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FINAL PROJECT REPORT

Advancing Demand Response in the Water Sector

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

A novel energy demand management software (DMS) called WaterWatch, designed and built by the University of California, Davis Center for Water-Energy Efficiency, offers safe recommendations for water distribution systems to adjust their energy loads in response to various signals. The software leverages hydraulic modeling, machine learning, and optimization research to produce near real-time operational recommendations. WaterWatch was piloted at the Moulton Niguel Water District in Southern California for 12 months, and it tracked water and energy consumption, along with greenhouse gas emissions. Additionally, a simulation model was created to assess the potential for energy load shifting across California's public water systems and its impact on the statewide energy grid. The statewide model identified that water distribution pumping accounts for at least 1.2 percent of California's total energy consumption. The model clearly demonstrated a high degree of capacity to shift, ramp, and modulate energy demand statewide throughout the day to meet nearly any energy sector objective, given a properly designed energy tariff or price signal. Under the idealized energy tariff without demand charges, the study found that the water distribution sector could annually shift energy demands by up to 1.07 terawatt-hour or reduce renewable electricity curtailment by 68 percent. The WaterWatch demand management software consistently reduced energy demand by 4.03 percent over five days with each use during the pilot. With continued weekly use, the pilot site would be expected to save up to 311.58 megawatt-hours of energy consumption annually, or 48.36 metric tons of carbon dioxide equivalent ($MTCO_2e$) of indirect greenhouse gas emissions. Scaled to all public water systems in California, it is anticipated that use of WaterWatch would result in the savings of up to 131.8 gigawatt-hours annually or 20,457 $MTCO_2e$ of indirect emissions.

Keywords: Demand management, decision support, hydraulic modeling, water sector, demand response

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Introduction

The project sought to better understand and empower the capabilities of the water distribution sector to perform energy demand management to shift, ramp, or change its energy demand to align better with the needs of the energy sector. The project aimed to better quantify the size and scope of water distribution pumping as well as the exact amount of energy available for load shifting, by developing an energy grid model to simulate and model the operations of all public water distribution systems in California. Moreover, the project aimed to introduce a demand management software (DMS) called WaterWatch to enable water distribution systems to readily perform energy load shifting in response to any objective. The project team hoped to enable the water sector to participate proactively in the reduction of energy curtailment, overgeneration, and volatility in the energy sector by introducing the tools and knowledge needed to shift energy demands safely in real time.

Project Approach

Demand Management Software

To generate safe recommendations for approaches to operating any water system in California under alternative energy tariffs or load shifting objectives requires the management and manipulation of hydraulic models and other data from a myriad of sources, including time-series records, geospatial information, and utility maps. Additionally, the recommendations must be timely and reflective of current, up-to-date asset availability and water storage characteristics.

To accomplish these requirements, the University of California, Davis (UC Davis) Center for Water-Energy Efficiency (CWEE) developed a novel DMS within a multi-layered architecture employing hardware-level optimizations, robust support for asynchronous computing, and dozens of embedded features or libraries used in enterprise software. The DMS is a stand-alone application built to enable high-performance analytics on hydraulic models and other unstructured data in real time. The DMS has been intentionally developed to enable the extension or addition of features and applications in the future, as interest arises. The key innovations introduced in this DMS tool were:

- The ability to perform complex, full hydraulic simulations in real-time.
- Support for operating staff to change the recommendations dynamically and to have those changes automatically incorporated into the simulations.
- The integration of machine learning into hydraulic modeling.
- Policy-based optimizations that were applicable for weeks to months.
- Data security by performing all computations and data storage in-memory on the local device without transferring water system data to the cloud or online servers.

Statewide Energy Grid Modeling

To estimate the capacity for and benefits of energy load shifting in the water sector, CWEE simulated water demands and load shifting of 702 water distribution systems using simplified hydraulic models based on publicly reported data and assumptions from literature. The hydraulic models were optimized for each agency to determine the ideal water pumping strategies for several scenarios and were aggregated to the statewide scale to demonstrate the flexibility of the water sector to shift demand in response to pricing signals and to aid in achieving statewide load-shifting and greenhouse gas emission reduction goals.

Project Design

The DMS was designed and built in California by the UC Davis CWEE. The installation and pilot operations were managed by Moulton Niguel Water District (MNWD) in collaboration with CWEE. High-resolution energy interval meter equipment was installed at all major pump stations at MNWD to perform continuous observation of system performance and resource consumption.

Piloting the Software

The DMS technology was successfully installed at MNWD in the city of Aliso Viejo, California, and operated for a pilot period of 12 months. Operations and use of the DMS tool were led by MNWD with support by CWEE, including supporting documentation, resolving issues with the software, and introducing additional features and tools in the software over time. Pilot data were collected either directly from WaterWatch or as historical copies from the MNWD Supervisory, Control, and Data Acquisition Database, and from energy meter records, for processing by CWEE. Savings achieved by the DMS were evaluated statistically based on short-term changes to energy use following interactions with the DMS throughout the year.

Project Results

Energy Load Shifting With the DMS

The DMS was piloted for 12 months at MNWD and reported a total of 31 email and phone interactions with operating staff, averaging 1.57 hours per issue. It was found that the DMS directly led to a reduction in the average energy demand of the water system by 35.57 kilowatts for the 5 days following each periodic use of the software, which translates to approximately 4.03 percent less energy consumption. Additionally, it was found that the energy intensity of water delivery was reduced for the same period by 0.025 megawatt-hours (MWh) per million gallons, or by 3.7 percent. It is estimated that the DMS directly influenced the energy demand at MNWD for 1,624.25 hours of the year-long pilot. It is anticipated that, had MNWD used the DMS each week, the net savings would accumulate to 311.58 MWh annually or 48.36 metric tons of carbon dioxide equivalent ($MTCO_2e$) of avoided indirect carbon emissions.

Potential for Energy Demand Management in the Water Sector

To estimate the broader potential impact of water distribution systems like MNWD adopting a DMS and participating in dynamic energy load shifting, the energy grid model was leveraged to simulate nine different energy pricing and emissions minimization scenarios at the public water systems throughout California. The study found that the potable water distribution sector accounts for at least 1.2 percent of the total electricity used in California and has the flexibility to shift its energy demands by up to 1,071 gigawatt-hours annually, or to reduce curtailment in California by up to 68 percent, or to reduce its contribution to peak net demand by up to 321 megawatts and avoid 330,627 $MTCO_2e$ of emissions. The scenarios that led to the greatest load shifting and emissions reductions included time-of-use energy rates that incentivize consumption during the middle of the day, whereas scenarios with demand charges prevented load-shifting and resulted in flat energy consumption profiles throughout the day.

Barriers to the DMS

This project identified two primary barriers to energy load shifting in the water sector.

First, the energy grid model illustrated that the presence of demand charges in energy tariffs, which penalizes peak energy demand, was likely preventing load-shifting programs and other incentivizing pricing schemes from successfully motivating the shifting, ramping, or increase to energy demand. With the removal of demand charges, the model showcased capacity for the water sector to effectively manage energy demands, enabling the achievement of various goals comparable to those pursued by the energy sector. These goals encompass peak-hour demand, net emissions, curtailment, and overgeneration.

Second, the lack of high-quality hydraulic models of water distribution systems is a clear barrier to the use of most DMS tools, especially those that seek to generate safe recommendations. While many water systems either have models or are procuring them, the vast majority are typically not calibrated sufficiently for trustworthy operational decision making. A key component of this gap is that there does not yet exist adequate mechanisms to measure and confirm the accuracy and quality of hydraulic models upon delivery to water systems.

Market Adoption

Regarding DMS technology, historically, water utilities have been conservative in adopting new technologies that lack multiple full-scale pilots or demonstrations. The adoption of WaterWatch is no exception. UC Davis CWEE has achieved success in disseminating WaterWatch to MNWD directly, including through planned expansion projects. CWEE discovered that this may have been achieved due to the high quality of the hydraulic models available to MNWD and the trust built over a year of piloting the DMS and demonstrating its match with real behaviors. It is anticipated that additional funding will be necessary to repeat this pilot with additional water systems before traction can be achieved.

Benefits to California

The project team sought to illustrate that energy load shifting of water distribution systems would present a significant opportunity for the reduction of energy imbalances on the statewide energy grid. In one part of this research, the DMS technology was piloted at MNWD, resulting in measurable energy savings that could be statistically isolated. Using the DMS technology as a tool used to explore the flexibility of the water system, it was estimated that, over approximately 1,624.25 hours of influence on the operating staff, MNWD directly saved 57.77 MWh in energy consumption. The project found that, had MNWD used WaterWatch throughout the year on a weekly basis, it was expected that the utility may have saved up to 311.58 MWh annually through direct performance gains discovered by operators following use of the DMS. Using the results of the energy grid model to estimate the size and scope of water distribution in California, it was anticipated that, if every public water agency in California leveraged DMS on an approximately weekly basis, there would be an aggregate annual savings of 131,815 MWh.

Additionally, MNWD demonstrated a small reduction to its energy intensity, which appears to have taken place during its daily peak energy demand. It is unclear if this change would scale to additional water systems. Assuming an energy intensity of 0.1552 $MTCO_2e$/MWh, it is expected that California achieved a savings of 8.97 $MTCO_2e$ and could achieve a reduction of 20,457 $MTCO_2e$ annually if all utilities used WaterWatch weekly.

CHAPTER 1: Project Summary

The Center for Water-Energy Efficiency

The Center for Water-Energy Efficiency (CWEE) is a research center at the University of California, Davis (UC Davis), within the Office of Research's Energy and Efficiency Institute. CWEE brings together a range of disciplines, agencies, and organizations across California to conduct, translate, and disseminate science- and policy-based research to advance innovations in water efficiency and the water-energy nexus.

Moulton Niguel Water District

Moulton Niguel Water District (MNWD) is a California water agency that provides potable, reclaimed water and wastewater services to approximately 170,000 customers in the cities of Aliso Viejo, Laguna Niguel, Laguna Hills, Dana Point, and San Juan Capistrano (MNWD, 2016a). The water agency imports all of its drinking water from either the Colorado Watershed or the Sierra Nevada Mountains through the State Water Project, and it purchases all of its electricity from two retail electricity investor-owned utilities (IOUs), Southern California Edison Company (SCE) and San Diego Gas & Electric Company (SDG&E) (MNWD, 2016b).

