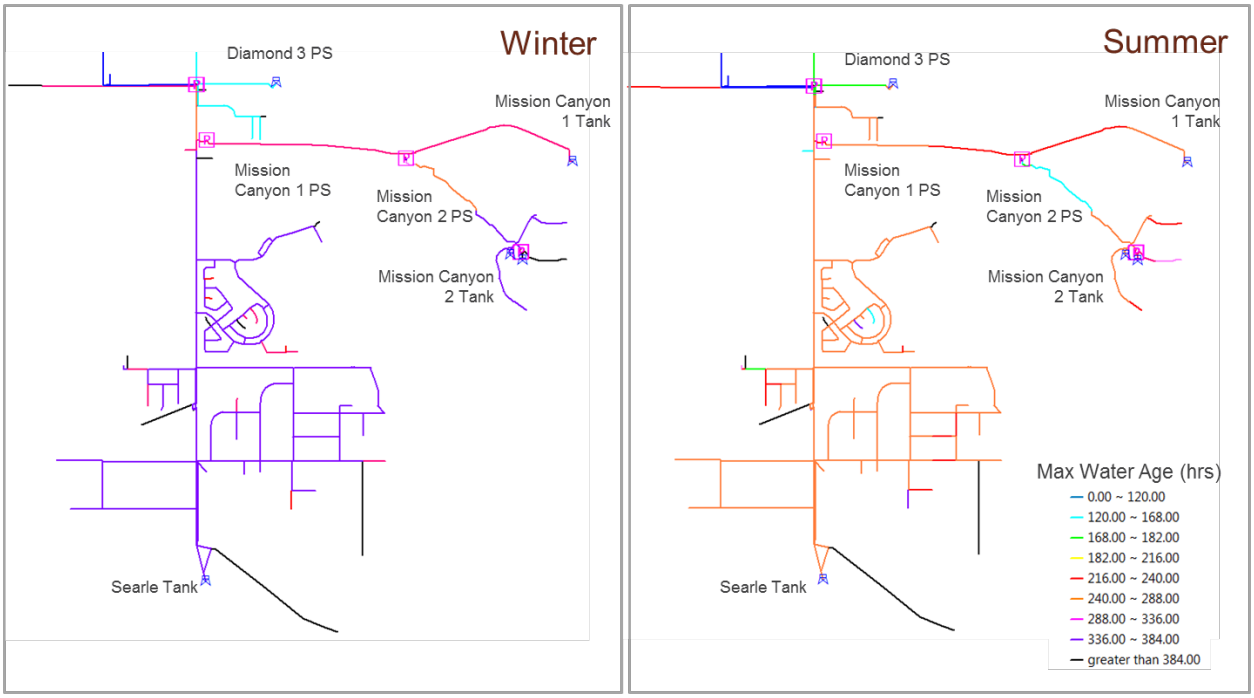
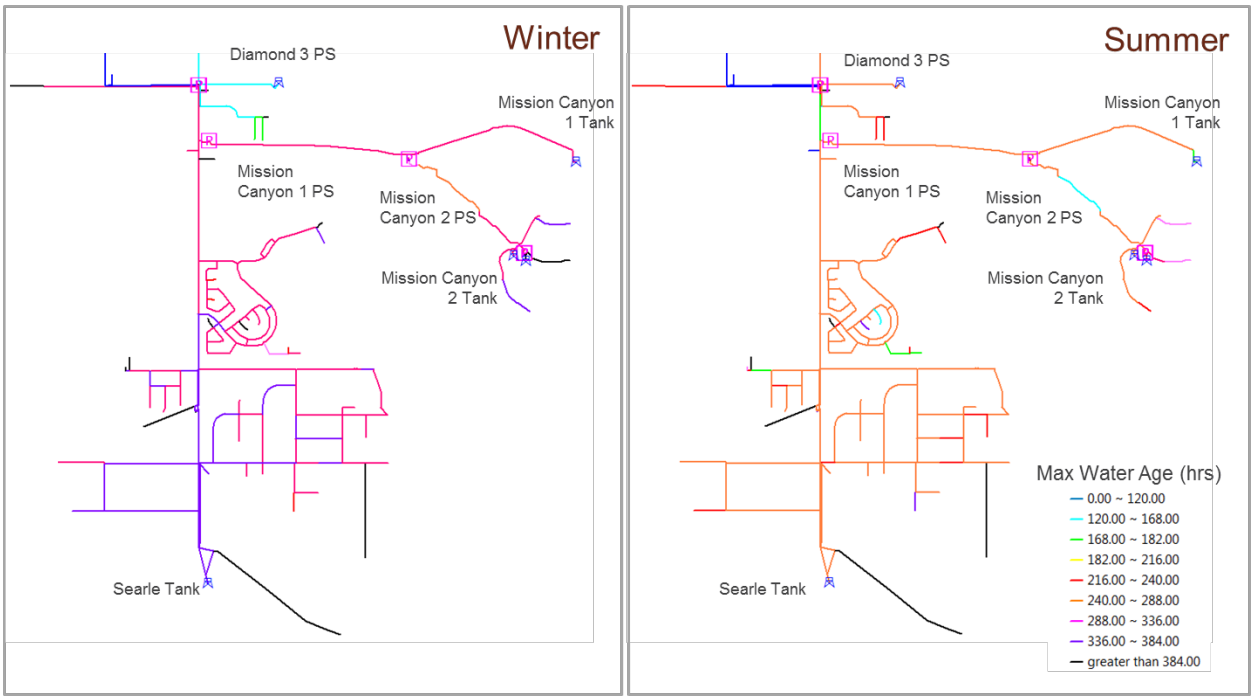


Figure 6.25: Representation of maximum modeled water age for GHG optimization in summer and winter at EMWD



Predicted mean water age in the distribution system is presented in Table 6.9 and Table 6.10 for summer and winter scenarios, respectively. A further refinement in the calculation has been provided by including the demand weighted average age, which accounts for the fact that although water in the network at the customer connection may be aged, it is only liable to impact customers (leading to taste and odor complaints) when the customer is drawing water. Hence, older water during night periods may have less chance of causing customer complaints.

In summer the mean age of water received by customers is between 120 and 132 hours. Allowing for differences in volumes drawn during day and nighttime, the weighted mean is between 109 and 132 hours. The GHG minimization strategy provides the best water quality (least age) to the most customers. However, the improvement in water age is slight, and may not provide any noticeable difference in quality in practice.

In winter, due to the reduced demand, all customers receive older water than in summer. The mean age of water varies from 199 to 215 hours. Weighted for demand, the mean age is 188 to 205 hours. Again the GHG minimization strategy appears to provide the best quality (of strategies tested). However, again the difference in water age may not provide any noticeable difference in quality in practice.

Table 6.9: Predicted water quality in distribution system for the summer scenario

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Age (hrs.) - 5% percentile	30	29	34	29
Age (hrs.) - Mean	125	124	132	120
Age (hrs.) - 95% percentile	217	220	223	219
Age (hrs.) - Demand Weighted Mean	112	116	132	109

Table 6.10: Predicted water quality in distribution system for the winter scenario

	Baseline	Cost Optimization	kWh Optimization	GHG Optimization
Age (hrs.) - 5% percentile	35	42	49	41
Age (hrs.) - Mean	214	202	215	199
Age (hrs.) - 95% percentile	354	352	363	351
Age (hrs.) - Demand Weighted Mean	205	190	204	188

The water quality investigations have revealed that there is little clear difference in water quality impact from the four operating modes investigated in the off-line studies for the East Valley/Diamond 3 system. Detailed inspection of model predictions has shown that strategies that run all three pumping stations simultaneously do provide marginally reduced water age to customers across the system, on average. In practice, customers benefiting are located in Mission Canyon network and closer to Diamond 3 Pumping Station than to Searl Tank.

The strategy that selects simultaneous pump operation more frequently is GHG minimization. Actual operating modes also tend to favor running all three pumping stations concurrently. Minor differences in the optimization results for least cost and energy operation lead to occasionally running Mission Canyon 1 and 2 pumps when Diamond 3 Pumping Station is off. This causes older water to be drawn from Searl tank further into the network, affecting customers in Mission Canyon sub-system. After blending in Mission Canyon 1 and 2 tanks, the effect on water quality is small, but customers drawing water directly, prior to the tanks, may see a small benefit.

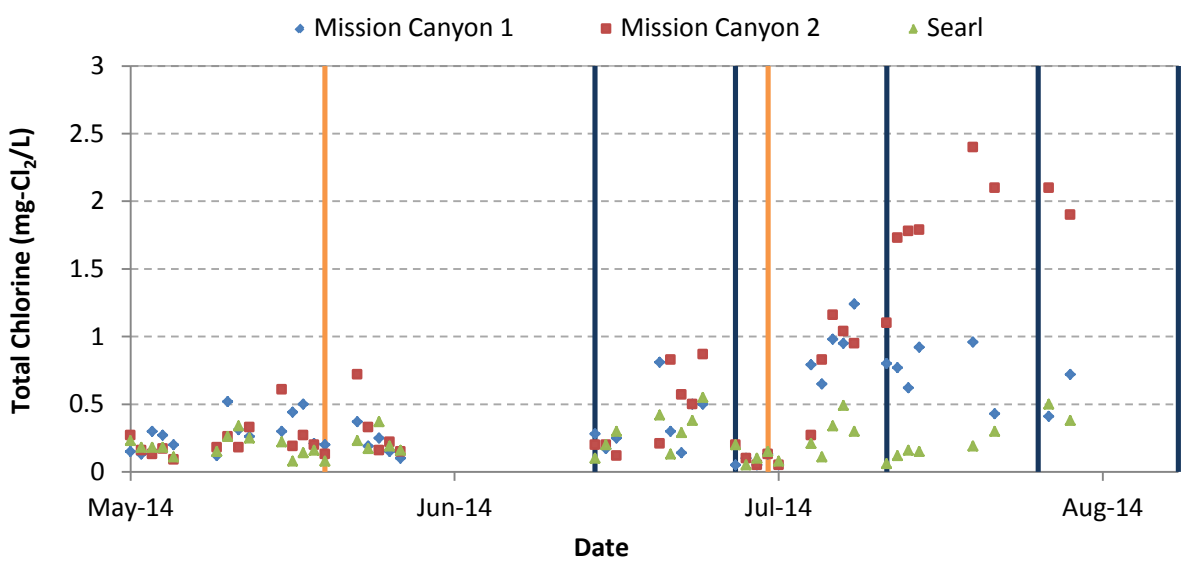
The overriding impact on water quality (age of water as surrogate measure) in the Diamond 3 system is the low demand and large retention times in Searl, Mission Canyon 1 and 2 tanks. Disinfectant residual concentrations are not directly compared in the off-line studies. This is due to the lack of time series information and the complications of modeling chlorine decay in networks (ideally conducted using a calibrated water quality model). It is worth noting that, subject to compliance with disinfection byproduct rules, chlorine boosting could also improve the quality of water delivered to customers.

5.4.2 Results from Real-time Operations on Water Quality

Regular monitoring of water quality parameters was performed during the real-time pilot operations at EMWD for operations with different optimization objectives. Chlorine residuals (mg/L as Cl_2) profiles at the East Valley system tanks (Searl, Mission Canyon 1 and Mission Canyon 2) during the pilot are shown in Figure 6.26. Similar plots for historical chlorine residual in in the sub-system pumping stations and in tanks for the years 2013-2014 are shown in Figure 6.27 and Figure 5.28, respectively.

Before and during the pilot, the water source was changed in two different instances, as shown in Figure 6.26. On June 6, the State Water Project was supplemented with Colorado River Aqueduct Water. On July 17, the principal water source for East Valley system changed from State the Water Project to Colorado River Water (the other sources of Lake Skinner and groundwater wells remained unchanged). Immediately following the change in source water on July 17, the chlorine residuals rose across the pilot zone. Colorado River Water chemical composition is different from that of State Water Project). Changes in the system chlorine demand are likely to be the cause of higher residuals in Mission Canyon 1 and 2 tanks, and not the pump scheduling under EWQMS control. Owing to the change in source water mid-way through the project, the water quality results cannot be directly used to corroborate performance predictions made during the offline simulations. However, there is some evidence that quality in all three tanks is maintained in a stable balance by manual operation. When the optimizer is allowed to select for energy minimization (kWh and GHG optimizations) Mission Canyon 2 is seen to contain fresher water than either Mission Canyon 1 or Searl tanks. This is possible when energy minimization leads to series pumping regardless of TOU tariff.

Figure 6.26: Chlorine residual during real-time operations at different optimization scenarios



Tank residuals do have a seasonal trend, as would be expected with greater winter retention times. However, pumping station values are quite variable. Mission Canyon 1 and 2 pumping

station trends mirror each other. They also match incoming water quality at Diamond 3 pumping station, but not in all cases. Often Mission Canyon 1 and 2 pumping station values are very similar suggesting they are broadly the same water being sampled. One explanation for the swings in quality is that if Diamond 3 pumps are off, then Searl water may be sampled (low values), compared with fresher Diamond III water (high values) when the pumps are on. Generally, there are lower residuals during the real-time operations compared with those of a similar period in the previous year. The effect is most noticeable for Searl tank, which exhibited low chlorine residual throughout the test period. Low residuals were also apparent in Mission Canyon I and II tanks.