Project Description

The purpose of this project is to develop and pilot a demand management system (DMS) that could enable a water utility distribution system to reduce or shift energy demand loads, or ramp up energy demands, in response to different tariff structures. Additionally, the short- and long-term net grid impacts from water utility demand management were analyzed for a specific water utility and also on a statewide basis using a smart grid optimization model. The pilot formally began January 1, 2021, and CWEE stopped observation on December 31, 2021.

Project Goals and Objectives

The project goals included:

- Developing a DMS for a water distribution system capable of providing actionable intelligence for water system energy demand management.
- Using the DMS to analyze the system and develop an operational plan for flexible operation of water systems in response to applicable energy tariff structures.
- Demonstrating a pilot using the water system operational plan and assessing the ability of the water district to reduce, ramp up, or shift energy loads, as desired.
- Developing a smart grid optimization model to analyze the grid impacts from water system demand management and optimize grid operations under different supply and demand scenarios.

Project objectives included:

- Serving as a demonstration of generating safe, trustworthy recommendations for operating a water system from a decision support tool (rarely practiced in the United States).
- Developing a full understanding of the barriers to hydraulic modeling in the water sector and how they can be addressed.
- Developing a full understanding of the potential for energy load shifting in the water sector and how it could assist the energy sector.

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A technical advisory committee was formed to support the design and implementation of the DMS technology. The technical advisory committee provided insight on the past experiences of the water sector in implementing DMS technologies, including the reasons for their failures to penetrate the water sector to date.

CHAPTER 2: Introduction to Energy Load Shifting in the Water Sector

To reduce the greenhouse gas (GHG) intensity of the California electric grid, the state has set aggressive renewable energy objectives, calling for 50 percent of the state's electricity to be provided by renewable resources by 2025 and 60 percent by 2030 (Senate Bill 100, De León, Chapter 312, Statutes of 2018). However, renewable energy integration has caused new institutional and technical challenges for energy systems, particularly when integrating wind and solar, due to their intermittent, variable, and non-dispatchable nature (Liang, 2017). These challenges are compounded by current limitations on large-scale energy storage, meaning that most energy produced must be consumed immediately (Aneke and Wang, 2016). Renewable energy generation leaves increasingly substantial temporal gaps. To meet customer demand, energy providers must fill these gaps with dispatchable energy sources such as hydropower, geothermal, natural gas, and coal (Verzijlbergh et al., 2017) or provide incentives for customers to shift energy usage, known as energy demand management.

Promoting energy demand management can ease and increase renewable integration, further reducing GHG emissions (Paterakis et al., 2017). In California, this typically means shifting energy out of the evening time periods and into the middle of the day, when solar generation is most prevalent. California's three largest IOUs, Pacific Gas and Electric (PG&E), SCE, and SDG&E, transitioned to default time-of-use (TOU) rates under the direction of the California Public Utilities Commission (CPUC) in 2019. These TOU rates promote more efficient use of energy under seasonal scenarios based on the generalized needs of the California electric grid. In addition to TOU rates, the IOUs typically offer several demand response (DR) programs and seasonal incentives designed to help improve the management of the electric grid as the integration of renewable energy increases.

Opportunities for Demand Management in the Water Sector

The California Independent System Operator (California ISO), charged with managing the flow and reliability of electricity across many of the long-distance power lines in California, has observed significant changes to the energy profile of the statewide grid due to the growth of renewable energy (CAISO, 2016). Energy sources in California have shifted toward less predictable variable energy resources, such as solar and wind power. As a result, short-term intermittent changes to energy production are leading to increasingly common periods of excess energy generation, characterized by an imbalance between energy supply and demand (Denholm et al., 2015). Energy imbalance is currently managed with the practice of curtailment, which typically is accomplished through an economic dispatch where generators get paid to reduce generation (Younghein and Martinot, 2015). Overgeneration, which occurs when excess energy generation is not completely consumed or curtailed, has the potential to reduce the reliability of the electricity supply (CAISO, 2017). One way to reduce the negative impact of overgeneration is to shift energy consumption to eliminate energy imbalance with pricing incentives or electricity demand-responsive technologies (Action et al., 1983).

In 2015 the CPUC directed the electric IOUs, the major suppliers of energy to retail customers in California, to update TOU energy rates to incentivize electricity customers to shift demand to correspond with key periods of excess energy generation due to renewable integration (CPUC, 2015). In 2019, all of the ISOs updated their TOU rates in fulfillment of this ordinance. In addition to these static TOU rates, dynamic DR programs and the California ISO wholesale market incentivize customers to respond to real-time price signals reflecting the moment-to-moment needs of the grid. Responding to static and dynamic load incentives presents unique challenges to California's energy-intensive water sector.

As a large energy user, the water sector has a significant opportunity for energy demand management. Water utilities, including wastewater facilities, are energy-intensive systems, with water-related energy use accounting for approximately 20 percent of California's total energy consumption (Klein et al., 2005). Additionally, energy can account for 33 percent to 82 percent of water and wastewater utilities' nonlabor operating costs (Limaye and Jaywant, 2019). Participating in time-based pricing mechanisms can reduce costs for the facility and increase renewable integration for the energy sector. Both the water and wastewater sectors have several sources of operational flexibility that can be used for energy load shifting. These include water (Santhosh et al., 2014) and wastewater (Lekov et al., 2009) storage facilities, excess system capacity (Olsen et al., 2012), and potential energy generation sources such as in-line turbines in water distribution systems (Williams, 1996) or cogeneration facilities at wastewater treatment plants (Schäfer et al., 2015).

The extent of the ability of water utilities to shift energy into new TOU time periods and how these operational changes impact operating costs or water customer experience is not known. Similarly, the capacity for water utilities to respond to dynamic price signals is not well understood. Demand management in the water sector is a critical path to increasing the reliability of the statewide energy grid and to reducing grid curtailment and overgeneration. An improved understanding of how water distribution systems can load shift should empower water utility operators to better incorporate DR technologies and plan for future energy rate structures while continuing to meet the requirements of water customers. If water utilities had the tools and knowledge to shift energy consumption to periods of variable energy resource generation, they might be able to reduce their GHG emissions and simultaneously reduce the energy imbalance in the statewide energy grid.

Current Landscape of Water Distribution in California

Water distribution system operators focus primarily on meeting water demands to ensure customer needs are met; optimizing energy use to save on operating costs is often a competing concern (Beyer, 2017). Forecasting the impact of energy load shifting on system operations requires data analysis that is typically outside the technical ability of most water utilities (Menke et al., 2016). Although California's water utilities are in a unique position to assist with the energy grid's need to reduce energy imbalances, to date they have been largely unable to perform load shifting into periods of energy imbalance. If water distribution systems were able to shift energy demands successfully and significantly, it is anticipated that they could help mitigate concerns of grid reliability while improving sustainability and energy efficiency (GEI Consultants and Navigant Consulting, 2010). However, due to the complexity of energy demand management in the water utility sector and the lack of knowledge in the effectiveness of available market solutions for this objective, energy load shifting in the water sector is not currently an available approach for most water systems.

Existing Energy Technologies for Water Distribution

Hydraulic simulation models have been effectively leveraged in the water treatment, water distribution, and manufacturing sectors as a cost-effective and reliable methodology for predicting fluid behavior under most conditions (Cherchi et al., 2015). Using physical laws, including the conservation of mass, energy, and momentum, computer models are capable of forecasting water demand, pressure, flow, velocity, and water quality for specified system design and operating conditions (Boulos et al., 2006). In the water distribution sector such forecast tools are used to simulate capital infrastructure improvement, maintenance schedule impacts, emergency flow conditions, and water delivery operations.

The hydraulic calculations and modeling performed by many commercial software packages are primarily based on the methods developed by the United States Environmental Protection Agency's Model for Water Distribution Piping Systems (EPANET) (Rossman, 2000). EPANET's hydraulic modeling engine can report the hydraulic status of complex water distribution networks and has been leveraged in academic and commercial applications to determine pump station operations that satisfy the required system performance measurements, including tank levels, pipe flows, and pump curves (Rossman, 2000). By incorporating data from accurate, up-to-date water distribution network designs, pipe networks, and element characteristics, the use of hydraulic water models in offline simulations has been shown to be an effective tool for predicting the outcome of expected real-time operations under various optimization goals (Cherchi et al., 2015).

There is a growing trend in the water industry to use hydraulic modeling software as one part of an operational framework for controlling water quality, water supply, and energy management problems simultaneously, typically called an energy and water quality management system (EWQMS) (Jentgen et al., 2004). The first EWQMS began with research by the American Water Works Association (AWWA) Research Foundation, the Electric Power Research Institute's Community Environmental Center, and the East Bay Municipal Utility District (Beyer et al., 2005). Commercial products such as Derceto's Aquadapt (Cherchi et al., 2015) and Innovyze's InfoWater (Boulos et al., 2014) offer optimizations for pump scheduling and cost minimization under specified system constraints and operating requirements, with each working independently to validate its products through case studies and peer-reviewed publications.

Previous Research on Pump Operation Optimization

Energy optimization of pump operations at water distribution utilities has been the subject of research since the 1970s (Coelho and Andrade-Campos, 2014; Mala-Jetmarova et al., 2017). These studies have typically focused on optimizing water distribution system operations based on a pump status (on/off) for specified durations. However, operating pumps on a rigid schedule can result in an unreliable water supply to customers, given that actual water usage often varies from forecasts. In practice, water utilities ensure reliability by enforcing rule-based controls determined by operators rather than duration controls optimized by hydraulic simulation. Typical pump operation control triggers include tank level, downstream pressure reading, and time of day. More recently, optimization of rule-based controls has been explored due to its ability to produce more reliable and robust pump operating policies (Alvisi and Franchini, 2016; Marchi et al., 2017; Linz et al., 2020).

The optimization of water distribution system pump operations is a mixed integer nonlinear problem, due to the relationship between flow and pressure required in hydraulic simulation and the discrete statuses of valves and pumps (open/closed and on/off) in the network. Both classical and heuristic methods have been applied to the optimization of pump operations (Coelho and Andrade-Campos, 2014; Mala-Jetmarova et al., 2017). Although much of the research in this field has concentrated on energy reduction through optimal control of pumps, also known as load shedding, water distribution systems can load shift operations because of water storage. This can be accomplished by optimizing the timing of filling and draining tanks according to an energy price profile (discussed in greater detail in Chapter 4).

Energy Price Structures

Depending on their size and function, water utilities may be able to access many of the time-based incentives offered by their local energy suppliers, such as PG&E, SCE, or SDG&E. Time-based pricing can help promote energy demand management within the water sector by incentivizing beneficial time periods with lower prices for energy consumption. As an illustration of such a system, Table 1 summarizes the electricity rates and DR programs that are currently available to water utilities within the SCE energy service territory. However, limited information is known about how well water utilities are able to adapt to these tariffs and programs, what barriers there are to participation, and whether the water sector is being properly incentivized.

Table 1: SCE Business and Industrial Rates and DR Programs Accessible to Water Utilities

Name (Format)	Example Requirements	Description
General Business or Industrial Customer Time-of-use (TOU) Rates, for General Service (GS) (Rate Plan)	TOU-8: demands exceeding 500 kilowatts (kW) TOU-GS-3: demands between 200 kW and 500 kW TOU-GS-2: demands above 20 kW but below 200 kW	Each TOU rate consists of four main charges: a monthly customer charge that does not vary based on usage, the TOU energy charges, facility-related demand (FRD) charges and the time-related demand (TRD) charges. There are two options for these rate structures: option D has higher TRD and FRD charges and lower energy charges per kilowatt-hour (kWh), and option E has lower TRD and FRD charges with higher energy charges. Customers on the TOU-8

Name (Format)	Example Requirements	Description
		rate must meet additional requirements to participate in option E.
Agricultural and Pumping (PA) TOU Rates (Rate Plan)	At least 70 percent of the customer's electrical usage must be for agricultural power service, general water or sewage pumping, or oil pumping; no energy use can be for domestic purposes. TOU-PA-3: demands between 200 kW and 500 kW. Customers with demands above 500 kW are eligible for this rate schedule if they meet additional eligibility criteria. TOU-PA-2: demands below 200 kW	There are two options for these rate structures: option D has higher TRD and FRD charges and lower energy charges per kWh, and option E has lower TRD and FRD charges with higher energy charges. Additionally, agricultural and pumping customers can choose which on-peak time period works best for their business operations: 4:00 p.m. to 9:00 p.m. or 5:00 p.m. to 8:00 p.m.
Real Time Pricing (RTP) (Rate Plan)	Open to all nonresidential customers receiving bundled service (delivery and generation of electricity).	Real-time pricing is pricing that reflects the hourly variation in electricity costs due to changes in demand. Typically, energy prices are highest when the demand for electricity increases on days when the weather is warmer or during evening hours.
TOU Base Interruptible Program (BIP) (Rate Plan or DR Program)	Demands of 200 kW or greater On a TOU or RTP rate schedule Ability to reduce at least 15 percent of maximum electrical demand (a minimum of 100 kW) during each interruption event Must have an interval meter.	A TOU-BIP event may occur at any time. TOU-BIP events are limited to: • One event per day (up to six hours) • 10 events per calendar month • 180 hours per calendar year Upon receiving a BIP event notification, the customer has 15 or 30 minutes (based on the selected participation option) to reduce electrical usage to an amount of the customer's choosing called the Firm Service Level (FSL). The facility's electrical usage must not exceed the FSL throughout the event to avoid excess energy charges.
Agricultural and Pumping Interruptible Program (Rate Plan or DR Program)	Demand of 37 kW or greater, or with at least 50 horsepower of connected load On an agricultural and pumping rate schedule	SCE transmits a signal to the load control device installed on the customer's pumping equipment, which automatically turns off the total load served for the entire duration of the interruption or test event. The customer needs to perform a manual reset of the main circuit breaker or pump controller after each interruption or test event. An interruption can occur at any time. Interruption events are limited to one

Name (Format)	Example Requirements	Description
		event per day (six hours), 25 events per calendar year, and 150 hours per calendar year.
Critical Peak Pricing (CPP) (Seasonal Incentive or DR Program)	Most business customers receiving bundled service (delivery and generation of electricity) from SCE are eligible for CPP. Many businesses industrial/business customers' rates may already be enrolled in CPP.	CPP is an optional rate that offers a discount on summer electricity rates in exchange for higher prices during 12 CPP event days per year, usually occurring on the hottest summer days. CPP events can be called year-round on nonholiday weekdays between 4:00 p.m. and 9:00 p.m. CPP event notifications are sent a day ahead of the event so customers can plan their usage. Bill credits are applied to reduce customers' power costs during the summer months (June 1 through September 30).
Capacity Bidding Program (CBP) (DR Program)	Must have an approved metering device. Cannot be enrolled in certain other DR programs.	A year-round, event-based program. Participants may be called on any weekday (excluding holidays) between 1:00 p.m. and 7:00 p.m. to temporarily reduce energy usage. Events are called in response to weather- or system-related energy shortages or high energy prices, or they may be called up to three times a year for testing purposes. Each month, customers choose how much they can commit to reduce, and they receive incentive payments for meeting the bid. Even if no CBP event is called, the customer still earns incentives. Events can be scheduled on a day-ahead or on a day-of basis and can last from one to six hours. Event participants are not required to reduce load for more than one event per day and not for more than 30 hours per month.
Optional Binding Mandatory Curtailment (OBMC) (DR Program)	Eligible customers are those who can independently or in aggregate reduce their entire circuit's load by up to 15 percent, in increments of 5 percent, during every rotating outage, as determined by the prior year's same-month average peak period load, adjusted for major changes in facilities.	This program exempts customers from rotating outages. In exchange, customers must make 15 percent of the load on their entire circuit available for reduction during every rotating outage. Customers are required to file an OBMC Plan that is acceptable to SCE, prior to participation in this program.

Name (Format)	Example Requirements	Description
	Customers need to provide certain circuit load information.	There are no monetary incentives for participating in OBMC. Excess energy charges apply if the customer fails to achieve the required circuit load reduction of up to 15 percent. The 15-percent load reduction is determined by first finding the participating customer's 10-day average baseline.
Scheduled Load Reduction Program (SLRP) (DR Program)	Must have bundled service and an average monthly energy demand of 100 kW per month. Must commit to a load reduction of at least 15 percent based on the maximum demand over the previous 12 months, which cannot have been less than 100 kW. If the customer has service through an alternate provider (Direct Access) or is enrolled in a California ISO program, it is not eligible.	With SLRP, customers can receive a credit for reducing load to at least the minimum requirement on prescheduled days and times on weekdays during the summer months of June 1 through September 30. SCE uses the 10-day average baseline methodology to determine the Customer Specific Energy Baseline, which is used to calculate actual energy reduction.

Source: SCE Business and Industrial Rates and Demand Response Programs, 2021

General studies investigating how industrial systems, including water utilities, can respond to typical TOU rate structures and DR programs have highlighted several issues that may limit participation and reduce the effectiveness of incentives, particularly for water utilities. Many TOU rates include non-time-based demand charges; one observed issue is that, as water utilities (IRWD, 2021) and similar industrial customers (Ashley et al., 2013) try to shift energy into the off-peak time period, they may be subject to increased demand charges. This can significantly offset the incentive to shift energy from the on-peak to the off-peak time period. Several studies investigating how industrial customers (Mohajeryami et al., 2017; Song et al., 2018), including a study examining a wastewater treatment plant (Musabandesu and Loge, 2021), can participate in DR programs have also shown that using typical averaging baseline calculation methodologies can lead to highly inaccurate estimates of demand reduction, greatly impacting the profitability of participating in certain DR programs (Li et al., 2021)

In 2019, Water Energy Innovations conducted a two-phase study for SCE, examining how the water sector can provide flexible DR and help with over-generation mitigation (Water Energy Innovations, 2019). Through case studies and interviews of several water utilities within the SCE territory, the water sector was shown to be a resource for flexible DR. The study asserted that the energy sector needed to transition the water sector's current role as a customer into a more expansive role of a reliability partner. This investigation further highlighted barriers to participation in DR programs and time-based rate structures, including diminished incentives as a result of demand charges and the limited ability of water utilities to participate in auto-DR, respond to short notifications, or follow prescriptive demand reductions because of the complexity of water systems.

Recently, Irvine Ranch Water District (IRWD), in partnership with SCE, also performed an investigative study to explore the financial incentives for the water sector to shift non-dispatchable, continuous energy use from on-peak to off-peak hours (IRWD, 2021). It used the construction of a recycled water storage reservoir to increase energy load shifting as a case study to examine current incentives and explore improvements to energy rate structure design. This study identified several areas where incentives could be improved to increase water-sector participation, including eliminating facility demand charges to increase energy use in off-peak time periods, allowing water utilities to participate in shorter time-frame DR events, and expanding SCE incentives for water utilities to build water storage facilities.

Both the 2019 SCE study and the 2021 IRWD study identified the need for the energy sector to work collaboratively with water utilities to improve current incentives or develop a water-sector-specific rate structure or DR program to expand the water sector's role as a reliability partner.

Barrier to Energy Demand Management

All approaches to generating recommendations for alternative operations for water distribution systems have leveraged hydraulic models or simulations as the primary mechanism for testing and validating recommendations. More generally, many approaches to resiliency planning to drive efficiency require the use of a well-calibrated distribution system hydraulic model that can accurately represent and simulate complex water system operations. Hydraulic models are powerful companions to integrate drought management activities, including but not limited to helping execute water storage/reservoir management, evaluating new operations in response to drought conditions, monitoring water usage, planning water source integration and connections, planning capital improvements and technology adoption, performing water quality analysis, and many water loss control activities. Further, hydraulic models are relevant to all water systems for various planning and operational means. It is becoming more common for utilities to invest in hydraulic models but the calibration phase is the costliest and most overlooked aspect. There currently exists a lack of consistent and complete industry standards and methods for calibration and construction of hydraulic models to ensure that the model matches the true conditions of a real system (Robinson et al., 2012). Without effective standards or guidance, most models will not be of good quality for the benefits listed above; therefore, this knowledge gap is a major barrier to advancing planning and operations for water system resiliency.

CHAPTER 3: Demand Management System Design

Design of WaterWatch Software

Managing and operating a water system comes with some unique challenges:

- Hydraulic modeling and the generation of reliable, safe recommendations for operating water systems require the management and manipulation of unstructured data from unrelated sources. This data can take the form of time-series records, geospatial information, modeling characteristics, and more.
- To maintain high security of critical utility asset information such as pump or valve locations, it is essential that all processing and data storage be performed locally without the use of a remote computing environment or managed servers.
- The manipulation and generation of the information in a timely manner requires high-performance analysis that efficiently uses all computing and storage resources available to the software without delay.