The offline studies showed that water quality in tanks may not be representative of the water received by customers. This is because water continues to age (and chlorine decay) when in distribution. Pumping regimes may inhibit turnover in tanks, leading to aging of stored water, but customers close to the pumping station may benefit from fresher water. Some regimes may lead to imbalanced quality across the system. With sampling data collected from tanks only, it is not possible to quantify whether this occurred during the pilot phase. However, the closeness in recorded quality for all three tanks under State Water Project water supply suggests that the different regimes are not causing significant imbalances in the network. The overriding impact on water quality in the Diamond III system is the low demand and large retention times in Searl, Mission Canyon 1 and 2 tanks. Water quality is only marginally linked to pump operating philosophy. Quality is more influenced by reservoir operation, especially minimum and average volume stored.

Figure 6.27: Historic chlorine residuals at Diamond 3, Mission Canyon 1 and 2 pumping stations

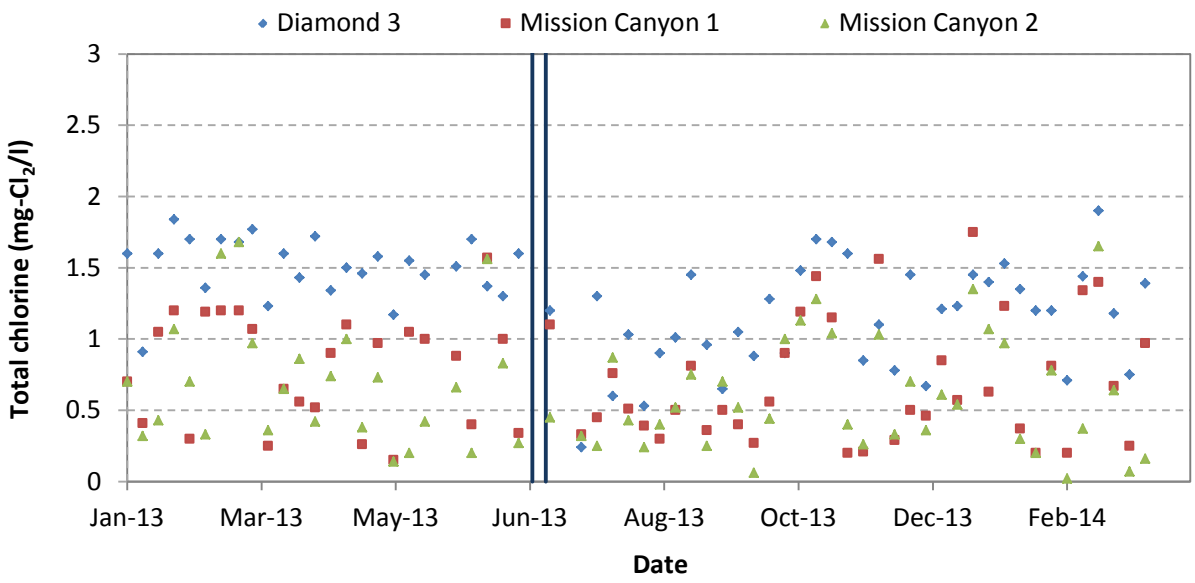
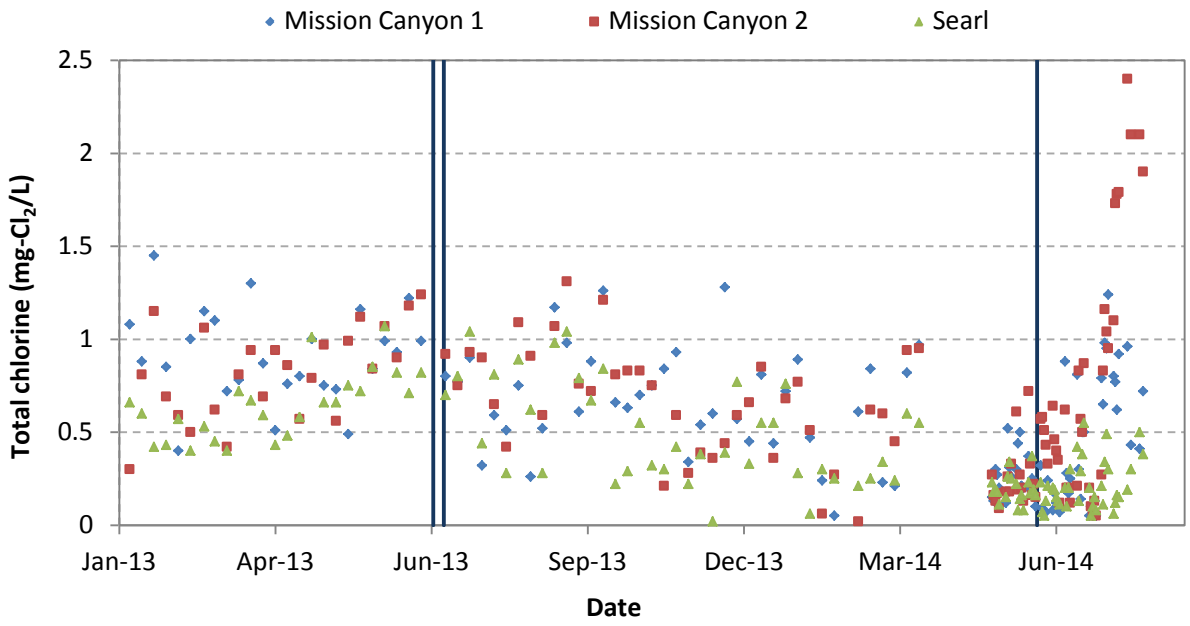


Figure 6.28: Historic chlorine residuals and pilot sampling data for Searl and Mission Canyon 1 and 2 Tanks



CHAPTER 6:
EWQMS Implementation Guidance at Water Utilities

The objective of this chapter is to present critical steps of EWQMS implementation and recommended best practices associated with each implementation step. This chapter also describes important elements of a business case, and presents guidance on how to evaluate cost-benefits for an EWQMS implementation project. The information presented here was collected through reviewing literature, interviewing case study utilities and EWQMS solutions providers, and analyzing the pilot study results obtained in this project.

6.1 EWQMS Implementation Steps and Best Practices

6.1.1 Implementation Steps

Regardless of the optimization scenario, the hardware and software needed for EWQMS implementation is shown in Figure 7.1. As the first step, the utilities willing to implement EWQMS should check whether their current capabilities meet these requirements. EMWD, EPWU and NWL conducted this analysis prior to implementing EWQMS (Ghaderi, 2013; Perez, 2013; Dellow, 2013a).

Typically, an EWQMS project life cycle can be grouped into five major stages: (i) pre-design/feasibility, (ii) design/development, (iii) implementation, (iv) operation and maintenance, and (v) performance evaluation (measurement and verification). During the pre-design and feasibility stage utilities address opportunities to reduce their expenditures and develop a business case for the EWQMS. The major tasks associated with each stage are presented in Figure 7.2.

Figure 7.1: Initial requirements to enable installation/implementation of EWQMS

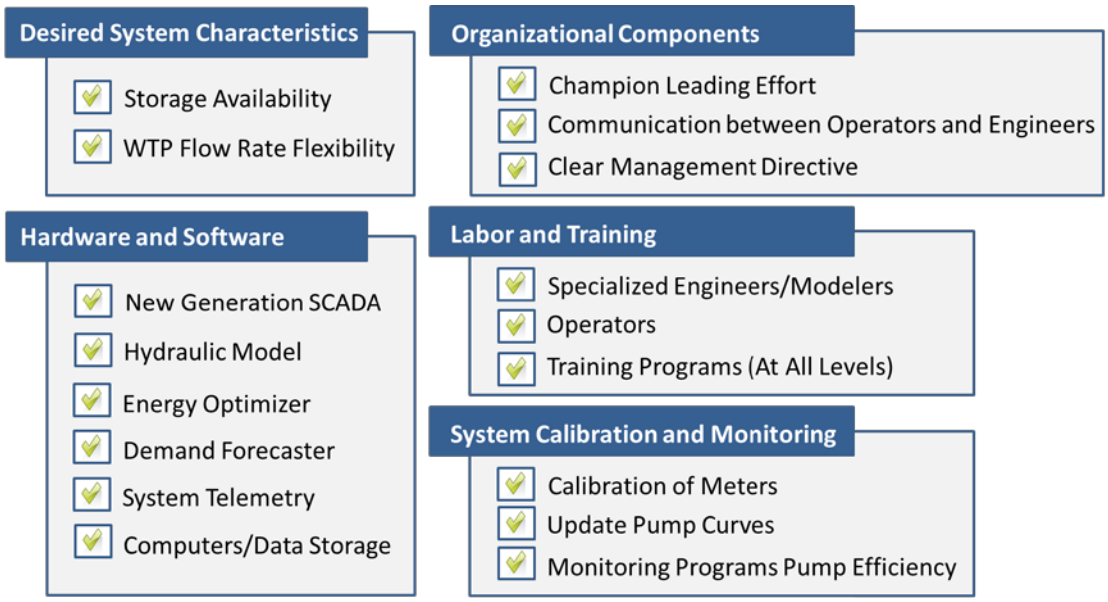


Figure 7.2: Breakdown of tasks and activities during a phased EWQMS implementation

Pre-Design/Feasibility

- Define the project development plan
- Select and understand the operational requirement of the control areas
- Identify the functional requirements and specifications (e.g., IT and network)
- Perform the analysis of constraints
- Identify the current and future operational challenges
- Identify financial and non-financial benefits
- Provide recommendation for next phases

Design/Development

- Finalize selection of water transmission network and examine electricity supply options
- Examine SCADA control system
- Hydraulic modeling and calibration
- Review of process control
- Refine the constraints and the cost-benefit analysis
- Create new operational strategies
- Develop EWQMS prototype and specifications for implementation
- Develop the implementation plan

Implementation

- System design, customization and configuration of optimization software
- Software design and coding of software interfaces and offline simulations
- Audits, witnessed factory acceptance and site acceptance
- On-site installation
- Manuals and “on the job” labor training
- Fine-tuning and initial operational handover sessions
- Develop KPIs for operators

Operation and Maintenance

- Annual operation and maintenance
- Software product updates
- Hydraulic model maintenance
- Tariff maintenance
- Demand forecasting updates
- Telephone and on-line support

Performance Evaluation

- Cost savings assessment
- Evaluation of actual benefits (kWh savings, GHG reduction, water quality impacts)

The feasibility study is an important stage for EWQMS project development. Data used in a feasibility study are gathered from various technical and managerial staff at different organizational levels from planning, operations and engineering. During this phase, distribution networks for potential EWQMS control are identified and existing operating issues and energy cost savings strategies are evaluated. The potential benefits from the optimization strategies are used as justification for system expenditures. In addition, by performing feasibility studies the utilities evaluate the software, the organizational requirements and the equipment needed before final design and implementation.

During the design phase, the EWQMS prototype is created and customized based on the functional specifications previously defined. During the implementation phase, the system is installed and made operational and continually refined according to operating environment changes. In order to assure maximum benefit and operational reliability, the following issues must be carefully reviewed at the onset of the project during the design stage:

- Consequences of failure (e.g., power, communications, data entry, process control, etc.);
- Consequence of low level as well as overflow conditions in clear wells, tanks, reservoirs, and elevated tanks;
- Full or partial loss of treatment plant;
- Infrastructure damage such as main burst or pump failure;
- Chemical and other safety hazards;
- Existing alarms and recommendations for additional alarms;
- Pump station energy use limits and metering;
- Raw water use limits and agreements;
- Maximum desired starts per hour per pump;
- Treated water storage tank operational levels, emergency levels and flexibility;
- Water age concerns;
- Maximum and minimum pressure limits;
- Treatment plant flows, ramp rates, start-up times, etc.;
- Data transfer between EWQMS provider and SCADA systems;
- Design for the operator interfaces, regionalization of displays, and hierarchy of access and authentication requirements;
- Communication failure procedures and requirements;
- Emergency control procedures and requirement;
- RTU program modifications;

- Specification of instrumentation changes and calibration; and
- Details of testing/verification procedure.

The implementation of EWQMS may take from six months to 2-5 years from pre-design to full operation. The activities performed under each phase and their durations were found to vary from one utility to the other. Figure 7.4 reports the breakdown of tasks associated with each phase of execution at EMWD (Ghaderi, 2013). Figure 7.3 shows a typical phased implementation of EWQMS at NWL and EPWU. NWL represents five separately installed systems covering 100 percent of their assets, although the fifth and smallest system for Suffolk is awaiting final SCADA upgrades.