To accomplish these design goals, the CWEE developed the energy demand management software WaterWatch, with a multi-layered architecture employing hardware-level optimizations, robust support for asynchronous computing, and dozens of embedded features or libraries used in enterprise software. WaterWatch is a stand-alone application built to enable high-performance analytics on hydraulic models and other unstructured data in real time. WaterWatch has been intentionally developed to enable the extension or addition of features and applications in the future as interest arises.

Software Architecture

WaterWatch is a stand-alone application that builds and deploys on Windows 10 and 11 desktops, tablets, and laptops. The application is built as a series of components: the C++ Static Library, the C++ Dynamic Library, the C++/C# Windows Runtime, and the C# Windows Application. Each component ingests the previous component and leverages the completed features or modules throughout. Over the entire architecture, there are over 117,200 defined functions to support the application.

The C++ Static Library is the bottom-most component of WaterWatch and is where most data structure definitions, hardware-level optimizations, and Windows-specific features are located. This component is composed of approximately 153,000 lines of code. Specific features or modules implemented in this library include:

- Robust, Generalized Multi-threading Support
- Windows-Specific File System Management
    - Router/Server and Publisher/Subscriber Socket Tools
    - HTTPS and cURL Request Tools

    - Zip/Unzip File Tools
    - SQLite, MSSQL, and MySQL Database Query Tools
- Geocoding and Reverse Geocoding
- Hourly Historical Weather Streaming
- Real-Time Scripting Language
- Machine Learning and Neural Network Tools
- Generalized Optimization Tools
- Basic Data Containers and Data Structures
    - Lists, Maps, Tree Structures, Time-Series, Curves, Matrixes, etc.

The C++ Dynamic Library is the second component of WaterWatch, building off the Static Library's foundation and services. The Dynamic Library supports runtime activities specific to energy load shifting, hydraulic modeling, and interfacing with the Windows Application. This component is composed of approximately 45,000 lines of code. Specific features or modules implemented in this library include:

- Self-Contained Package of Python 3.7
- Self-Contained Package of EPANET 2.2
- Hydraulic Model Definitions and Simulation Tools
- Supervisory, Control, and Data Acquisition (SCADA) Tools
- Water System Billing Data Tools
- Dynamic Water System Control Logic Tools
    - Programmable Logic Controller (PLCs), Proportional, Integral, and Derivative (PID) Controls, Machine Learned Controls, etc.
- CEC's MIDAS Energy Rate Tools
- California ISO Wholesale Energy Rate Tools
- Hydraulic Model Optimization Tools
- Statewide Energy Grid Modeling Tools
- Measurement and Verification Tool

The C++/C# Windows Runtime is the third component of WaterWatch, consuming the C++ Dynamic Library and converting select features, originally written in C++, to be fully callable from C#. This component bridges the difficult gap between the two programming environments and allows for the high-performance C++ code to be leveraged directly in the Windows Application. This component is composed of approximately 2,000 lines of code.

Finally, the C# Windows Application is the last component of WaterWatch; it consumes the C++/C# Windows Runtime as well as the C++ Dynamic Library to visualize and perform all the functions and features in the energy demand management software. The application is written within Microsoft's Universal Windows Platform, so that it may automatically deploy to Windows 10 or 11 environments, using the default installers and deployment tools, and so that it can be safely deployed behind firewalls in accordance with Microsoft's standards and requirements. This component is composed of approximately 23,000 lines of code and contains over 20 highly interactive screens or pages, allowing the user to explore their hydraulic model, perform energy load shifting, and more.

Time-Series Data Management

Time-series data in the WaterWatch data engine are uniquely handled to support a large number of observations efficiently in-memory while providing interpolation, extrapolation, and compression services.

Data Interpolation and Extrapolation

All time-series datasets in WaterWatch are characterized by a method of interpolation that allows the engine to evaluate the expected value at a date and time where a measurement does not currently exist. Four methods of interpolation are supported: 1) Linear, 2) Left Snap, 3) Right Snap, and 4) Spline. Linear performs a distance-weighted blend between the two nearest values, while the two snapping approaches return the associated value immediately to the left or right of the requested date and time. The spline approach uses a generalized Catmull-Rom spline algorithm to smoothly transition the previous two and the upcoming two measurements, such that the resulting curve is continuous in velocity and acceleration.

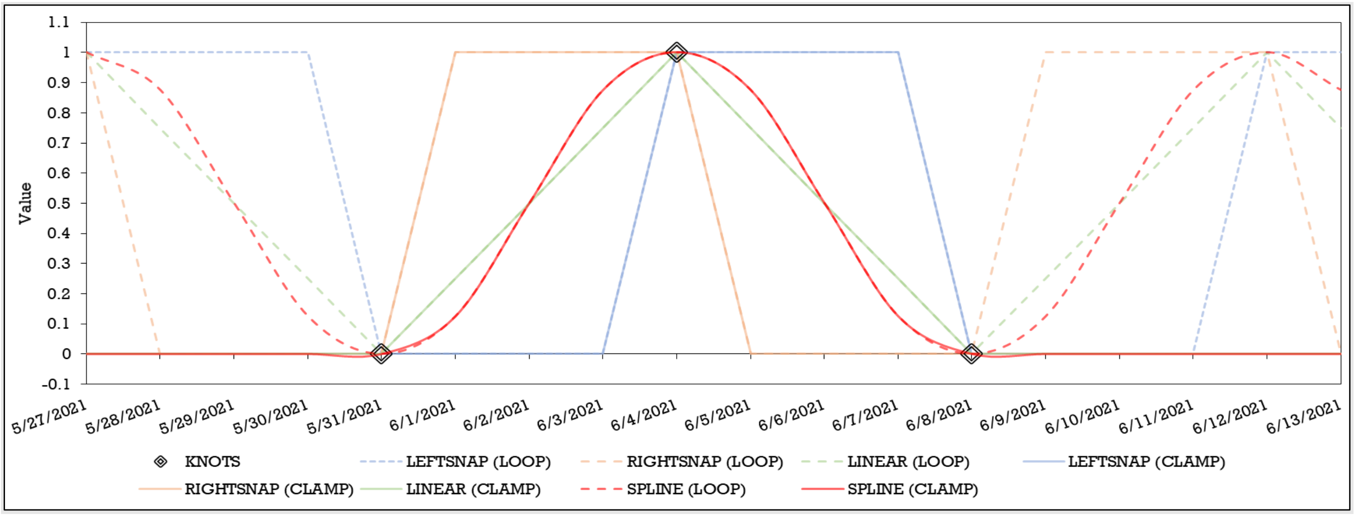
Additionally, all time-series data in WaterWatch are characterized by their boundaries, or how the data extrapolate beyond the first or last observations. Boundaries include 1) Loop, which identifies the data as intending to extend beyond the first or last value, and 2) Clamp, which assumes the first and last value extend infinitely forward and backward, respectively.

Using these features, WaterWatch may query a measurement at any date or time, using the strategy selected by the boundary and interpolation methods. There is a guarantee that sampling at an original observation's time will return the exact, original value.

Figure 1 illustrates how WaterWatch produces a resulting time-series figure dynamically from three measurements, depending on the selected interpolation and boundary characteristics. This approach is critical to allowing WaterWatch to handle data from a variety of sources, including:

- *Snap-Left* and *Clamp* characteristics are typically used with SCADA measurements, such as retrieving the last valid or known position of a pump or valve.
- *Snap-Right* and *Loop* characteristics are typically used with water customer monthly bills, allowing the engine to back-calculate the water usage for a household using the water bill observed at the end of the month.
- *Linear* and *Clamp* characteristics are typically used with simulation results such as reservoir levels, pipe flows, and hydraulic head.

Figure 1: Time-Series Data Interpolation and Extrapolation Examples



An illustration of how WaterWatch generates data on reconstruction using the selected interpolation and extrapolation characteristics.

Source: EPRI, 2021

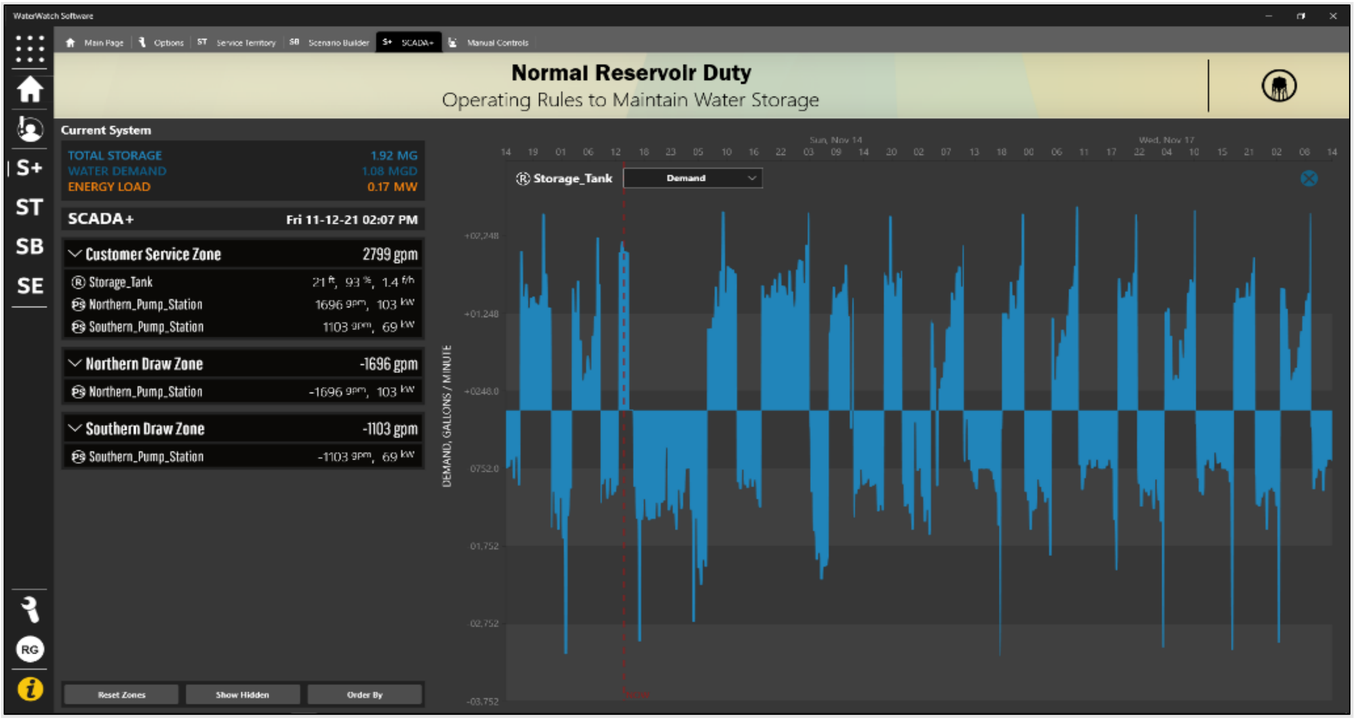
Data Compression through Idealized Interpolation

By designing the time-series tools to require that stored observations be retrieved through the interpolation and boundary modes, it becomes evident that not all observations are necessary to generate identical results. Specifically, in the circumstance that five observations in a row fit a straight line, then the middle value can be safely removed without changing the results with any combination of characteristics. WaterWatch automatically employs this logic on all time-series data and it has been demonstrated to significantly reduce the number of observations for data in the water sector, including pipe flows, pump and valve status, and even water customer advanced metering infrastructure data.