Figure 7.3: Timeline of a phased implementation of EWQMS at NWL (top) and EPWU (bottom)

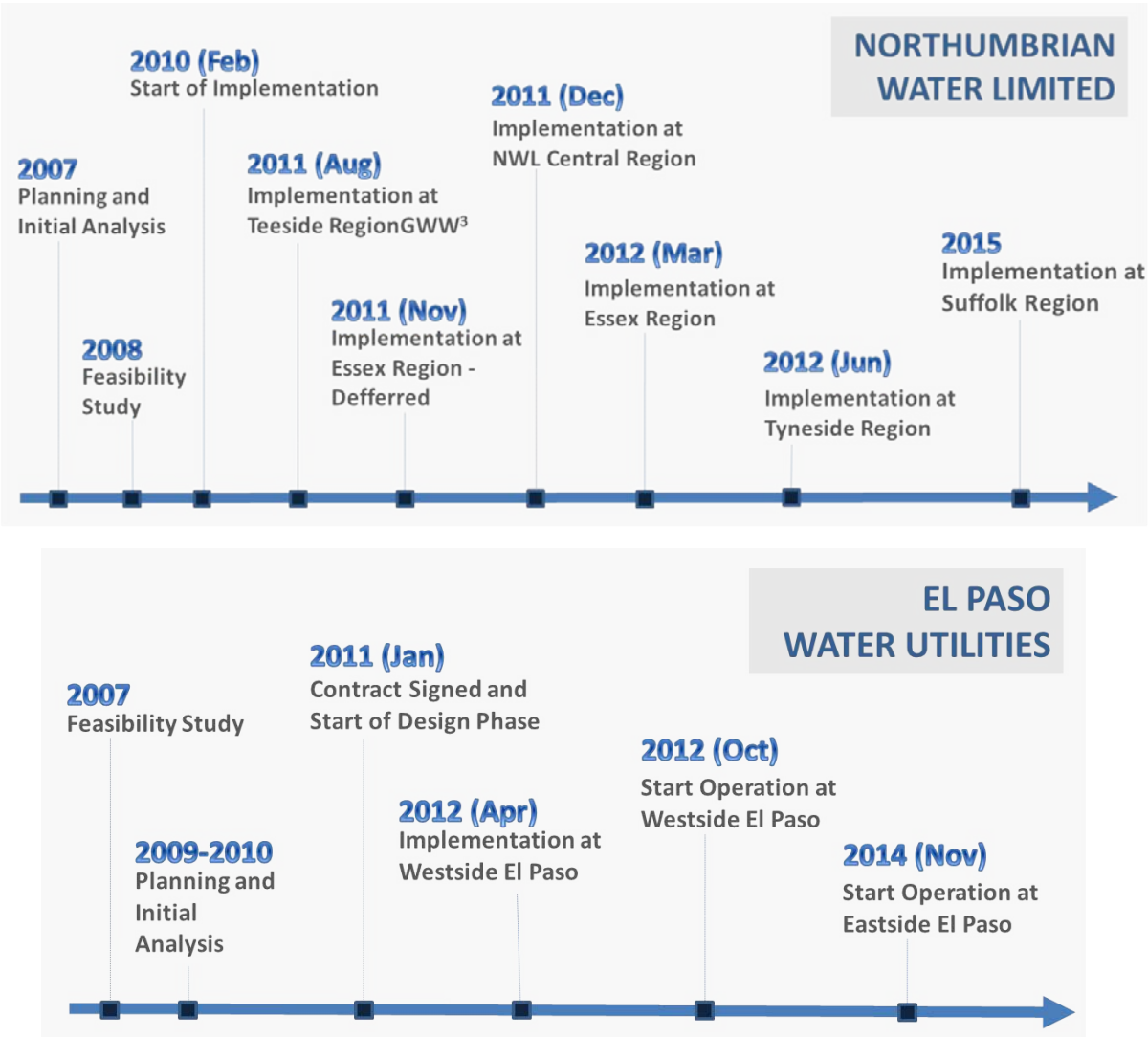
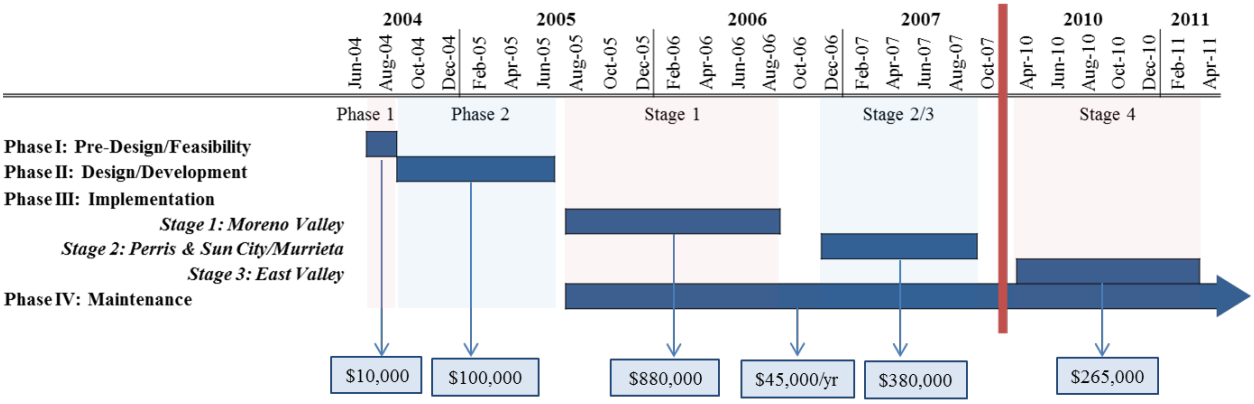


Figure 7.4: EWQMS life cycle, estimated time duration and associated costs for each phase of project implementation at EMWD



6.1.2 Implementation Challenges and Recommended Best Practices

Water utilities face a number of challenges during the implementation and subsequent operations of an EWQMS. When moving towards innovation and technology, such as for the implementation of EWQMS, water utilities face an important cultural change at all levels of the organization. Managers, engineers and operators rely on different cognitive models for adapting to the new technology, which often give rise to conflicting perspectives (Von Meier, 1999). Resistance from the operations team towards installation of full system control automation is often encountered. Although some operators are engaged with the program, others preserve their conservative and empirical mode of operating the system (Chan, 2013). Their acceptance of the new technology is important since they are held responsible for safe operation without outages. It is important that management and engineers consider the alternative perspectives of these different occupational groups when planning on installing EWQMS. The expectation of optimization needs to be realistic and clearly defined before implementing an EWQMS and consensus needs to be reached at all levels of the utility organization. There is a mistaken general belief that no human inputs or operations are required when an EWQMS is installed. The EWQMS still relies on the operator's input, especially for planned or unplanned maintenance events, and on identification of problems, so that the EWQMS can continue to find a feasible solution.

In the sections below, the recommended good practices for critical activities of different stages of EWQMS implementation are presented.

6.1.2.1 Pre-Design and Feasibility Stage: Lessons Learned and Recommended Good Practices

Two important activities during the pre-design and feasibility stage are: i) the identification of the functional requirements and specifications, particularly those related to IT and networking, and ii) the identification of constraints. In this section, the issues, challenges, lessons learned from installed EWQMS, and the recommended good practices associated with these activities are presented.

IT and Networking. Often the SCADA and control system are in a network environment outside of the direct remit and control of the company information technology (IT) department. This can lead to issues of security of access, connectivity limits between the corporate Local Area Networks (LANs) and the automation LAN, Internet access and remote access to servers for support and maintenance. Security concerns may arise when remote users access the servers for updates and patches (e.g., access to remote data, like electricity tariffs especially in real-time spot markets), especially if the optimization server is on the SCADA network. On the other hand, moving SCADA under IT control might not be advantageous since the IT personnel may lack the 24/7 100 percent availability mentality that operations technicians are more sensitive to.

RECOMMENDED GOOD PRACTICES

IT and Networking

- Investigate the use of demilitarized zone (DMZ) rules in firewalls to permit limited connectivity only where required and with strict authentication (ICS_CERT, 2013).

Follow the Industrial Control Systems Cyber Emergency Response Teams (ICS-CERTs) recommendations on access, security, authentication and validation (ICS_CERT, 2013).

Identification of Constraints. Water utilities have a tendency to increase the complexity of the optimization by building the optimization program with a high number of initial constraints. This may result in algorithms unable to find a solution. When selecting the constraints, physical and technical conflicts may be generated. Physical conflicts are generated when the imposed constraints yield conflicting operational solutions (e.g., at least one pump must run at all times but reservoir overflows are not permitted and this is not achievable when demand is low). Technical conflicts may occur if the same constraint is designed on the basis of operator practice as well as maintenance and engineering design principles. Some constraints applied by the utility are often overly conservatively, such as reservoir operating limits, with conflicting rules and restrictions set by operators without proper empirical testing or technical reviews (e.g., pump start and stop constraints). System operational rules and procedures on constraint definitions are often not documented.

RECOMMENDED GOOD PRACTICES

Identification of Constraints

- Provide operators with a simulation tool to allow them to evaluate the capability of the system using historical data, build confidence in the system, and identify constraints, rules, and practices they currently deal with under normal and critical conditions.
- Initially set the system with the lowest number of constraints possible. The number of constraints can then gradually be increased once operation with the EWQMS is better understood. It is recommended that operators must evaluate the positive and negative impact of all possible constraints with the EWQMS system developers.
- Identify any conflicts in order to rank and prioritize the constraints based on their level of importance.
- ~~Increase communication between engineers and operators and find agree~~ment on constraints and operational schedules.
- Increase communication with equipment manufacturers and follow guidance; technically review traditional mode of operations by using SCADA historical data.
- Standardize documentation of system operation rules and change control procedures to formalize operations. Train operators to operate under standardized rules.

6.1.2.2 Design, Development and Implementation Stage: Lessons Learned and Recommended Good Practices

Some of the important activities during the design, development and implementation stages are: i) the selection of distribution networks, ii) the software selection and customization, iii) calibration of the models and infrastructure, and iv) prediction of water quality and system operation through offline simulations. In this section, the issues, challenges, lessons learned from installed EWQMS, and the recommended good practices associated with these activities are presented. The utilities that are interested in implementing an EWQMS are recommended to adhere to these practices.

Distribution Network Selection. The important criteria used by water utilities for the distribution network selection are:

- Level of hydraulic isolation and interconnection;

- Presence of adequate telemetry;
- Existence and quality of the hydraulic model;
- Geographical (topographical) features; and
- Potential for savings.

Implementation and operation may be difficult if the distribution network selected is not isolated from parts of the network that are not included in the project or if there is no telemetry. Water utilities may decide on a phased implementation of an EWQMS by selecting isolated networks, as previously shown for EMWD, NWL and EPWU (Ghaderi, 2013; Chan, 2013, Perez, 2013; Dellow, 2013a).

At EMWD, the Moreno Valley was first selected since it not only included the greatest number of pumps but also had greatest associated energy cost savings potential (Ghaderi, 2013). At EBMUD, the San Ramon area accounts for about 30 percent of the total energy use even though it only represents 20 percent of the total geographical area of the district (Chan, 2013). Although other regions at EBMUD have a similar level of complexity (approximately 30 pumping plants), they may only yield 20% of the savings achieved in the San Ramon network. Thus, a potential expansion of EWQMS to the full network may not achieve substantial increase in energy cost savings at EBMUD (Chan, 2013).

RECOMMENDED GOOD PRACTICES
Distribution Network Selection

- Identify criteria for distribution network selection. Example of these criteria are:
  - ✓ Level of hydraulic isolation and interconnection;
  - ✓ Presence of adequate telemetry;
  - ✓ Geographical (topographical) features; and
  - ✓ Potential for savings.

Level of customization. A significant degree of customization is typically required to address the distinctive features of each system network and the utility's ultimate goals. The use of customized software prepackaged by commercial vendors may not be suitable to specific networks prior to customization (e.g., generalized operations may not work for networks characterized by cascade systems). Optimization features are tailored according to a number of factors, such as system topography, network topology, demand, customer distribution, existing infrastructure and control systems. The commercial EWQMS and the in-house software developed at LVVWD, for example, use different temporal windows for optimization. EWQMS forecasts daily water demands on a zone by zone basis for the next 24 to 48 hours and generates optimized solutions every 30 minutes (i.e., 48 solutions in a day) after evaluating all equipment

availability and water source constraints (Derceto and EPWU, 2008). The LVVWD formulates one operating plan per day, intended to run without deviation for 24-hours. This is made possible due to use of a detailed and calibrated hydraulic model to formulate the plan. Any deviations from anticipated demands or outages generally result in minimal impact on tank levels and water ages due to large storage capacities throughout the system, and are rectified the next day (Jacobsen, 2013a). According to EPWU, this approach is not applicable where a line break can interfere with the best laid-out plan or a power outage in a very short time (e.g., 1-2 hours) (Perez, 2013).

RECOMMENDED GOOD PRACTICES

Level of Customization

- Use Pre-Design to define customization criteria for each system and then apply this criteria to specification for software development or application to a commercial product;
- Customize the software and adapt it, even if pre-packaged by commercial vendors, and fine-tune it in order to be successfully implemented.

Software Solutions and Interface with the Operators. Operators can access the software functionalities for everyday decision making using the EWQMS operator's interface. The software should allow easy viewing of results for the operators. The interface has to be interactive and the number of inputs that have to be inserted manually has to be minimized. Through the interface, operators or modelers can actively interact with the software (pump starts and stops throughout the day) and decide on manual overrides, tagging pumps in and out of service, modifying pre-set inputs such as season demand profiles, setting reservoir target levels, changing production limits, etc.

Aquadapt's operator screen page displays the recommended pump operations for the next 24 hours based on predicted water demand, reservoir levels and flows, and the schedule is continuously updated every 30 minutes (Derceto, 2013). Based on the water usage profile, storage availability and the tariff structure, the software selects the timeframe a specific pump in a given pump station has to run (Ghaderi, 2013). An intranet-based dashboard reports key performances indicators in real-time (e.g., energy used per MG of water delivered, pump starts per day, volumes per pump station and WTP, etc.). One distinguishing aspect of the LVVWD approach is the use of a calibrated hydraulic model to develop the daily operating plan. A user interface allows for easy changes to operating commands within the hydraulic model, and a view of the impacts of those changes on the water system. Additional software applications allow the user to evaluate energy costs, water age, and power use by those stations for which power must be used in pre-ordered quantities. Various model scenarios may be generated and

the best may be chosen to be implemented in the real system by the EWQMS. Predicted versus actual system performance for the day may be viewed at any time, allowing for quick discovery of any discrepancy, such as may arise from a valve being in the wrong position, or a faulty flow or level sensor (Jacobsen, 2013a).