Data Extrapolation Through Machine Learning

WaterWatch supports automated machine learning of all time-series data using a support vector regression machine learning algorithm. This algorithm attempts to associate the year, season, month, day of the week, and hour of the day for all observations within a dataset to generate a predictive tool that can generate novel data outside the boundaries of the original dataset. In WaterWatch, if any time-series boundary is set to Loop and a machine-learned result is available, the engine attempts to use the machine-learned parameters to estimate the requested value instead (Figure 2). In particular, this approach is used extensively with weather and GHG emission data and water customer usage data, and for extending simulation results when the hydraulic simulation has not yet completed.

Figure 2: Time-Series Data in WaterWatch



A screenshot of WaterWatch using the time-series tooling to generate high-resolution figures with no data loss.

Source: Good, 2021

Interface with Hydraulic Modeling

Generating safe recommendations for energy load shifting requires that the recommendations are examined through a complete hydraulic simulation of the water system, to give operators the opportunity to evaluate changes to the water storage, customer pressures, operating costs, and more. Most commercially available hydraulic modeling tools leverage a modified version of the EPANET 2.0 or EPANET 2.2 hydraulic modeling codebase and support exportation of their internal formats to the generalized EPANET format for interoperations and data sharing.

WaterWatch adopts this industry practice and expects the user, for energy load shifting purposes, to have already developed and provided a calibrated EPANET-based hydraulic model for importation into the engine using the custom definitions and data structures within WaterWatch. When WaterWatch performs a hydraulic simulation, a new EPANET hydraulic model is constructed in-memory and simulated using a customized version of the EPANET codebase. The main contribution or change that WaterWatch makes to the EPANET hydraulic simulation is the ability for arbitrary logic, such as human-machine interfaces or machine learning, to generate control changes in the simulation in real-time without knowing the control logic ahead of time.

Hydraulic Model Components

Water distribution systems have been virtually represented by commercial and open-source modeling software for several decades, with most software sharing hydraulic definitions with the EPANET hydraulic modeling engine (Rossman, 2000). From the hydraulic modeling standards, the following types of data sources can be represented:

- **Junctions.** These can represent one to many water customer meter connections and are the location of "water demand" for the purposes of all hydraulic calculations. Junctions are often connected to by pipes, pumps, or valves to represent a collection of customers.
- **Reservoirs.** These represent water storage as well as water sources for all calculations. Reservoirs tagged in WaterWatch as "terminal storage" indicate a boundary condition for the operation of a water system and are considered to be an infinite source of water in the hydraulic modeling community. Reservoirs not tagged as "terminal storage," often referred to as tanks in hydraulic models, may receive or supply water from a limited volume to meet the needs of the water customers. Reservoirs may be connected to pipes, pumps, or valves.
- **Pipes.** These represent closed water pipes that transport water without interruption from one end to another. Complex pipes (such as T-fittings) are often represented by multiple pipes with one or several junctions between them. Pipes have one start and one end, which must be either a junction or a reservoir. Pipes can be controlled by logic to open or close based on water system operations.
- **Pumps.** These represent water pumps that move water from upstream to downstream. Pumps have one start and one end, which must be either a junction or a reservoir. Pumps have a large variety of parameters to specify their operation and performance. They can be controlled by logic to open or close based on water system operations.
- **Valves.** These represent hydraulic equipment such as remote-controlled plug valves and pressure sustaining valves. Valves have one start and one end, which must be either a junction or a reservoir. Valves have a large variety of parameters to specify their operation and performance. They can be controlled by logic to fully or partially open and close based on water system operations.

Additionally, WaterWatch introduced two new types of data sources that can be represented:

- **District Metered Areas.** These represent collections of junctions, reservoirs, pipes, pumps, and valves that are hydraulically isolated from other district metered areas (DMAs). Small water systems are often defined by less than a dozen DMAs, while larger water systems may have a hundred DMAs. Any asset related to a DMA is classified by its hydraulic relationship to the zone: those whose flow is entirely within the DMA, whose flow exits the DMA, or whose flow enters the DMA.
- **Pump Stations.** These represent collections of pumps under the same energy cost system and with the same upstream, indirect carbon intensity of energy use. Pump stations are declared with one upstream DMA and one downstream DMA.

The presence of DMAs and pump stations enables WaterWatch to present results and recommendations in the same context as how water system operators already view their system.

Arbitrary Hydraulic Modeling Controls

Water distribution and collection systems (water systems) of cities, townships, and municipalities are obligated to serve their communities by providing customers with safe drinking water at all times and in all circumstances. To accomplish this requires the operational staff of the water systems to balance operating set points, such as water purchasing and pump flows, with water storage limitations, while simultaneously accounting for maintenance schedules, pipe breaks, and water quality, among other concerns. Such decisions are frequently made dynamically by human operators based on their experience and professional judgement to meet time-sensitive operational requirements. Operational set points for assets of hydraulic models of water distribution or collection systems are defined to include any property or assets that may change automatically through remote control or intermittently with human interaction, such as, but not limited to, pump status, valve settings, energy prices, and water purchases.

Civil engineers have often employed hydraulic modeling solutions to simulate and predict hydraulic conditions based upon a hydraulic model of the water system. A hydraulic model will typically include a plurality of assets (for example, pipes, pumps, valves, storage tanks) that represent the range of operational decisions and concerns experienced by the water system. A hydraulic solver, for example, the EPANET Solver available from the United States Environmental Protection Agency, Washington D.C., may be employed to simulate a hydraulic model to predict flows, hydraulic pressures, and other conditions. A hydraulic solver typically solves a series of mathematical matrices descriptive of the model for various qualities given certain supplied conditions. Such matrices would be solved in succession by the model while obeying pre-defined control logic, typically in the form of IF-THEN-ELSE logical statements. Following simulation, hydraulic models can produce the observed set points for assets, thereby producing recommendations for civil engineers or water system operation staff for how the hydraulic model would have operated the system under ideal conditions.

Wu et al. (2008) (Patent Number: US-8265911-B1) provided an improvement on the traditional IF-THEN-ELSE approach by incorporating the use of variable speed pumps and enabling complex controllers to react to the hydraulic model forecasts mid-simulation. This advancement, however, still relied on executing a single pre-determined controller for each characteristic of their variable speed drive pumps and did not address the need for real-time human overrides, interaction with machine learning controllers, or have the ability to integrate the results from multiple controllers simultaneously.

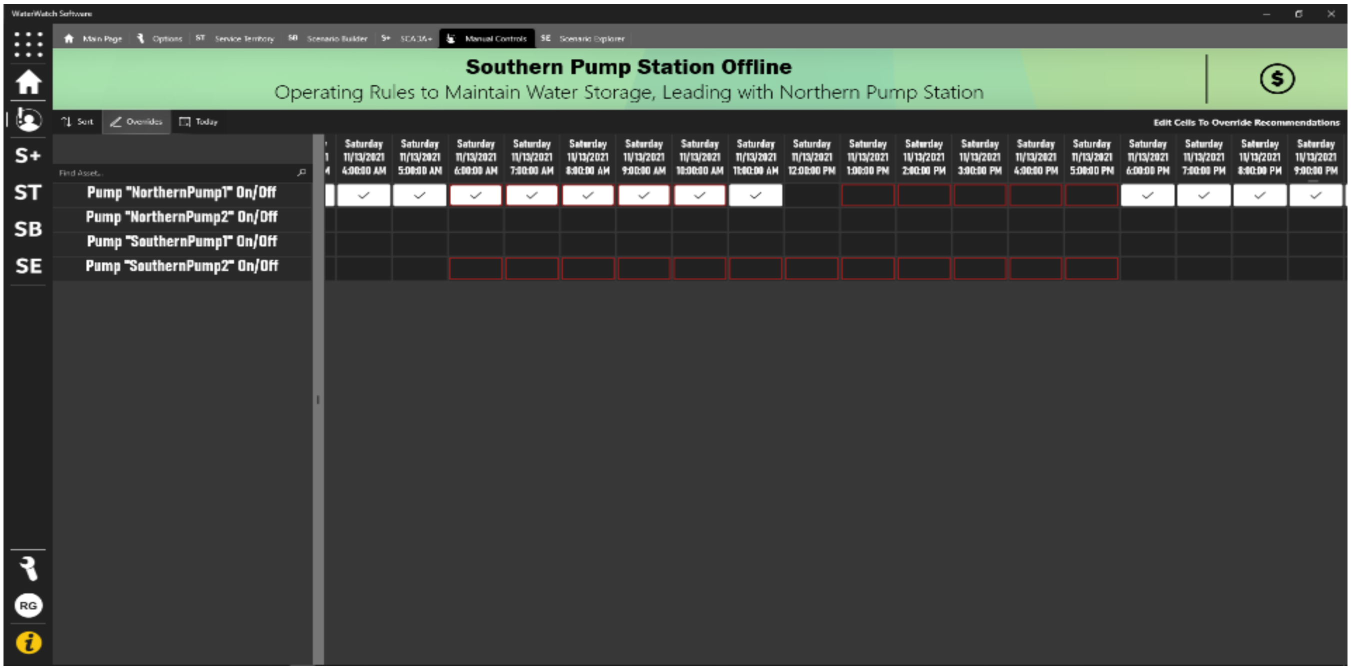
As a result of traditional hydraulic models' inability to incorporate dynamic, unprogrammable logic into the simulations, to date, water system operations have relied on heavy automation, wherein the output of the hydraulic model is deployed directly. This approach, however, has not successfully saturated the water system market, in large part due to the inflexibility of the design in unforeseen conditions such as maintenance, pipe breaks, and high energy prices. To address this gap, a new approach was developed for WaterWatch, which allows for the evaluation of complex operational set points within hydraulic models while incorporating dynamic, unpredictable control logic within a hydraulic simulation.