RECOMMENDED GOOD PRACTICES

Software Solutions and Interface with the Operators

- Determine a limit on time the operator has per shift to set up the system and build an interface that will allow completion of this task for normal and difficult situations.
- Perform testing with the operators to determine how long it takes to set up the system.
- Modify the interface based on experience with the operators until the time limit is achieved.
- Design a software to be interactive and straightforward for the operators to utilize, which clearly visualizes the operations and schedules.
- Match the operator knowledge and naming conventions in the software to make operators more comfortable in interfacing with the software.
- Continuously monitor the software to confirm conformance to operational rules and occasional operator intervention is required.

Selection of pump priority. Typically, water utilities operate using different strategies to select which pumps to operate within a pumping station and for how long. EBMUD, for example, uses a rotation strategy that evenly rotates the pumps within a pumping station based on the total run time. The selection is typically performed without consideration of cost, kWh or GHG savings opportunities. Thus, a pump prioritization test should be determined to identify the more beneficial strategy for the given pumping station for the utility targeted goals.

RECOMMENDED GOOD PRACTICES

Selection of Pump Priority

- Perform additional testing to evaluate the impact of pump prioritization on the cost and energy savings and to identify best practices for pump selection at the utility.
- Typical pump prioritization test approach includes:
  - ✓ Identify the pump with highest priority (efficiency) within pumping stations.
  - ✓ Run the most efficient pump combination identified in the previous step.

C***alibration of models and infrastructure.*** Mass balance equations may generate inaccurate results if inaccurate flow (or power) data are received from control infrastructure (flow meters, remote terminal units, telemetry and remote controls) with out-of-date calibration. In addition, demand forecasting models calibrated for planning purposes may be insufficient for operational control and optimization purposes.

RECOMMENDED GOOD PRACTICES

Calibration of models and infrastructure

- Calibrate and maintain control infrastructure to ensure the accuracy of generated data.
- Perform intensive pump curve testing programs to check for system calibration and accuracy before starting the EWQMS.
- Have a well calibrated model in order to match what happens in the system without artificial constructs, such as the use of pressure reducing valves (PRVs) in the model to match pressure when no physical PRV exists.

Offline simulations for system operation and water quality impact predictions. Offline simulations can be an effective tool of predicting the outcome of real-time operation for different optimization scenarios with different goals. Examples of different optimization scenarios to be tested are cost minimization, kWh and GHG emission reduction. Water quality impact of different operational or optimization strategies can also be evaluated by running EWQMS offline. This feature can allow operators to evaluate different operational strategies on the fly without affecting the online system. The simulator also allows engineers and planners to simulate the effect of changes to parameters and facilities, such as the installation of new or upgrade of existing pumps, the imposition of new tariff structures, and variation in storage capacity or water demand profiles.

RECOMMENDED GOOD PRACTICES

Perform offline simulations for system operation and water quality impact predictions

- Identify operational strategies and/or optimization targets to be tested.
- Select an appropriate baseline to be used for comparison and analysis.
- Perform a series of offline simulation and appropriately analyse the results.

6.1.2.3 Operation and Maintenance: Lessons Learned and Recommended Good Practices

Water utilities often encounter a number of issues during the operation of an EWQMS that needs special attention. The challenges and the recommended good practices related to some of these issues are presented below.

Operator interaction and training. Manager and operator training is a key action to achieve project success. Engagement of staff from the initial planning phase and throughout the implementation stage is needed to train the staff and increase their trust in the new technology (Chan, 2013; Perez, 2013). Utilities need to identify and adopt organizational development policies including training, staff knowledge/skills improvement, best shift schedules, compensation, operator performance measures (KPIs), and role definition and responsibility that address and encourage effective use of EWQMS. This should include clarifying decision making between competing factors of system reliability, operating costs, energy use, greenhouse gas emissions, and water quality goals. It is also important to understand that operators need to learn how to use the software system capabilities as well as how to best use it for all the operating conditions. Cross-training of all involved utility personnel is necessary to ensure that individuals have the necessary skills for EWQMS operations and are prepared to take the responsibilities associated with their specific roles.

Thus, managers and operators training sessions should be offered during the installation phase, and refresher courses provided in the following years. Six-weeks of staff trainings were initiated at NWL and EPWU during the feasibility study and the installation phase of their EWQMS (Dellow, 2013a; Perez, 2013). The presence of the software developers on site during implementation and training is also considered valuable and necessary for a deeper understanding of the tool.

RECOMMENDED GOOD PRACTICES

Operator interaction and training

- Start-up an entire network area in one piece to avoid conflicts between optimized and manually controlled areas.
- Organize meetings among the IT, operation, and management departments to discuss integration issues.
- Involve the operators at all stages of the project to better understand issues and provide useful inputs.
- Perform follow-on training programs after the initial planning phase to engage operators and increase their trust in the new technology.
- Training must be performed by experienced operators.
- Allow the software developers to be present on site during implementation and training. Formalize the training program with program times staggered to suit the shift patterns of all operators.
- Ensure timely communications with the software provider, particularly when on-site during the first stages of implementation.

RECOMMENDED GOOD PRACTICES

Recommended Training for Staff and Operators

- Multiple operator training sessions, using the simulator, should be offered during the installation phase to ensure that all operators on all shifts are trained. This should be carried out in a rigorous manner with training manuals, documentation and completion certificates provided.
- Training to the IT staff on the software interfaces, including the SCADA interface, remote support, and email and Intranet server should be provided. Diagrams, backups and support documentation are sufficient for a competent IT technician to rebuild the system.
- The following range of training deliverables should be dovetailed with the implementation project, namely:
  - ✓ **HMI (Human Machine Interface) operator training and initial Pre-FAT (Factory Acceptance Testing) operator training**
    - To be conducted once the software database is configured and provisional operator display screens are available for review
    - Initial training will be given to operational personnel who intend to witness the factory acceptance testing
  - ✓ **On-site training/verification during installation**
    - Structured presentations and on the job training sessions during installation
    - One-on-one sessions with training tutorials and verification
    - Training documentation & certificates
    - Training tutorials integrated with above documentation
  - ✓ **Follow-up training**
    - Dedicated 1-week site visit approximately 1-2 months after SAT (Site Acceptance Testing) to address specific training needs and operator experiences gained since handover.

System Overrides. Although a high level of automation can be achieved with both the commercial and the in-house applications, the cost savings may suffer if there is high incidence of manual overrides performed, particularly at the initial stage of implementation. Overrides are often justified by the operators based on safety, reliability and legal liability concerns that arise before they have established sufficient confidence in the software's solutions. If the

optimization conflicts with the operator's historical mode of operation, there is a natural tendency to override the optimizer for safety reasons. In general, the operator works within soft boundaries, while the software utilizes harder constraints. Traditionally, operators anticipated operational needs over shorter time windows (e.g., 6 hours, while the *Aquadapt* tool optimizes over the following 24 to 48 hours). The solution that the software anticipates in the short-term (e.g., 6 hours) is not likely to be 100% accurate since numerous events can dynamically evolve and change the system such as pumps failing to start or unpredictable short term water demand in industrial zones (Derceto, 2013). Because of these inherent uncertainties and the operator's natural risk adversity, the operator may reduce their trust in the program over time and with an increasing tendency to override the system (Chan, 2013). Typically, a system built on numerous and unrealistic constraints has a higher likelihood of being overridden by operators. Thus, an operational protocol should be in place that will clarify the roles and responsibilities for the 24-48 hour operation vs. the 6-12 hour operation (operator shift) in relation to EWQMS operation.

The software has a margin of safety that is much lower than what operators traditionally utilize (Ghaderi, 2013). So the number of constraints is a major factor that influences an operator's decision to override. For example, automated EWQMS systems are likely to use the full operational limits of storage, to the agreed minimum and maximum levels (e.g., >70 percent full tank). However an operator may have never lowered a tank's level below 90 percent full, thus feeling uncomfortable in seeing the tank heading towards 70 percent and thereby tending to override the system. A clear distinction between the operational constraints and operators' preference should be also discussed during the training.

Typical reasons for manual interventions are:

- Anticipated failure to meet consumer demand;
- Changes in source water quality;
- Unpredicted variations in weather or water demand;
- Emergency situations and unplanned maintenance;
- Optimization that does not converge to a solution (this is typical of a system built on a large number of constraints or during the initial learning phase).

EMWD attempts to not exceed 10% of *Aquadapt* recommendations for overrides (Ghaderi, 2013) while at LVVWD overrides rarely occur (Jacobsen, 2013a). For other utilities the percentage of overrides is specific to the operator shift and the frequency of external system events. No formal change control procedures are in place for deciding how to handle discrepancies between EWQMS proposed operations and actual operations (e.g., changes that occur as an override to the EWQMS schedule, which are not integrated back into the forthcoming optimization, result in divergences between the projected and actual optimization). LVVWD typically observed a 97 percent match between actual and predicted pump run times, whereas the pumping plan calls out pumps to run on the hour (Jacobsen, 2013a). The LVVWD EWQMS programming automatically translates the hourly pumping schedule to ramp the pumps on and off

incrementally. A match below 95 percent indicates that some sort of intervention to the system took place (mechanical issues, main breaks, etc.).

When running under an optimization it typically takes a few days for the system to obtain the best storage levels for the beginning of each day, so any disruption that an override generates, even for a few hours, can result in re-initialization of the distribution network requiring more energy (and cost) than those initially predicted. This type of practice can contribute to loss of confidence from managers and operators.

RECOMMENDED GOOD PRACTICES

System Overrides

- Limit the causes of overrides by reducing the number of constraints, improving field resolution and maintenance, and initiating training programs for operators.
- Limit overrides to true emergencies.
- Determine why the interventions are required and consider reconfiguring the solution to achieve the same outcome automatically when overrides are justified.
- Develop a method to estimate the cost of each override, review overrides that exceed a predetermined cost and perform a "lessons learned" to identify root causes and recommended improvements in software, training, constraints/rules.
- Define emergencies and include application of these in the training program.
- Set a goal for override impacts and measure these impacts to demonstrate if improvements are achieved over time.

SCADA Data and Operator Input. The solution accuracy may suffer if the inputs manually inserted by the operators or SCADA data are incorrect. Typical incorrect inputs include: incorrect electricity tariffs for a given pump station; supplied pump curves that don't match an existing pump; closed or open valves in the system that are opposite of the design and hydraulic model; instruments not calibrated or datum set incorrectly for pressure readings; and instrument range changed after implementation. For example, a pump flow may be shown as below 5 gph when the pump is off (but no zero), or under-reading the true flow when the pump is running (e.g., 1,000 gallons per hour instead of 2,000 gallons per hour). Although to the operator the discrepancy in these numbers is irrelevant, as the flow is just an indicator, it is a major issue to any form of automation or optimization.

RECOMMENDED GOOD PRACTICES
SCADA data and operator input

- Operators should be instructed to minimize the number of inputs that have to be inserted manually.
- Implement a change management system to track instrument calibration and range change processes. Periodically assess the accuracy of external data sources such as tariff information.

Pump start/stop. Operators have a tendency to override when the optimization solution generates a pumping schedule with frequent pump start/stop cycles due to concerns over pump "cool down" and premature breakdown of the windings insulation, even when these schedules are compliant with pump manufacturer operating goals. In some instances, such in some older submersible pumps, even if the motor operating frequency for a pump may be within the factory recommendations the pump bearings show accelerated wear at each start, thus requiring earlier major maintenance.

RECOMMENDED GOOD PRACTICES
Pump start/stop

- Ensure adequate communication with pump manufacturers and system operators on acceptable start/stop frequency of motors/starters and take this into consideration when looking at pump efficiency. These discussions should be included as part of the constraints analysis and agreed to by the operators.
- Include pump manufacturer's data on stop/start frequency in the system to allow operator verification of criteria for each unit during operation. The manufacturer data on start/stop frequency should be compared with the utility's practice to gain operators' confidence.

Field data issues. Often field issues are not recognized or they are deferred by operators causing the software to work on the basis of incorrect inputs, such as would occur if a pressure instrument had a continual offset error. For example, a pump station with three pumps may experience a pump failure. If the operator decides to continue running the system with only two pumps, it is possible that the pumping is scheduled and occurs during the most expensive tariff periods.

RECOMMENDED GOOD PRACTICES

Field data issues

- Prioritize attention to field issues and make sure that their resolution is a priority for operators.
- Instill a culture of focusing on getting the input data right as this has the greatest effect on reliability and success.
- Coordinate efforts between production and distribution, including automated control of the high lift pumps at the plant and the treatment production rates in order to achieve system optimization.

Water Quality. Current EWQMS programs incorporate solutions to minimize water age by improving water turnover in storage and minimizing the transfer of aged water between storage tanks in the same or adjacent pressure zones. Water quality issues are generally addressed by using a pragmatic approach such as imposing hydraulic operating rules (e.g., reservoir operating levels, deep cycling, etc.) to influence water age within the distribution system and in tanks and monitor compliance with regulatory standards. The main obstacle to including water quality predictions in the on-line optimization algorithm is related to the instrumentation and real-time data availability of water quality parameters. Additionally, many days of continuous modeling is needed to trace water for five to ten days in order to have accurate and reliable model results. Off-line water quality modeling remains an appropriate check on performance, combined with field measurements.

RECOMMENDED GOOD PRACTICES
Water Quality

- Verify that proper tank turnover is targeted by the EWQMS to ensure minimal water age. Determine correlation between minimal water age and disinfection by-product concerns to validate tank turnover operations relative to water quality objectives.
- Smooth flows from treatment plants to improve consistency of chemical dosing and further improve water quality.
- Undertake physical and/or chemical water quality modeling of their networks in calibrated all mains models as part of design and development studies.
- Maintain and test the calibrated models against the EWQMS optimizer controls at regular intervals. The models will help interpret actual network water quality sampling results and assist evolution of hydraulic rules to maintain water quality under optimizer operation.

6.1.2.4 Evaluation Phase: Lessons Learned and Recommended Good Practices

System performance is evaluated using different metrics and different frequencies from one utility to another. The EWQMS provides a solution every 30 minutes so a total of 48 solutions per day occur, within a 24-hr period. NWL monitors the success of the software by looking at the number of successful solutions per day. A satisfying number for NWL was determined to be in the range of 43-48 (Dellow, 2013a). Whenever the EWQMS doesn't find a successful solution, the software continues from the previous solution. NWL and EPWU evaluate their cost history once to twice per year and the $/MG is the parameter used for comparison (Dellow, 2013a; Perez, 2013). When EPWU attempted a monthly account, the numbers were distorted by items such as estimated meter reads by the power company rather than true meter values, thus the best metric to account for savings seems to be the yearly value (Perez, 2013). On the other hand, LVVWD does not generally produce an annual report on performance but provides daily calibration reports that track kWh/MG and monthly water quality results (e.g., THMs), etc. (Jacobsen, 2013b). The establishment of a baseline usually covers a one to two year period of normal system operations and it is not straightforward in a dynamic system experiencing evolving changes (e.g., energy tariff changes, infrastructure changes, etc.).

Yet, it is not a common practice for utilities that have implemented EWQMS to perform external QA audits in order to gauge system performance. Typically, as in the case of EMWD, it is the optimization software provider that performs internal operational audits. Recently, the EWQMS performance was evaluated at EMWD by an external consultant, with a major focus on the economics rather than on QA performance of the system (Ghaderi, 2013).

RECOMMENDED GOOD PRACTICES

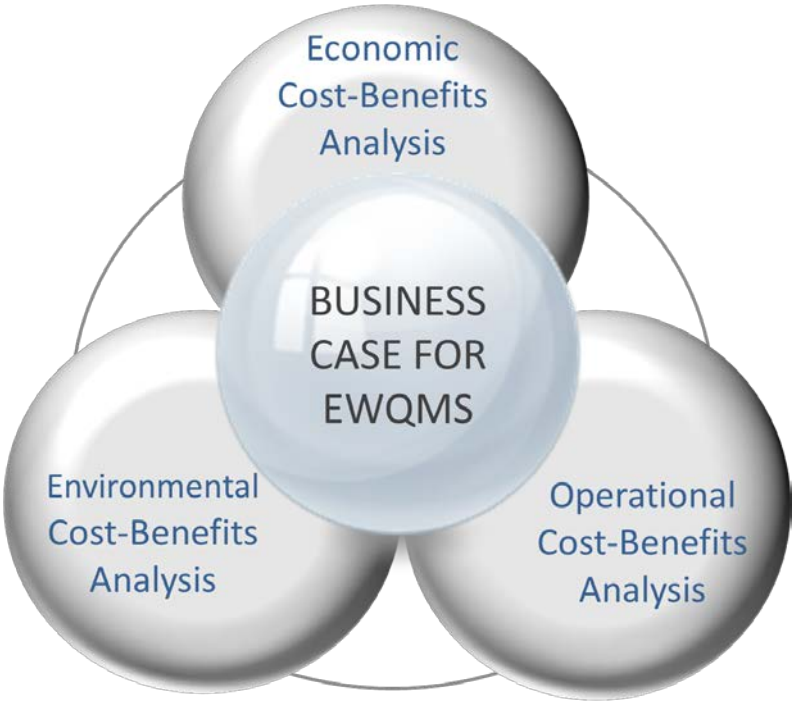
Evaluation metrics and QA audits

- Analyze optimization results and properly interpreted them in a standardized manner in order to learn how to solve specific problems and make necessary system improvements.
- Consider use of standardized measurements and verifications such as specific in the Internal Performance Measurement and Verification Protocol (IPMVP).
- Regularly audit optimization results using independent assessors.
- Present the results with standardized metrics such as kWh or lbs-$CO_{2\text{-eq}}$ per MG per feet water lifted.

6.2 A Business Case Evaluation of EWQMS

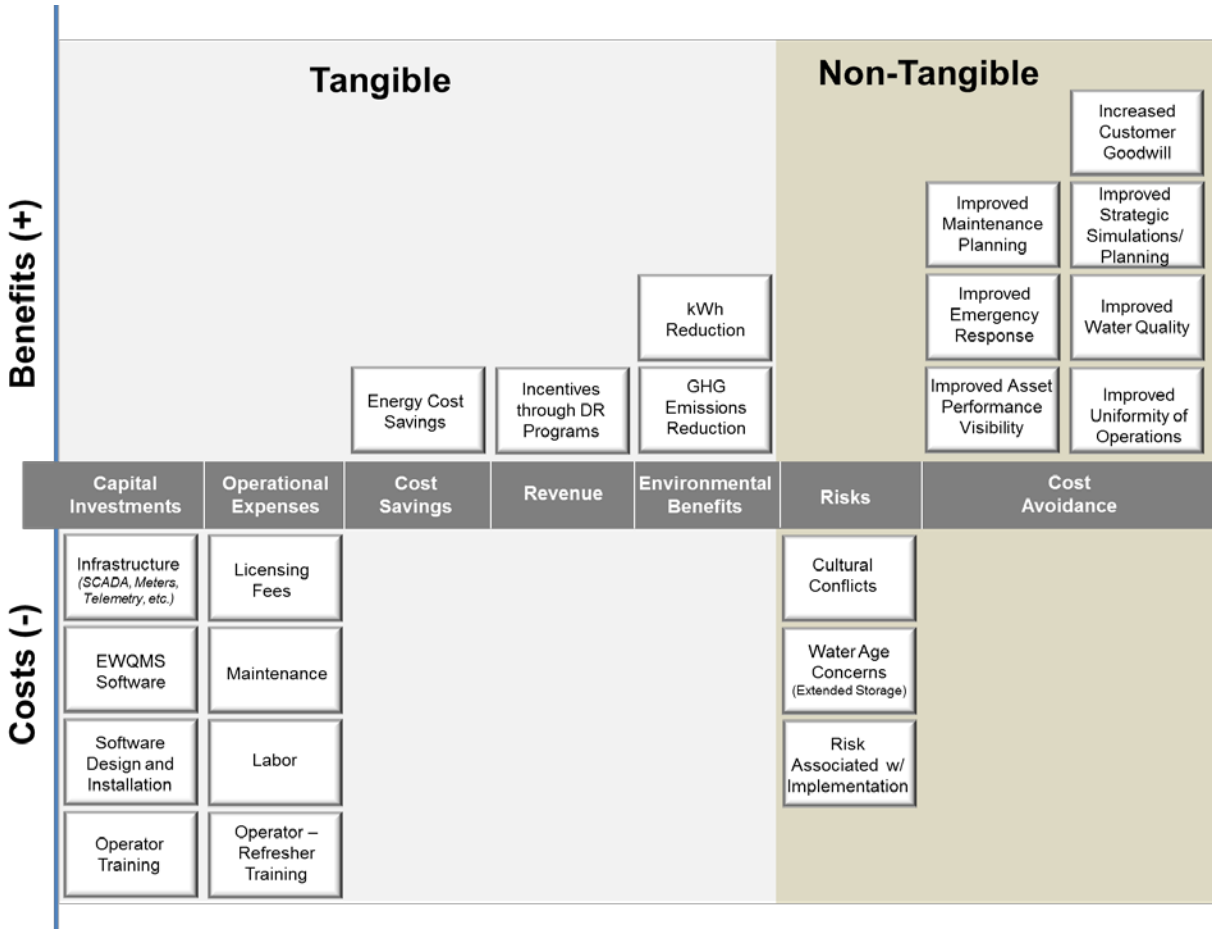
Implementation of energy management projects should be aligned with the overall business and operational management goals and practices at a water utility. Thus, the benefits of implementing EWQMS should be evaluated comprehensively and compared with the priority objectives set by the utility management. A business case for EWQMS should include economic, environmental and operational cost-benefit analysis as conceptualized in Figure 6.5. This section describes some of the key elements of such a cost-benefit analysis:

Figure 7.5: Conceptual elements of a business case evaluation



In most energy projects, the business case assessment is usually a financial benefit assessment based on a Return on Investment (ROI) capital budgeting model or a simple pay back calculation. The non-monetary dimensions of the project that go beyond the traditional economic evaluation should also be included in the decision process used to support the investment. These non-financial benefits for implementing an EWQMS could include long- and short-term environmental and operational value to the organization, and thus need consideration. It is important to include both tangible and in-tangible benefits when developing a true business case for an EWQMS. A conceptual cost-benefit analysis of implementing an EWQMS is presented in Figure 6.6. The following sub-sections provide details on the business case evaluation of utilities with EWQMS. The information might be considered for decision-making by water utilities seeking to implement EWQMS.

Figure 7.6: Example of conceptual business case of an EWQMS



Note: The relative cost or benefits are not in accordance with any scale

6.2.1 Economic Benefit Analysis for EWQMS

Water utilities with complex networks containing multiple pressure zones, a mixed water resource portfolio and highly variable energy and demand tariffs or peak penalties, should benefit from implementation of an EWQMS. As shown in Figure 7.6 an EWQMS may produce tangible and intangible benefits in the following four categories: cost savings (e.g., savings through energy consumption reduction), cost avoidance (e.g., demand charge avoidance), revenue increase (e.g., electric utility incentive through demand response program), and intangible benefits (e.g., improved uniformity of operations). This section summarizes the cost savings reported by the case study utilities and presents guidance on how an economic analysis should be conducted.

6.2.1.1 Cost Savings

Cost savings following implementation of an EWQMS vary annually and are utility–dependent. The predicted and actual cost savings achieved on selected utilities' energy bills are presented in Table 7.1 (Derceto and EPWU, 2008; Derceto and EMWD, 2010). The savings achieved by the

majority of these utilities are similar to those initially predicted and may vary annually depending on the changes in the tariff structure. The annual energy bills for the optimized distribution networks of the utilities listed in Table 6.1 range from $2.8 Million at EBMUD to $13 Million at LVVWD (Chan, 2013; Jacobsen, 2013a). The electricity cost reductions achieved by these utilities are similar to those reported in previous reports for Washington Suburban Sanitary Commission (11 percent), WaterOne (14 percent), Region of Peel (10 percent) and Gwinnett County Department of Water Resources (8 percent) (Bunn, 2006; Derceto, 2013; EMA, 2013). The high percentage of savings achieved at LVVWD (23 percent) may take into account numerous changes that occurred at LVVWD (power cost, variation in demand, increased urban growth in higher elevations, addition of solar facilities, etc.) (Jacobsen, 2013a). Due to its recent implementation, EPWU has not yet been audited for a determination of the savings achieved and recent drought conditions have focused operations on meeting demand rather than achieving savings (Perez, 2013).

Table 7.1: Operational energy costs and energy costs savings for selected utilities.

Utility	Operational Energy Costs ($/year)	Energy Cost Savings Predicted		Energy Cost Savings Achieved	
		($/year)	(%)	($/year)	(%)
EMWD	$1.7M	$260K – $490K	10-20%	377K[1]	22%[1]
EBMUD	$2.8M[2]	$200K – $460K	12%	360K[3]	12.5%[3]
EPWU	$6.7M	$500K - $800K[4]	7.5%[5]	N/A	N/A
NWL	$8.5M[6] $11M[7]	$520K[6] $1,1M[7]	7-8%[8]	$230K[9] $800K[10]	5%
LVVWD	$13M	N/A	N/A	$3M	23%[11]

[1]Result of on-going audits. Predicted savings were based on 2006 energy costs of $2.5M.
[2]Of the optimized distribution network area at EBMUD.
[3]Savings related to year 2004 through year 2008.
[4]Through load shifting and efficiency gains with *Aquadapt* optimization under TOU rates.
[5]Through efficiency gains with *Aquadapt* optimization and under a proposed (not actual) TOU rates.
[6]Estimated for the Essex Region (approximately 100 MGD, population of 1.5M).
[7]Estimated for the Northeast Region (approximately 180 MGD, population of 2.7M). Data from year 2012.
[8]Estimated in the optimized distribution network area at NWL.
[9]Evaluation performed 3 months after EWQMS installation without complete automation in place. Full evaluation still to be performed.
[10]Current savings achieved.
[11]Includes changes power cost, growth in the Las Vegas Valley area, variation in demand, growth at higher elevations, addition of solar facilities, and addition of aeration systems (not metered separately).