WaterWatch introduces an enhanced asset control technique that may be employed by a hydraulic solver of a hydraulic modeling and simulation application to calculate the set point for any asset while incorporating dynamic operational logic from external sources such as human water system operators. This technique toward enhanced asset control enables analysis of a variety of more challenging and dynamic control configurations that are required to support all real-world use cases. For instance, the enhanced asset control technique employed within WaterWatch:

- Enables modeled pumps and valves, which were operating to classic IF-THEN-ELSE logical statements, to dynamically incorporate a series of historical and real-time overrides from an external source. The enhanced asset control technique reconstructs dynamic overrides at any requested moment in time by interpolating between bounding override instances.
- Enables a hydraulic solver to detect a change to the operational logic and rapidly retarget evaluation, such that the hydraulic simulation immediately incorporates the new operational logic. The enhanced asset control technique intuitively detects whether the active hydraulic simulation would disobey a new, dynamic operational logic and, if so, restarts the simulation at a new time to accommodate the incoming logic.
- Enables any independent machine learning algorithm to generate unpredictable, dynamic recommendations for the flow through a modeled valve. The enhanced asset control technique is not dependent on the underlying source of the base asset control logic. This demonstrates that the technique can be employed with a hydraulic solver connected to third-party or external tools such as a machine learning algorithm.
- Enables a proportional, integrative, derivative (PID) controller to generate dynamic recommendations for the purchase of water from a water service inter-tie within the hydraulic solver. This demonstrates the enhanced asset control technique supporting self-correcting control logic at any time scale through detection of changes to the generated set point from the active set point within the hydraulic solver.
- Enables an external source, such as a human operator, to override the recommendations from a machine learning algorithm for all modeled pumps because of an upcoming, unforeseen power shutoff notice from the energy supplier of the water system. Such configurations demonstrate the enhanced asset control technique supporting temporary or unique changes to the control of the modeled assets, which are not expected to ever repeat at the same time, day, or frequency. Figure 3 demonstrates how, in WaterWatch, operators experience an intuitive interface for leveraging these enhanced controls to review or override recommendations in real time.

In this manner, the enhanced asset control technique enables calculation of set points for modeled water system assets in a hydraulic model under a wide range of more challenging real-world modeling configurations, which have not been adequately addressed by prior techniques or approaches.

Figure 3: Human-Machine Interface for Control Overrides



A screenshot of WaterWatch being used for overriding the recommended controls for two pumps. Overrides are highlighted in red, recommended pump runs are shaded white.

Source: Good, 2021

Data Streaming and External Data Sources

Several data services and streaming solutions were necessary to allow water systems located throughout California to use WaterWatch and access the most relevant, local, and up-to-date information available. These services include accessing weather data, SCADA measurements, water customer billing data, energy tariffs, wholesale energy market data, and forward- or reverse-geocoding.

Weather Streaming

Hourly historical weather data for any global location is queried dynamically from the National Oceanic and Atmospheric Administration (NOAA) hourly and sub-hourly observational dataset, typically covering from 1970 to the current month. Forecasted weather data for the upcoming five days are streamed using the OpenWeatherMap application programming interface (API). WaterWatch uses the longitudes and latitudes of the hydraulic model to estimate the location of the water system for all weather streaming services.

Utility Data Streaming

SCADA data represent the collection of all sensor and remote measurements that a utility may collect from its pumps, reservoirs, valves, and customer meters. WaterWatch supports generalized data streaming using the standard structured query language (SQL) from most SQL vendors, including MySQL, Microsoft SQL Server, SQLite, and the open database connectivity formats. Leveraging the automatic data compression features from the time-series tools, WaterWatch has demonstrated the ability to hold all SCADA and other utility measurements in-memory by exploiting the repetition in measurements typically seen from sensors in the water sector.

Energy Tariff Price Streaming

WaterWatch enables users to select the energy rate to apply to each pump station in the hydraulic model. While a small number of energy rates are included by default for offline analysis, most energy rates are acquired through streamed data access from the CEC Market Informed Demand Automation Server (MIDAS) and the California ISO Open Access Same-time Information System (OASIS).

The CEC MIDAS hosts a list of energy price tariffs available to commercial, industrial, and residential customers maintained by the energy service providers. Energy tariffs hosted through MIDAS define the data-time ranges and coefficients used to evaluate the consumption and demand charges of energy price tariffs. WaterWatch evaluates these rules for each hour of any simulation to identify the appropriate energy tariff charge components.

In contrast, the California ISO wholesale energy market does not use demand charges but instead uses a marketplace to determine the consumption price of electricity at day-ahead, hour-ahead, and nearly real-time intervals. WaterWatch streams the historical and day-ahead energy prices from the wholesale market as an additional, built-in energy tariff that a user can select for load shifting or program evaluation purposes.

Real-time Emission Intensity Streaming

The dynamic nature of variable energy resources on the energy market indicates that the emission intensity, or the amount of carbon emissions associated with each unit of energy generated, may dramatically change based on the time of the day as well as market conditions and the weather. To account for this, WaterWatch streams the estimated hourly emission intensity of the three major IOUs from the California Self-Generation Incentive Program (SGIP) greenhouse gas signal API.

Geocoding and Reverse Geocoding

Geocoding is the process of estimating the global coordinates of a street address, whereas reverse geocoding estimates the nearest street address of the given global coordinates. WaterWatch leverages geocoding for geolocating water customer billing information as well as identifying the initial location of a water system from its servicing city and state. This is performed using the API of Nominatim, the data service behind the popular OpenStreetMap mapping tools. When multiple valid addresses are returned from reverse geocoding, the address that most closely matches the input address is selected.

Multi-threaded Optimizations

The optimal management of controls within large-scale water distribution systems is a long-standing problem inside the field of hydraulic engineering (Sterling and Coulbeck, 1975). Optimally controlling pumps has been demonstrated to have large impacts on overall costs, energy use, and environmental impact of a water system (Makaremi et al., 2017). However, given variable water demands, interdependent system elements, and differing energy costs, it can be difficult to determine optimized pump controls to improve system performance (Mala-Jetmarova et al., 2017). This report presents the design of a new, efficient multi-threaded simulation optimization software platform for determining pump operating policies to improve the energy usage of a water distribution network (WDN).

WDN operators develop pump operating policies to match observed water demand while maintaining water storage levels required for system resiliency (Klise et al., 2015). This decision requires integrating implicit or explicit forecasts of customer water demand with operator intuition to design pump and valve management strategies. Operators determine pump operating policies, usually in the form of conditional rules, which turn pumps "on" or "off" or assign pumps a high or low setting based on water storage levels or the time of day. To model scenarios, engineers may use hydraulic simulation software to observe the impact of a given pump operation policy on the system's energy usage or hydraulic performance.

This report expands on previous research into pump schedule optimization within WDNs (Kang, 2014; Bonvin et al., 2021; Fantozzi et al., 2014). Typically, optimization models have focused on finding optimal pump settings defined across specific time periods to minimize the operational cost or energy consumption of a WDN (Mala-Jetmarova et al., 2017). Methods have included linear programming (Jowitt and Germanopoulos, 1992), non-linear and dynamic programming (Ormsbee and Reddy, 1995), and simulated annealing (Goldman and Mays, 2004), among others. Recent contributions to WDN optimization have expanded the available methodology to Bayesian optimization and random forests with decision trees to model correct pump settings (Candelieri et al., 2018).

Some research has leveraged optimization approaches to select optimal rule-based pump controls dependent on system parameters such as flow, pressure, and tank levels, to develop pump control strategies more resilient to uncertain demands (Mala-Jetmarova et al., 2017; Van Zyl et al., 2004). Researchers have used genetic algorithms to determine pump controls at WDNs based on fixed tank level triggers (Paschke et al., 2001) as well as variable tank level triggers where the control condition changes over time (Quintiliani and Creaco, 2019; Van Zyl et al., 2004). Later work has explored using a genetic algorithm for optimizing multiple layers of rules, which incorporate both system conditions and time-based conditions (Marchi et al., 2017; Blinco et al., 2016). Typically, these studies have limited their optimization methods to genetic algorithms. Additionally, optimization approaches may struggle with high-dimensional decision spaces in large-scale WDNs that contain many interacting pumps.

To address these computational challenges, which arise from determining pump operating policies in large, complex WDNs, this report introduces the design of a new multi-threaded optimization platform for the exploration of the optimal operation policy of pumps. In the platform, different simulation optimization approaches are combined with a domain division (a "divide-and-conquer" scheme) to break the larger optimization problem into sub-problems that prioritize optimizing interconnected pumps sequentially. The platform uses several global search methods formatted to a multi-threaded system to run hydraulic simulations in parallel, to maximize computational resources available to a user in a server or single-user environment. As a case study, this report explores the application of the platform to a hydraulic model of a single region of a real WDN. Results for each global search method are examined and opportunities to improve the discovery of optimal decision points for practical pump operations are discussed.

A multi-threaded simulation optimization platform was programmed in C++ to explore pump operating policies while performing EPANET simulations. The platform included several alternative derivative-free global optimization methods that can be applied to the hydraulic simulation results. The platform also allowed the user to specify a "divide-and-conquer" domain division scheme to improve the optimization efficiency for high dimensional decision spaces (X) where decomposing the system into smaller optimization problems may improve the computational efficiency of the optimization. The platform was designed to leverage multi-threading to run simulations and optimization algorithms in parallel to maximize performance with modern hardware on servers or individual computers (see Figure 4).