In order to quantify the actual economic benefits of an EWQMS installation, a baseline needs to be developed to allow a comparison of pre– and post–installation conditions. The establishment of a baseline usually covers a one to two year period of "normal" system operations and it is not straightforward in a dynamic system experiencing evolving changes (e.g., energy tariff changes,

infrastructure changes, etc.) (Thorstensen, 2007). The baseline for the dollar savings evaluation is usually defined by converting the energy and demand readings from electricity bills into dollars for a selected period of time, with adjustments for actual water volumes pumped, energy tariff changes and any special or abnormal operating constraints imposed (Derceto, 2013). The financial savings achieved are mainly associated with shifting pumping to lower tariff periods and additional efficiency gains due to pumping system optimization. Cost savings obtained with efficiency gains typically represent approximately 40 percent of the total cost savings at an installation which was confirmed by the cost savings predictions for EPWU (Derceto, 2013).

It is important to recognize that implementation of an EWQMS at a municipal water utility can be very complex and entail extensive resources and capital investment. So far, only large utilities that are able to sustain the financial burdens of an automated platform and are equipped with sophisticated hardware and software have opted for EWQMS control. For EMWD and EPWU, justification for the EWQMS installation was based on the estimated yearly energy cost savings (energy cost reductions and demand charge avoidance) as well as the return on investment (ROI) of the initial capital investment (Ghaderi, 2013; Perez, 2013). Table 6.2 shows the estimated project costs (includes software package cost, design and implementation of EWQMS) and expected return on investment (ROI) for the implementation of the EWQMS at the each of the selected water utilities, with payback periods ranging from 2 years for NWL and up to 5 years for the implementation at EMWD. LVVWD, which opted for an internal effort for the in-house development of the software, did not require new capital and infrastructure investments (Jacobsen, 2013a). The ROI was not the justification factor for EBMUD where the implementation cost was repaid based on actual savings achieved over a four year period against a sliding scale. This was a low-financial risk contract stipulated by EBMUD with the software provider (Chan, 2013).

Different factors can contribute to the capital investment and operating expenditures that a utility sustains for implementing an EWQMS. It is important to note that the highest share of the initial capital investment is reported to be associated with the upgrade of the SCADA and of the network telemetry and remote control (e.g., flow meters and reservoir control levels, etc.). For the utilities listed in Table 6.2, the cost of SCADA was not considered as part of the ROI estimation, since this upgrade occurred prior to the EWQMS installation. The project costs presented in the table includes software license and the labor fee for implementation, configuration and personal training. The costs associated with the SCADA upgrade were not available from the case study utilities since these utilities upgraded the SCADA long before the EWQMS implementation.

Table 6.2 also shows additional expenditures associated with a commercial software installation, such as annual maintenance fees, which are typically within 8 percent to 10 percent of the project cost. As a general trend, one to two full time employees are required for EWQMS supervision and control. It should also be noted that the initial project costs and annual maintenance varied from one utility to another depending on the system complexities, suggesting a utility specific cost-benefit analysis is needed for determining the business case for any particular utility.

Table 7.2: Project cost and estimated payback period, and other fees for EWQMS implementation at the selected water utilities

Utility	Project Cost[1] ($)	Estimated Payback Period (years)	Annual fees[5] ($)
EMWD	$1.87M	5	$70K
EBMUD	$0.75M[2]	N/A[2]	$60K
EPWU	$1.30M	3	$100K
NWL	$3.75M	2-3[3]	$225K
LVVWD	N/A[4]	N/A[4]	-

[1]Includes software license, implementation, configuration and personnel training. Hardware costs (~20K are excluded from this cost evaluation).
[2]The implementation cost was repaid based on actual savings achieved over a four year period against a sliding scale.
[3]Estimated for the Essex Region.
[4]Information not available since EWQMS development at LVVWD was an internal effort.
[5]Includes licensing fees, model maintenance, telephone and on-line support.

6.2.1.2 Recommended Practice for Economic Cost-Benefit Analysis

A convenient way to display the costs and benefits associated with the implementation of EWQMS is to examine the cash flow of the investment and savings using a net present value (NPV) analysis. Such analysis allows the timing of the cash flow to be more apparent and increases the chance of applying time value of money. An example of a NPV economic analysis for an EWQMS project for a hypothetical water utility is presented in Figure 7.7. In this example, Water Utility A, with an annual energy bill of $7 Million, conducted a 10-year NPV cash flow analysis for an EWQMS project based on a feasibility study conducted in 2013. The feasibility study suggested that the potential EWQMS project would provide about a 7.1 percent energy cost reduction using a commercial solution. Based upon that assumption, the net present value of the savings in 10 years was found to be $3.45 Million with a simple pay-back period of investment of 1.1 years. The outcomes of the analysis were dependent on the following key assumptions:

- Cost of construction: The cost of construction associated with debt financing was assumed to be 5 percent.
- Energy price escalation: Usually savings accumulate over time. A standard assumption when estimating energy savings is that electric utility rate increases are matched with inflation. When utility rate increases outpace the rate of inflation, escalation occurs. Although predicting the future is risky business, the trends are estimated by the Department of Energy for the foreseeable future. In this example, a 2 percent energy escalation was used.
- Operation and maintenance cost increase: In this example a 3 percent inflation of operation and maintenance costs was included.

The outcome of the cost-benefit analysis of an EWQMS project depends on the economic assumptions and energy savings estimates that might vary from one utility to another. Thus, it is recommended that the utilities interested in implementing an EWQMS conduct a feasibility study to determine the savings potential prior to conducting the economic analysis.

Figure 7.7 NPV economic analysis for an EWQMS project for a hypothetical water utility

Project Name:	**NPV Analysis for EWQMS Implementation at Water Utility A**		
Currency Units:	$'000		
Inputs & Assumpitons:			
Annual addressable energy spend	$ 7,000.0		Assumed that a Feasibility Study was conducted; Basis: 2013 operations
Annual savings estimate	$ 450.0	6.4%	Assumed that a Feasibility Study was conducted; Basis: 2013 operations
Operating year basis for savings	2013		
EWQMS implementation services & software license fee	$ 1,200.0		
Annual support and maintenance fee (for Y1; prepaid)	$ 50.0		
Annual energy cost increase	2.0%		Estimated; EIA CAGR in avg. industrial retail electricity price (c/kWh) for [state / power utility] 2001-2011
Annual Support and Maintenance price escalation	3.0%		Estimated
Cost of capital	5.0%		Estimated

Costs & Benefits ($'000)

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	10 Year Total
Year of operation		1	2	3	4	5	6	7	8	9	10	
Investment / Cost												
EWQMS implementation services & software license fe	$ 1,200											$ 1,200
EWQMS software annual support & maint. Fee	$ 50	$ 52	$ 53	$ 55	$ 56	$ 58	$ 60	$ 61	$ 63	$ 65	$ 67	$ 640
Total Investment / Cost	$ 1,250	$ 52	$ 53	$ 55	$ 56	$ 58	$ 60	$ 61	$ 63	$ 65	$ 67	$ 1,840
Savings / Benefits												
Energy cost savings	$ 0	$ 478	$ 487	$ 497	$ 507	$ 517	$ 527	$ 538	$ 549	$ 560	$ 571	$ 5,229
Total Savings / Benefits	$ 0	$ 478	$ 487	$ 497	$ 507	$ 517	$ 527	$ 538	$ 549	$ 560	$ 571	$ 5,229
Net Savings / (Investment)	**$ (1,250)**	**$ 426**	**$ 434**	**$ 442**	**$ 450**	**$ 459**	**$ 468**	**$ 476**	**$ 485**	**$ 494**	**$ 504**	**$ 3,389**
Cumulative Net Savings / (Investment)	$ (1,250)	$ (824)	$ (390)	$ 52	$ 503	$ 962	$ 1,429	$ 1,906	$ 2,391	$ 2,885	$ 3,389	

Investment Analysis ($'000)

PV of Savings		$ (1,250)	$ 406	$ 394	$ 382	$ 371	$ 360	$ 349	$ 338	$ 328	$ 319	$ 309
NPV		$ (1,250)	$ (844)	$ (451)	$ (69)	$ 302	$ 662	$ 1,011	$ 1,349	$ 1,677	$ 1,996	$ 2,305
IRR (cumulative)		NA	-66%	-22%	2%	15%	22%	27%	30%	32%	33%	34%
Payback (Years)			-	-	2.88	-	-	-	-	-	-	-
NPV over 10 years	10	$ 2,305	@	5.0% COC								
IRR in year 10	10	33.7%										
Simple payback (years)		3										

Note: The intent of presenting this example was not to show a real world example of an EWQMS implementation; instead to show how a NPV economic analysis can be used for examine the costs-benefits of a potential application of EWQMS.

6.2.2 Environmental Benefit Analysis for EWQMS

6.2.2.1 Potential Avoidance of GHG Emissions

EWQMS operations have a high potential for energy savings and consequently GHG emission reductions mainly through operating pumps more efficiently. Table 7.3 shows the energy consumption and corresponding energy savings observed in selected utilities. The energy savings are about 10-13% for the utilities surveyed that utilize commercial optimization software. The energy use reduction achieved by these utilities is in the order of those reported in previous studies for Washington Suburban Sanitary Commission (8 percent), WaterOne (6 percent), Region of Peel (6 percent) and Gwinnett County Department of Water Resources (6 percent) (Bunn, 2006; Derceto, 2013; EMA, 2013). A similar magnitude of energy savings was also observed by LVVWD utilizing an in-house developed optimization software. The energy consumption per MG of water delivered from 2004 to 2012 at LVVWD decreased from 1,464 to 1,377 kWh/MG, which correspond to an estimated energy savings in the range of 6 percent.

Since the GHG emission reporting is still a voluntary practice for U.S. utilities, GHG accounting is not routinely assessed. Besides, as pointed out by EBMUD, it is difficult to determine how much reduction in GHGs was achieved without knowing the actual metered energy consumption reduction (Chan, 2013). None of the utilities interviewed was fully equipped with power meters for real-time efficiency readings. Thus, GHG emissions reduction due to EWQMS implementation was not readily available. A couple of utilities estimated an annual CO_2 savings using predicted energy savings.

Table 7.3 reports the GHG emissions reductions predicted by EMWD, EBMUD and EPWU by the EWQMS operations.

Table 7.3: Operational energy expenditures and energy savings with correspondent reduction of GHGs for selected utilities.

Utility	Energy Consumption (MWh/year[1])	Energy Savings (MWh/year[1])	Energy Savings (%)	GHG Reduction Predicted (tons CO_2/year)
EMWD	5,700[2]	600	11%	300
EBMUD	26,127[3]	3300	13%[4]	800
EPWU	66,980[5]	4,019[5]	6%[5]	2,200
NWL	67,605[6]; 87,509[7]	In progress	In progress	N/A
LVVWD	1377 kWh/MG[8]	87 kWh/MG[9]	6%	N/A

[1]If not otherwise stated.
[2]Actual energy saving (audit performed in 2005-2006).
[3]Of the optimized distribution network area at EBMUD.
[4]Related to years 2004 through 2008.
[5]Predicted based on the energy bill from year 2006.
[6]Estimated for the Essex Region (approximately 100 MGD, population of 0.65M).
[7]Estimated for the Northeast Region (approximately 180 MGD, population of 1.17M). Data from year 2012.
[8]As for year 2012.
[9]Calculated from year 2004 to year 2012.

6.2.2.2 Recommended Practice

The pilot studies conducted in this research project demonstrated that the optimization function for an EWQMS operation can be either based on cost reduction or on energy consumption reduction (i.e., GHG emission reduction). However, the findings revealed that there may be a trade-off between cost optimization (dollars) and energy use (kWh), particularly where the differential tariff is high. In other words, it may cost more (dollars) to reduce energy use (kWh) and hence GHG emissions to a minimum. The cost of pumping water expressed in $/MG and the energy consumption of pumping water expressed in kWh/MG at EBMUD and EMWD is presented in Table 7.4.

According to the EBMUD pilot results, by implementing cost optimization, the pumping energy consumption could be decreased from 590 to 561 kWh/MG with corresponding cost reduction from $110 to $84 per MG. By implementing energy optimization, an additional 3 kWh/MG reduction was achieved (from 561 to 558 kWh/MG) but with an additional cost of $2/MG. This example suggests that there was a clear trade-off between energy reduction and costs. On the other hand, the EMWD pilot results suggest that simultaneous reduction of pumping energy consumption (from 609 to 591 kWh/MG) and cost reduction (from $77 to $71 per MG) was possible by implementing cost optimization. By implementing purely energy optimization, no additional energy reductions were achieved over cost optimization but resulted in a cost increase of $11/MG.

Table 7.4 Trade-off between cost optimization and energy consumption optimization

Optimization Scenarios	EBMUD Pilot		EMWD Pilot	
	$/MG	kWh/MG	$/MG	kWh/MG
Baseline	110	590	77	609
Cost Optimization	84	561	71	591
kWh Optimization	86	558	82	591

A least energy / GHG solution requires continuous EWQMS operation of the treatment plant and pumping equipment. Avoiding peak tariffs inevitably compresses pumping hours, requiring greater pump capacity and flow when operating, which leads to greater velocity based head loss in transmission. Assuming the installed pump duty is properly matched to the system (and it may not be) then stable, continuous pumping at the lowest average flowrate required to meet demand will most likely require less energy than the controlled switching in flow rates requiring pump changes. The costs incurred per pound of CO_2 emission reduction for the pilot sites are presented in Table 7.5. The data indicates that the lowest cost for a pound of CO_2 reduction might be achieved through kWh optimization at EBMUD and through cost optimization at EMWD.