Figure 4: Optimization Framework with Multi-threading Design

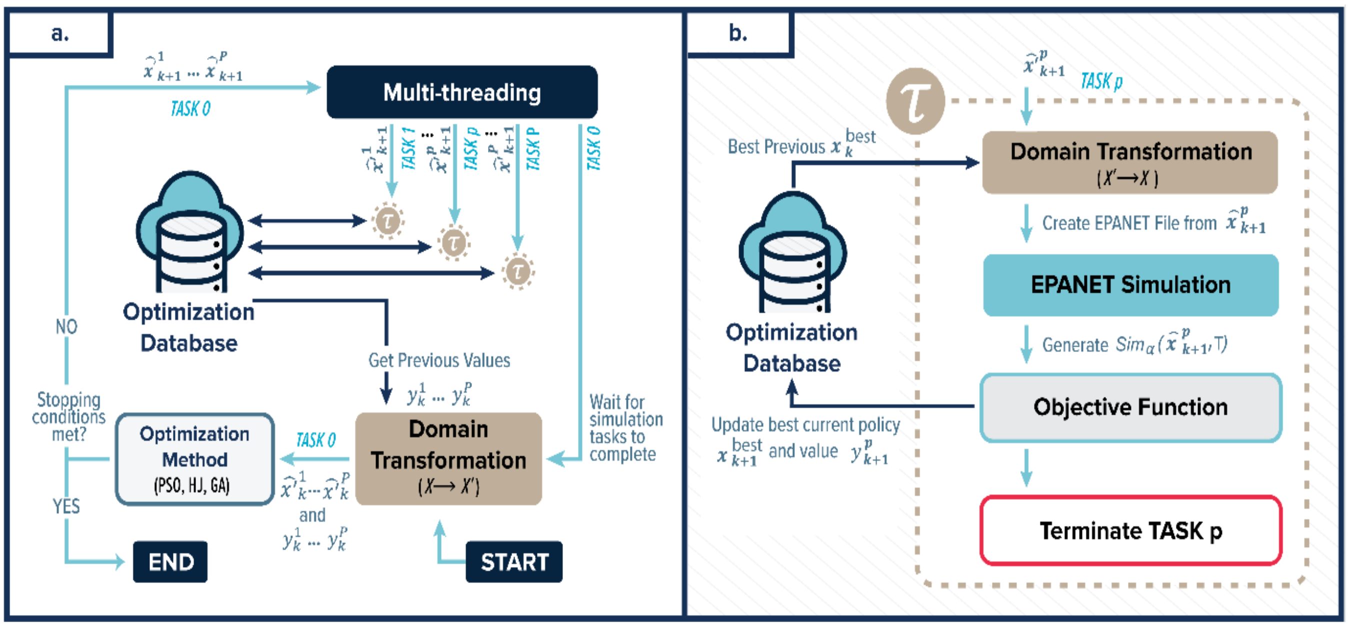


Figure 4A shows the platform first transforming the domain (domain division), point sampling via the optimization methods, and the beginning of the multi-threaded component of the platform. Figure 4B shows the activity inside a single thread, first performing a domain transformation by combining the sampled point with the best previously sampled point, running the simulation, and then computing the objective value before terminating the thread.

Source: Linz et al., 2020

Throughout the optimization, the platform maintains a central data repository, the "optimization database" that houses policy vectors, hydraulic simulation results, and other intermediate results required to perform the optimization and which is safely accessible to all parallelized tasks simultaneously using mutual exclusion (mutexes) for each data collection within the database. At a given iteration k, the optimization process decomposes the problem to search on a smaller domain X'. Using the previous policies $({x'_k}^1 \ldots {x'_k}^P)$ and previous objective values $({y'_k}^1 \ldots {y'_k}^P)$, a selected optimization algorithm generates a batch of a given population of sampled policies (P) new policy inputs, $({x'_{k+1}}^1 \ldots {x'_{k+1}}^P)$. For each policy (P), a task (τ_p) is submitted into a multi-threaded queue to perform the hydraulic simulation. Then, on each thread, a domain transformation $X' \ to \ X$ is performed by combining the partial policy $({x'_{k+1}}^{P})$ with the best current policy to form a full policy $({x_{k+1}}^{P})$. Each full policy is used to write the controls for an EPANET simulation, which runs on the thread τ_p to generate a set of hydraulic values $(Sim_{\alpha}({x_{k+1}}^{P}, T))$. Finally, the objective values are computed from the hydraulic values, and then the objective values $({y'_{k+1}}^{1} \dots {y'_{k+1}}^{P})$ are updated to the optimization database for the next iteration, and the threaded task τ_p terminates. Optimization iterations continue until the maximum number of function evaluations are exceeded or the performance does not improve over a given number of iterations.

Three common optimization algorithms were implemented in the platform, and they performed the domain transformations, batching, and policy computations, including particle swarm optimization (Kennedy and Eberhart, 1995), Hooke-Jeeves pattern search (Hooke and Jeeves, 1961), and a simple genetic algorithm (Eiben et al., 1994). The format of each method is briefly discussed, along with modifications used inside the simulation optimization platform to make the algorithms compatible with the multi-threaded design.

Particle swarm optimization is a popular population-based search algorithm that searches a domain based on moving a set of sampled policies (particles P). Each particle's movement is characterized as a proportion (ω) of a random velocity and bias (φ_1) toward the best policy observed by a single particle and a bias (φ_2) toward the best policy observed by the entire system of particles. To enable batching of the simulation optimization tasks, at the start of every iteration all potential moves are determined simultaneously with updated values and used to generate the numerous simulation optimization tasks.

The Hooke-Jeeves pattern search optimization method is a common pattern-search algorithm where new solutions are located by moving a starting policy in a random direction within a given domain with a fixed step size (δ). After a direction no longer improves the objective function observed, the algorithm selects a new random direction and moves with a step size reduced by a ratio (ρ) until the objective function no longer improves. The method was formatted to increase its efficiency by the inclusion of multiple starting points (P). Additionally, each non-improving point checks only one random direction before attempting to move. The algorithm batches one new policy for each point, which represents either an improving direction or a test direction. Particle locations are updated at the beginning of each iteration and individually batched as tasks for computation.

Lastly, the basic genetic algorithm focuses on an evolutionary approach to exploring new potential policies, based on the recombination and variation of already discovered policies with promising objective values. Starting with a P, a designated number of well-performing "elites" are copied over to the next batch (C_{elite}), and the best points from the current population are then recombined randomly to create a proportion (ρ recombine) of the new potential policies for the next iteration. Finally, the remaining percentage of poorly performing policies are "mutated" by re-selecting them uniformly across the bounds of the domain. After recombination and mutation, updated policies are batched and run on multiple threads.

WDN operators and engineers seeking to improve pump operations themselves typically explore pump or pump station controls one at a time or based on geographic or network grouping. Improvements are often iterative, starting from an initial, trusted set of pump controls and changing certain thresholds to measure the overall impact on the system performance. Since pumps at different locations may have independent operation, optimizing geographically distinct or hydraulically distant pump groups may more efficiently determine promising pump control policies. Incorporating the concept of this approach, the platform allows users to specify a "divide-and-conquer" scheme, dividing the optimization problem into sub-problems. In each sub-problem, the optimization focuses on limited pump variables while keeping the remaining variables set at the best currently known values. The division creates a new search space ($X' \subset X$) as a subset of the total domain and can potentially reform an intractable high-dimension optimization problem into a series of easier-to-solve lower-dimension sub-problems.

Altogether, the simulation optimization platform provides a variety of options for exploring optimal pump settings. First, the platform uses three provided simulation optimization methods. Second, the platform offers the option of a "divide-and-conquer" scheme to separate a larger pump control problem into a series of smaller pump control problems. Based on each one of these selections, a variety of different optimization approaches are available to a user. To illustrate the available methods for pump policy determination, the report explores a case study and compares the relative efficiency of the various methods for determining energy-efficient pump policy recommendations.

Real-time Scripting Engine

Due to much of the data in WaterWatch being accessible only after reconstruction, which was necessary to facilitate low memory usage on tablets and laptops, it became a requirement to support real-time programming or scripting so that users could access and manipulate the data within WaterWatch while the software was active and running. This feature required supporting a generalized programming language that could also access functions and methods defined within the original C++ codebase. To accomplish this, the scripting language Chaiscript was embedded into WaterWatch. The scripting language was updated to support interfacing with the original functions and data types of WaterWatch, as well as to enable dynamic, real-time visualizations of arbitrary data types, including text, numbers, lists, maps, and time-series data. Connecting Chaiscript to the data structures of WaterWatch enabled the user to explore and modify the underlying, unstructured data that composed the water system's hydraulic model, SCADA, billing, and other information that traditionally would be disconnected or accessible through a myriad of specialized tools without generalized access to one another's data.

This feature was used extensively to perform the measurement and verification of this project, by enabling the project team to access all underlying data from the software during and after piloting. Access to the underlying data structure empowered the project team to identify the exact actions taken during the pilot and to extract or generate any data from any period necessary from the WaterWatch application.

CHAPTER 4: Statewide Energy Grid Model Analysis

Summary

To estimate the broader potential impact of water distribution systems like MNWD adopting a DMS and participating in dynamic load shifting, CWEE simulated water demands and load shifting of 702 public water distribution systems in California. CWEE simulated the water demand, pumping, and energy demands of the water distribution systems in California under nine different energy pricing and emissions-minimization scenarios. This simulation found that the potable water distribution sector accounts for 1.2 percent of the total electricity used in California and has the flexibility to shift its energy demands by up to 1071 gigawatt-hours (GWh) annually, to reduce curtailment in California by up to 68 percent, to reduce its contribution to peak net demand by up to 321 megawatts (MW), and to avoid 330,627 $MTCO_2e$ of emissions. The scenarios that led to the greatest load shifting and emissions reductions included time-of-use energy rates that incentivize consumption during the middle of the day, whereas scenarios with demand charges prevented load-shifting and resulted in flat energy consumption profiles throughout the day. The findings of this work highlight not only the potential of the water sector to help meet future energy and emissions goals but also how the energy sector can best incentivize this shift.

The entirety of the research reported in this chapter can be found in a forthcoming publication:

Rupiper, A., R. Good, G. Miller, and F. Loge. 2024. "Mitigating renewables curtailment and carbon emissions in California through water sector demand flexibility." *Journal of Cleaner Production*, 437, 140373. Available at https://doi.org/10.1016/j.jclepro.2023.140373.

Background

The ongoing transition from historically fossil-fuel-powered electric grids toward increased integration of renewable and low carbon energy sources has created new challenges for electric grid operation (Denholm and Hand, 2011). Some renewable energy sources are variable and intermittent, resulting in potential misalignment between the timing of renewable energy generation and electricity demand. The largest share of renewable electricity in California, solar energy, is available during the day and typically dissipates before peak energy demand around 7:00 p.m. The addition of more renewable energy sources each year has increased the frequency of occasions where anticipated generation exceeds the demand for electricity at that same time, resulting in oversupply. To prevent over-generation, excess energy is frequently curtailed by reducing output to match demand (U.S. EIA, 2021). In 2020, California curtailed more than 1,500 GWh of solar and wind generation due to projected supply exceeding demand (CAISO, 2021a). Increased deployment of renewable energy is likely to exacerbate this problem, resulting in wasted opportunities for grid decarbonization.