Table 7.5 Cost of per pound of CO_2 reduction observed in the pilot operation

Relative optimization scenarios	EBMUD ($/lbs-$CO_2$ reduction)	EMWD ($/lbs-$CO_2$ reduction)
Change from Baseline to Cost Optimization	$2.2	$0.5
Change from Baseline to kWh Optimization	$1.9	-$0.4
Change from Cost to kWh Optimization	-$2.1	-$66.3

Note: "-"sign indicates that GHG reduction occurred with an increase in cost.

Thus, it is important to recognize that the optimization strategy that supports the GHG emissions reduction in a cost effective manner is utility-specific and should be evaluated season-by-season through pilot scale studies or offline simulations. It should also be noted that both EBMUD and EMWD installed their EWQMS primarily for cost optimization. If they decide to change optimization from cost to kWh for the lowest GHG emissions operation, additional cost will be incurred for an increase in GHG emissions reduction. Thus, it is strongly recommended that the utilities conduct appropriate analysis to understand the trade-offs, if any, between GHG reduction and cost reduction in determining the business case for EWQMS. Also note that pumps were not operated during the peak 6-hour tariff period each week day to avoid peak period charges. Without this lockout, the cost differential arising from pursuing just GHG reductions over cost reduction would have been significant.

6.2.3 Intangible Operational Benefit Analysis

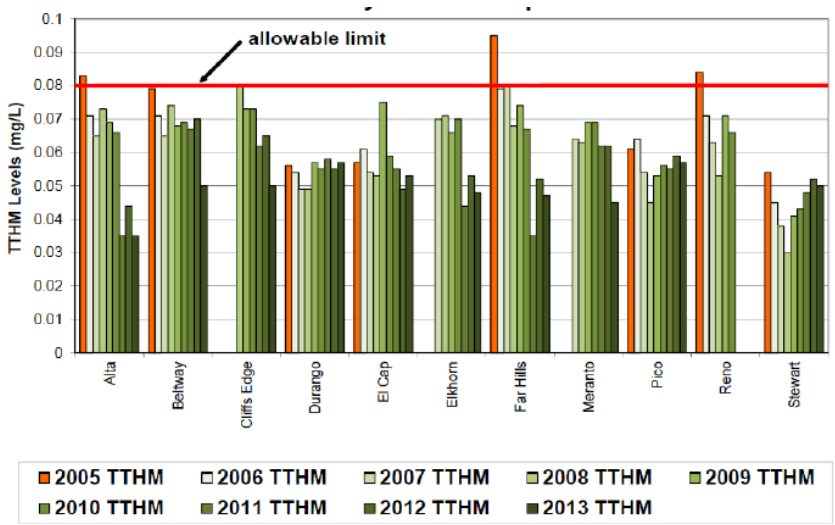
6.2.3.1 Operational Benefits

In addition to the economic and environmental benefits presented above, utilities that opt for EWQMS implementation might take advantage of other operational benefits as indicated below:

Improvement of water quality. Selected utilities experienced improvement in water quality, using water age as a surrogate, due to the ability of the EWQMS to manage water turnover and reduce the retention time (water age) in tanks. This typically translates to a reduction in the formation of total trihalomethanes (TTHMs) within the distribution system due to the lower contact time of trihalomethane precursor materials in the water and the applied chlorine disinfectant. However, it can be difficult to demonstrate this correlation at water facilities that utilize continually varying blended sources or a single source with wide variations in organic precursor materials or chlorine demand characteristics arising from changing weather or seasonal impacts.

Figure 6.8 shows the improvement in water quality (reduction of TTHM levels) in different locations of the LVVWD network after EWQMS was installed in 2005. In addition to reduced water age and DBP levels, at LVVWD a modeling application of their EWQMS contributes to meeting the requirements of the Groundwater Rule by providing the laboratory with a follow-up 24-hour sampling plan for monitoring water quality in sampling locations that record a positive coliform sample (Jacobsen, 2013b).

Figure 7.8: Comparison of TTHMs concentration in different years at LVVWD. Implementation of in-house EWQMS at LVVWD occurred in year 2005



Source: Jacobsen, 2013b

Improved uniformity of operations through automation. Automation provides a way to reduce error rates as well as increase the uniformity of operations. Through EWQMS automation, operational inconsistencies typical of pump scheduling practices are minimized, particularly between operator shifts, and plant production rates are smoothed. EMWD estimated that most of the savings from their EWQMS automation were likely due to the reduction of human error and increased independence of operations from human judgment (Ghaderi, 2013).

Model and field issue resolution. LVVWD achieved substantial energy savings (thus also cost savings) not only by optimizing the pumping schedule, but by correcting field conditions that were costing money through detailed analysis of the EWQMS outputs (Jacobsen, 2013a). Similar benefits were seen in the commercial model rollout that identified discrepancies that often turned out to be stuck or incorrectly set manual field valves. EWQMS also provides more timely data on system operation that helps identify pressure bottlenecks, unknown constraints (at least by management) and water leakage from upper zone to lower zone.

Improved emergency response and maintenance planning. EWQMS can be used as a diagnostic tool for prompt emergency response (Perez, 2013; Jacobsen, 2013a). Divergence between SCADA (actual performance) and model projection at LVVWD helps to identify major issues that are associated with both the model and the infrastructure (e.g. valves malfunction, etc.). LVVWD estimated a response time as low as 1 hour for unplanned outages and field issues. Planned maintenance activities requiring facility outages were incorporated into the pumping plan in advance (Jacobsen, 2013a). Fast troubleshooting allows utilities to save more money in the long-term. The hydraulic modeling software at LVVWD is utilized to run multiple scenario analyses to plan and organize the response to emergency events. *Aquadapt* has an "operations simulator" version that allows scenario tree analysis for both short- and long-term capital planning.

Improved knowledge on distribution network system operations. The EWQMS captures the knowledge base of historical operations and can provide optimal control strategies for the specific utility. However, as highlighted in the interview with the EPWU staff, there is a fear that reliance on the automation could lead to loss of operational knowledge and could make it difficult to return to manual operation in an emergency (Perez, 2013). These issues may be minimized by continuous training of operators with simulated emergency scenarios, so that operators can gain confidence in the software predictions.

Strategic operations simulation and planning capabilities. This feature, typically included in commercial or in-house software, allows operators to evaluate different operational strategies on the fly without affecting the online system. The simulator also allows engineers and planners to simulate the effect of changes to parameters and facilities due to new pump curves, tariffs, storage capacity or demand patterns. For example, districts that foresee local population growth can utilize the EWQMS in system wide planning to maximize the use of available resources and assets (Jacobsen, 2013a; Derceto, 2013).

Improved asset performance visibility. An EWQMS give utilities the opportunity to view asset performance data such as kWh per MG per pump and thereby make informed decisions to extend the life cycle of assets, improve system performance and restructure operations, perform capital planning, and finally provide high levels of customer service.

6.2.3.2 Recommended Practice

The above section suggests that there are a number of intangible benefits for adding EWQMS. However, this study also revealed that the utilities currently utilizing EWQMS made a business case only based solely on a cost savings in their energy bill. A number of utilities mentioned that the payback is much more than just the energy cost savings. However, when these utilities were requested to provide quantitative information on such benefits, they mentioned that such data was not available because there were no pressing needs to find other benefits to justify the investment since the payback period was short. They added that there were difficulties in quantifying such benefits because of changes in many variables between pre- and post-EWQMS operations. Utilities that decide to install EWQMS in the future are strongly recommended to keep records of quantitative benefits of EWQMS implementation with respect to the following topics:

- Improvement in meeting water quality regulations;
- Cost avoidance through improved emergency response;
- Benefits of more informed decision making;
- Supporting a culture of operational excellence; and
- Impacts resulting from developing stronger customer ties.

CHAPTER 7:
Conclusions and Recommendations

This chapter summarizes the major findings of the study and identifies the remaining knowledge gaps for moving towards wider scale applications of EWQMS. The chapter is divided into two main subsections: a summary of findings, and a list of key recommendations.

7.1 Summary of Findings

Key Finding 1: Since inception in the early 1990's, the EWQMS, a comprehensive energy and water quality management system, has been implemented by a number of large drinking water utilities and has successfully reduced their annual energy costs.

- Two decades after the EWQMS framework was first introduced, approximately twenty water utilities have installed the EWQMS at their facilities. Utilities need to have an EWQMS software package, an upgraded SCADA, in-house modeling capabilities, remote control equipment, interfacing between the different software packages, sufficient storage tanks or reservoirs, and dedicated skilled staff for EWQMS implementation and operation. The estimated project costs for EWQMS design and implementation (i.e., software license, implementation, configuration and personnel training) may vary depending on the utility size and complexity of the system (e.g., $0.75 Million at EBMUD, $1.87 Million at EMWD, $1.3 Million at EPWU and $3.75 Million at NWL).
- For utilities with an installed EWQMS, operating electricity cost savings of 5–20 percent have been reported due to higher use of cheaper tariff periods and better operating efficiencies have resulted in an approximate reduction in energy consumption of 6–15 percent (with potential contemporaneous carbon emission reduction).
- In addition to these economic and environmental benefits, utilities with installed EWQMS have opportunities to better manage their water supply portfolios and simulate the impact of water demand patterns and energy market profiles on utility water resources management for decision making and planning.
- EWQMS also assists water utilities in monitoring water balance and identifying water losses in distribution systems, thus reducing overall water consumption.

Key Finding 2: Cost optimization, the objective function of currently installed EWQMS operations worldwide, not only enables operation in the least costly tariff period but also can reduce energy consumption and consequently GHG emissions.

- The driver for implementing EWQMS has historically been annual cost reduction primarily through tariff management and demand charge avoidance. Very little emphasis was given to identifying how cost optimization could result in energy consumption reduction as well.

- In the pilots conducted in this study at EMWD and EBMUD, the cost optimization significantly reduced overall cost but also reduced kWh consumption and GHG emissions even though these were not the prime goal of the optimization. The optimizer accomplished both by avoiding higher priced tariff periods and minimizing energy consumption, as both of these strategies led to cost reductions.
- At EMWD, optimizing for cost greatly reduced the cost associated with pumping compared to the other optimization scenarios analyzed, with an overall 7.8 percent cost reduction over the baseline. Under the same optimization a 2.9 percent decrease in energy consumption, thus also of GHG emissions, was observed compared to the baseline.
- At EBMUD, optimizing for cost significantly reduced the cost associated with pumping compared to the other optimization scenarios analyzed, with an overall 23.7 percent cost reduction over the baseline. Under the same optimization a 4.8 percent decrease in energy consumption, thus also of GHG emissions, was observed compared to the baseline.
- Offline simulations can be an effective tool for predicting the outcome of real-time operation for different optimization scenarios with different goals. When targeting cost savings, the online EBMUD simulations produced savings that were similar to the offline scenario predictions. The online EBMUD cost scenario reduced energy usage more than predicted by the offline scenario.

Key Finding 3: If the driver is to reduce GHG emissions, an EWQMS can be implemented for kWh/GHG optimization; however, a trade-off between cost reduction and least GHG/kWh operation should be carefully examined.

- The kWh optimization strategy was successfully able to find the lowest energy use operation for both pilot sites. The kWh optimization generated the lowest demand charge cost due to a more efficient pump operation (i.e., using the lowest peak kW), which also translates into an overall 21.8 percent cost reduction compared to the baseline value. In addition, it achieved a 5.3 percent reduction in energy usage and GHG emissions.
- This study suggests that there may be a clear trade-off between energy reduction and costs According to the EBMUD pilot results, by implementing cost optimization, the pumping energy consumption could be decreased from 590 to 561 kWh/MG with corresponding cost reduction from $110 to $84 per MG. By implementing energy optimization, an additional 3 kWh/MG reduction was achieved (from 561 to 558 kWh/MG) but with an additional cost of $2/MG. On the other hand, the EMWD pilot results suggest that simultaneous reduction of pumping energy consumption (from 609 to 591 kWh/MG) and cost reduction (from $77 to $71 per MG) was possible by implementing cost optimization. By implementing purely energy optimization, no additional energy reductions were achieved over cost optimization but resulted in a cost

increase of $11/MG. It is important that water utilities conduct independent studies to evaluate the significance of this trade-off for their operations.

- At EBMUD all online scenarios realized higher kWh reductions than predicted by the offline model. This is consistent with the fact that the online trial used the much more sophisticated multi-pump station optimization technique whereas the off-line trial had only considered one pump station at a time. The EMWD online simulations had less kWh savings than predicted by the offline scenario, and, as discussed, this was due to asset reliability issues.
- For EBMUD, the offline scenarios demonstrated that a pure kWh optimization approach could be more expensive than the cost optimization as it allowed pumps to operate when both peak kWh tariffs and peak kW demand charges applied. However, the online scenarios showed that, with some simple pre-optimization rules to avoid peak tariff period pumping, it was possible to optimize operation only during mid- and off-peak periods to achieve kWh/GHG optimization and still obtain cost savings similar to the cost optimization approach. From the utility's perspective it is more desirable to minimize kWh or GHG without compromising cost savings from avoiding peak period operations.
- The GHG optimization generated higher GHG emissions than the kWh optimization scenario. The explanation for this observation lies in the understanding of the optimization principles presented in Chapter 3. The GHG optimization is based on the assumption that emission factors vary throughout the day. Under the GHG optimization, the operational goal was to run the pumps when the emission factors were minimal, regardless of the energy consumption. Thus, unlike kWh optimization, the GHG optimization was not the lowest energy operation and required more energy compared to the kWh optimization. Therefore, the GHG optimization produced higher emissions compared to kWh optimization. Based on these results, the data suggest that water utilities should just focus on kWh optimization to achieve the lowest GHG operation until the variability of GHG emission factors for a given water utility are well established by the electric utilities.
- In summary, the data shows that cost optimization provides opportunity to achieve substantial reduction in GHG emissions. Additional GHG emission reduction just by focusing on kWh optimization may not be economical until the utilities have a large increase in the cost of carbon credits or more stringent regulations on carbon reduction. In addition, several other factors may also influence GHG management practices at water utilities, such as the availability of real-time GHG emission factors and understanding the correlation between TOU cost and GHG profiles, and most importantly the organizational commitment of the utility to sustainability.

Key Finding 4: Establishing pump priority strategies based on a pump's efficiency instead of its operational run time provides cost-effective and energy efficient operation.

- Typically, water utilities select pumps based on a rotation strategy that evenly rotates all the pumps within a pumping station. At EBMUD, the pump stations (Blackhawk, Blackhawk East and Acorn) used to rotate three pumps based on the total run time. The pilot testing was conducted to determine the benefits available from selecting the most efficient pumps within each station, rather than using a rotation policy to evenly spread run time over all pumps. The results of our analysis indicate that there are cost and energy benefits if the pumps are selected based on efficiency instead of the rotation policy. For instance, when the cost optimization was conducted based on the efficiency-based rotation policy, about 1.8 percent additional energy consumption reduction was possible on top of the energy savings observed by the manual pump rotation policy. Although the savings associated with the efficiency-based pump selection may not appear to be substantial in this case, this finding provides an indication that in-depth analysis of the importance of efficiency-based pump selection is warranted during the implementation of an EWQMS.

Key Finding 5: Operational consistency without an operator's interruption is critical to ensure maximum benefits from the EWQMS operation.

- All forms of optimization scenarios successfully avoided peak period kW demand charges which resulted in significant cost reduction. It was also observed in a few incidents that these savings were not sustained when even a single fifteen minute period of manual operation triggered by operator interference during a peak electricity demand period incurred kW demand charges. In order to avoid such cost increases, operational consistency was crucial. In addition to operational consistency, accurate and calibrated monitoring of equipment was also critical to realize the maximum benefits from an EWQMS operation.
- Cooperation between the water utility and the electric utility is needed to maximize benefits from energy projects. The results obtained at EBMUD were easier to analyze and led to stronger conclusions because the fifteen minute interval metering data provided by PG&E for the EBMUD pilot was more useful than the manual single daily readings collected at EMWD without assistance from SCE.

Key Finding 6: Avoidance of gas pumps operation may result in economic and environmental benefits; therefore, a pump station specific comparative analysis is needed during EWQMS implementation.

- The analysis conducted at one of the pump stations at EMWD suggested that a gas pump was significantly less efficient than an electric pump, with typical operations at 17% efficiency compared to the 65 percent wire-to-water efficiency observed for the electric pump. It should be noted that gas price per kWh was 1/5th of electric price and was not charged with peak kW demand charges. The comparative analysis of gas pump and electric pump operations suggested that when daily water demand averages above 0.31 MGD, electric pumping appeared to be the lowest cost choice for the pump station analysis. When average daily water demand was below 0.31 MGD, the electric demand

charge impact made the electricity cost per kWh higher than the equivalent gas cost, thus making gas pumping the lower cost choice. In all optimization scenarios tested, electric pumps had a lower GHG output than gas pump usage and the GHG emissions per MG for gas engine driven pumps could be five times higher than electric pumps. It should be noted that the volatility of gas prices will impact any comparative cost analysis.

Key Finding 7: Little to no noticeable differences in the distribution system water quality were observed among difference optimization scenarios (baseline, cost optimization, kWh optimization and GHG optimization).

- EWQMS operations do have the potential to affect water quality distribution across water supply networks by decreasing turnover in tanks or by changing the way customers receive water (direct pumped versus gravity supply). This has been recognized by EWQMS operators and strategies such as deep cycling or pulse flow operation have been used to overcome such deficiencies. The strategies are typically implemented as operating rules rather than optimization objectives. The impacts of the optimization scenarios on the distribution system water quality were evaluated based on water age simulations through offline hydraulic modeling and on residual chlorine monitoring during online operations. For the systems piloted, the results indicate that the overall impact on the water quality when running the optimizer was slight or not detectable. This study did not observe any adverse effects of pump schedule optimization, either for minimization of cost, energy or GHG. However, some evidence of increased water aging and stratification has been seen in the EBMUD study. Due to the short pilot study periods and changing demand and seasonal temperature differences between each mode of operation, it was not possible to attribute these changes directly to the results of the optimized operations.

7.2 Recommendation for Future Research

Major recommendations for future research on the implementation of EWQMS are presented below:

Recommendation 1: Simplified EWQMS suitable for small utilities needs to be developed for application of the energy and water management framework in the United States.

The current version of EWQMS is complex and can provide an attractive payback on investment (less than three years) for large utilities with high annual energy costs ($2M or higher). It is timely research to develop and demonstrate a simplified version of EWQMS that would be affordable and beneficial to mid- and small-sized utilities. Although the core optimization module is not expected to change, the simplified version of EWQMS that is designed to be substantially easier to configure and implement without reducing the benefits, has not been tested in the US for its cost-benefit for mid to small-sized utilities. If an attractive business case can be demonstrated for these utilities, a broader adoption of EWQMS may be possible.

Recommendation 2: Real-time GHG emissions profiles should be further defined.

The carbon intensity of electricity is dependent on the generation processes utilized, which is time-dependent. The emission factors commonly employed in calculating the carbon footprint of water supply systems are regional and are typically expressed as a flat rate lbs of CO_2-e/kWh regardless of time of use. Marginal emissions rates vary between on-and off-peak hours, but do not vary substantially by season. The variation of emission factors with respect to the electricity tariff structure may be of importance when optimizing pumping schedules. In fact the use of time-dependent emissions factors against more conventional static emission factors for pump operational management could result in further reducing operational GHG emissions. In this study, a proof of concept study was conducted and a variable GHG structure was developed from a California market model called PLEXOS used in longer term planning. The model provided a preliminary indication that as electricity demand increased during the day, less efficient generators entered the market with greater CO_2 per MWh of energy production. However, the correlation between the energy used by an individual water utility and its GHG emissions variation on a real-time basis has not been validated. Further research is needed to refine the time-of-use energy use and GHG emission factors.

Recommendation 3: Water quality optimization should be included in the objective function of the EWQMS.

Current EWQMS systems do not include chemical water quality parameters (e.g. chlorine residuals) in the objective function or as constraints in the optimization algorithms. Water quality issues are generally addressed by using explicit hydraulic operating rules, such as cascade pumping, reservoir operating levels, deep cycling and pulse flow, to influence retention times within the distribution system and in tanks. Actual system compliance with regulatory standards is then monitored. This is a pragmatic approach. The main obstacles to including water quality predictions in the on-line optimization algorithm are the availability of real-time water quality data (e.g., chlorine residuals) and the computational speed required for the optimization. Accuracy and reliability of model results is a further concern. Processor speeds will improve with time and may mean on-line optimization of physical or chemical water quality becomes a practical option. Utilities considering implementing EWQMS should undertake physical and/or chemical water quality modeling of their networks in calibrated, all mains models as part of design and development studies. The calibrated models should be maintained and tested against EWQMS optimizer controls at regular intervals. The models will help interpret actual network water quality sampling results and assist in the evolution of hydraulic rules to maintain water quality under optimizer operation.

Recommendation 4: Cultural differences between operators and engineers needs to be addressed for widespread application of EWQMS.

Although all EWQMS installations rely on similar structural features, each one needs to be tailored to the specific system characteristics, objectives and limitations or constraints of each installation site. In addition to budgetary constraints to invest in equipment and software packages, an important challenge in implementing EWQMS is the conflict in cultural

acceptability. For instance, "operators" and "engineers" have different perceptions about system control, often giving rise to conflicting evaluations of the benefits of an EWQMS. While motivated by a common interest in terms of the successful performance of their system, they value different sets of criteria (benefits, risks, etc.). In order to promote the application of EWQMS, it is important to address these diverse perspectives carefully when planning and instituting such innovations. Further research is needed to develop the methods and tools necessary to effectively communicate the EWQMS benefits to operators and engineers, so it will be appropriately designed, operated, and maintained. Also needed is the identification of the requisite knowledge, skills, and abilities for an operator, supervisor, engineer, and manager to successfully perform their job at a water utility with an EWQMS, including a definition of roles and responsibilities. Finally a more refined/formalized definition of system operating requirements (normal and emergency conditions) using an EWQMS needs to be identified.

Recommendation 5: Extend the application of the EWQMS for joint water and electric utility planning.

Bringing energy and water utilities together may allow for greater saving opportunities and increased knowledge of the relationship between water and energy resources. Further research is needed to understand how an EWQMS may assist in the development of joint programs between the two sectors that could result in adoption of energy efficiency strategies, increased savings of both energy and water resources, and shared financial opportunities between the two sectors. Power utility incentive programs and benefit allocations can be developed to support Permanent Load Shifting (PLS) solutions that would be beneficial for both water and electric utilities.

Recommendation 6: Evaluation of the long-term performances of EWQMS.

The published literature only documents the benefits of EWQMS observed for a limited number of utilities operated for a short duration. Water utilities are often impacted by watershed events (e.g., drought/rain cycles which impact source water portfolios), national and/or regional regulations (e.g., water quality, air quality issues), budgetary constraints and electric utility tariff structure changes that force them to make major operational changes from year to year. Some utilities have been under EWQMS operation for many years, however, due to the variation of typical water utility operations (e.g., raw water source quality, demand, energy tariff structure, etc.); limited data is available on long-term performance with constant operating conditions and controlled variables.

7.3 Potential Benefits to the Investor Owned Utilities Rate Payers in California

The water utilities that are paying annual energy bills higher than $3 million may be able to implement the current form of EWQMS with an attractive payback period (3-4 years) and achieve energy cost savings. The extent of savings of EWQMS for a particular water utility depends on tariff rate structure, demand to storage ratio, and other operational characteristics as discussed throughout the report. If EWQMS is implemented by water utilities, the benefits

will reach to the Investor Owned Utilities' (IOUs) rate payers serving those water agencies. The benefits to the IOU rate payers, include, but are not limited to the following:

- The EWQMS tool can optimize a water utility's operations for energy costs savings (5-20 percent) and energy consumption reduction (6-9 percent) using the existing assets. Thus, the implementation of EWQMS will reduce absolute energy demand by water utilities in their IOU rate payer service area.
- The implementation of EWQMS will improve the energy efficiency of the pumping equipment and of the entire water operations, and therefore, the energy intensity (kWh/MG) of the water production in the IOU service area will be reduced;
- The EWQMS can move energy consumption patterns from peak to off-peak periods. Thus, a flattening effect of the IOU's aggregate system electric demand profile will occur as a result of load shifting and peak demand time avoidance by the water utilities;
- The EWQMS may assist water utilities to participate in the IOU rate payers economic and synchronized Demand Response (DR) program, and thereby, ensure more predictable energy demand management in the IOU service area; and
- The EWQMS will assist the IOU in reducing GHG emissions of their operations and thereby adopting climate change mitigation strategies.

It should be mentioned that if the simplified version of EWQMS becomes available in the future, these benefits will extend substantially since additional mid-and small-scale water utilities with energy bills of $1-2 Million will be able to also implement EWQMS economically. However, additional research with participation of both water and electric utilities is warranted in order to critically evaluate and quantify the above-mentioned benefits through implementation of EWQMS, and to develop an integrated framework that promotes a symbiotic relationship between the water and electric utilities.

GLOSSARY

Term	Definition
ANN	Artificial neural network
AWWA	American Water Works Association
BEP	Best Efficiency Point
CAISO	California Independent System Operator
CARB	California Air Resources Board
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalents
CPUC	California Public Utilities Commission
CRW	Colorado River Water
DBP	Disinfection By-Product
DR	Demand Response
DSS	Decision support system
EBMUD	East Bay Municipal Utility District
EMWD	Eastern Municipal Water District
EPC	Economic Pump Control
EPWU	El Paso Water Utilities
ERU	Energy recovery units
EWQMS	Energy and Water Quality Management System
G	grams
gCO_2/MG	grams of carbon dioxide per million gallons
GHG	Greenhouse Gas
IOU	Investor-owned utility
IT	Information technology
KPI	Key performance indicators
kW	kilowatt
kWh	kilowatt-hour
LAN	Local area network
Lbs	pounds
LVVWD	Las Vegas Valley Water District
MDL	Method detection limit
MG	Million Gallons
MRL	Minimum reporting unit

MW	Megawatt
MWh	Megawatt-hour
NPV	Net Present Value
NWL	Northumbrian Water Limited
NYSERDA	New York State Energy Research Authority
O&M	Operation and Maintenance
PAC	Professional Advisory Committee
PG&E	Pacific Gas and Electric
PLS	Permanent Load Shifting
QA/QC	Quality assurance/quality control
RD&D	Research, Development and Demonstration
ROI	Return On Investment
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SOP	Super off-peak
SWN	Smart Water Network
TDS	Total dissolved solids
TOU	Time-of-Use
TTHMs	Total Trihalomethanes
U.K.	United Kingdom
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
UV	Ultraviolet
VBA	Visual Basic for Applications
VFDs	Variable Frequency Drives
WTP	Water treatment plant

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