In order to minimize curtailment of renewable energy resources, multiple solutions have been proposed, including storing energy that would otherwise have been curtailed, and DR, which shifts demand to use renewable resources when they are available. One form of DR, load shifting, moves the energy load to alternate time periods and has emerged as a method to increase grid reliability and assimilation of renewable resources (Park et al., 2019; Wimmler et al., 2017). The water conveyance and distribution sector, excluding end uses, uses approximately 7.7 percent of the total energy supplied in California (GEI Consultants and Navigant Consulting, 2010). Mobilizing the water sector to influence statewide energy consumption may involve the implementation of different methodologies, such as shifting water distribution and storage pumping to times when renewable energy is prevalent on the grid.

Despite the promise of the water sector acting as a load shift resource, there have not yet been any attempts to quantify the scale of this opportunity in California (Park et al., 2019). This study, by using a mass-balance model of water distribution system operations, paired with a pump scheduling algorithm, seeks to estimate the statewide potential for load shifting resources from California's water distribution systems under different goals and pricing scenarios. The objective of this research is to estimate how much energy demand flexibility is realistically available from California's water distribution system, determine the impacts of this flexibility on grid emissions and renewable integration, and identify how the electricity sector could most effectively incentivize beneficial load shifting through its rate structures.

Water distribution systems are responsible for reliably delivering safe water to end users at an adequate pressure, accomplished through a combination of pumps, storage reservoirs, and gravity. Like an electrical system, supply and demand must always be balanced to maintain system pressure. Closed pressure zones, which do not contain any water storage, may require variable speed pumps that ramp their flows up and down to match the real-time water demands in that zone. Pumping too little water will drop the pressure, and pumping too much can over-pressurize the system, leading to damage. For this reason, many parts of a water system are in open pressure zones, which contain storage facilities. In these open zones, pumping water at a rate greater than demand fills the water reservoir. Turning pumps off or operating below demand causes the water storage tanks to drain and provide pressure to the system. From the standpoint of the flexibility of pump energy timing, closed pressure zones have no flexibility; the only way to modify the load shape of these pumps would be to modify the timing of when end users consume water. In open pressure zones, the primary factor that determines flexibility is the amount of water storage available relative to water demand and pumping capacity. With enough storage volume, pumps could be run to fill the reservoirs at one time of day and turned off at another time of day to meet demand using the water retained in the storage reservoirs.

How well the flexibility within the water sector aligns with the needs of the electric grid depends on the electric rate structure. Electricity can be the single largest operating cost of a water distribution system, and pumps will be operated to minimize these costs to the extent that they are still able to reliably supply safe water. Electric rates are often made up of two primary factors: a consumption charge (per kWh), and a demand charge for peak consumption interval (per kW). Consumption charges account for the actual energy used and demand charges account for the generation capacity required to meet the peak demands of the system (Sherwood et al., 2016). High demand charges may encourage utilities to pump at constant rates to keep any one moment of demand at a minimum. TOU consumption charges, with variable pricing dependent on the time of the day, may encourage water utilities to shift the time at which they consume energy, to take advantage of low energy prices or avoid high costs at a different time (Faruqui and Sergici, 2013). Many electric utilities offer several different rate structures for a consumer to select from, which may be comprised of different types of demand and consumption rates.

Design of Energy Grid Model

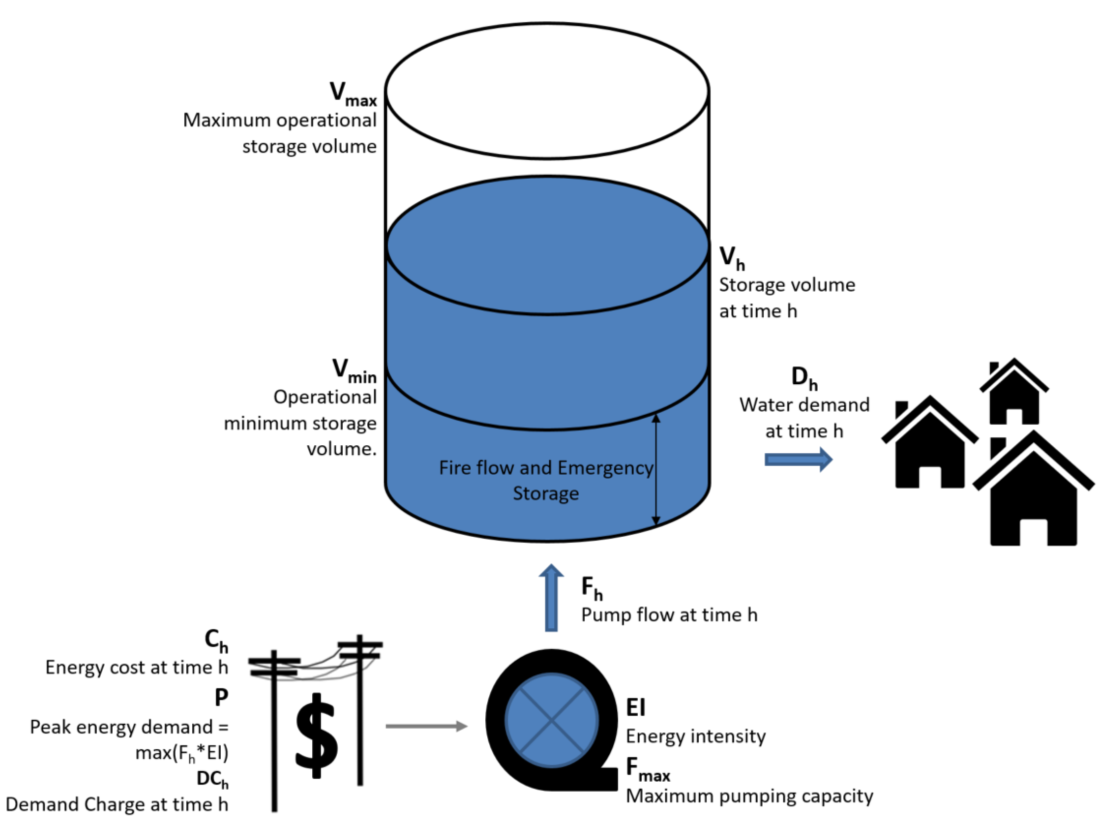
This study models 702 individual agencies serving potable water throughout California that are responsible for water quality, storage, and pressurization of water distribution systems. Simplified hydraulic models were created for each individual utility based on publicly reported data and assumptions from literature. The model was optimized for each agency, to determine the ideal water pumping strategies for several scenarios and were aggregated to the statewide scale to demonstrate the flexibility of the water sector to shift demand in response to pricing signals and aid in achieving statewide load shifting and GHG emission reduction goals.

Representation of Water Distribution Systems

Typical hydraulic models are used to represent detailed water distribution systems, including pipe networks, pressure zones, storage facilities, pumping stations, and demand nodes. These models can predict hydraulic operation of a water system, including pressures, energy consumption, pumping rates, and hydraulic head throughout the modeled region (Robinson et al., 2012). In order to represent the potable water distribution systems of all utilities throughout California, it was necessary to make assumptions and simplifications to traditional hydraulic models. These assumptions include 1) representing water demand and distribution by a single demand center and single pressure zone, 2) representing water storage by a single aggregated tank volume within the same pressure zone, 3) ignoring pipe networks, and 4) representing pumping by a single aggregated pump station that can operate at variable or continuous speeds.

The simplified model for each utility is shown in Figure 5, which highlights the primary components of the model as well as the static characteristics applied to each component, such as total storage volume (V_{max}) and maximum pump rate (F_{max}). These characteristics were estimated for each utility using data such as individual utility water sales and water storage data extracted from multiple years of California electronic annual reports (SWRCB, 2018).

Figure 5: Components of Simplified Utility Model



Components of a simplified single utility model with a single water demand, energy demand, and pumping and storage capacity.

Source: Rupiper et al., 2024

The model was used to conduct a mass balance on the water within the storage tank, such that volume in the tank at any time increment was equal to the volume at the last time increment (V_{h-1}) minus the water used to meet demand (D_h) plus the water pumped in (F_h), as shown in Equation 1. A pump scheduling algorithm was used to optimize the system, such that costs were minimized, considering variable energy prices throughout the day and different pricing schemes. The algorithm allowed for changes in pump timing and rate to minimize the cost while constraining the solutions to satisfy the mass balance in Equation 1:

$$V_h = V_{h-1} + F_h - D_h \qquad \textbf{Equation 1}$$

Where $0 \leq F_h \leq F_{max}$ (pump flow must not exceed pump capacity); $V_{min} \leq V_h \leq V_{max}$ (storage volume must not exceed capacity or fall below minimum requirements); F_h = pump flow million gallons [MG]) during hour h; V_h = volume of water (MG) in the storage tank at the end of hour h; D_h = water distribution demand (MG) during hour h.

Optimization of Water Distribution Systems

We used dynamic programing optimization to determine the optimal pump rate and timing to minimize costs while obeying constraints. This approach solved for the optimum series of controls by starting at the final time-step and evaluating all possible decisions in reverse until the current time-step was met. An initial penalty was provided for any scenario that would result in final storage levels less than the initial storage level (assumed as the average of V_{max} and V_{min}). The total performance of potential decisions was evaluated as the accumulation of all future consumption costs, the maximum of all future demand charges, and the accumulation of any penalties from constraint violations, as shown in Equation 2. An indicator function was used to apply a steep penalty charge if the potential pumping scenario exceeded one of the constraints, such as max or min storage volume and max or min pump flows. The penalty cost variables in Equation 2 were used to exclude any potential scenarios that did not adhere to the physical limits of the water system and to ensure that the tank volumes at the end of the optimization run were at or above the starting levels. For each time-step, for each possible pump flow, the best future decision was found by selecting the pumping rates and timings that resulted in the minimum future total cost. This process was repeated recursively until the current time-step, at which point the optimum pump rate and timings were known deterministically. This approach produces reliable, optimum decisions for an explicit analysis period when all inputs are known, including the future water sales and energy price patterns.

Additionally, the team ran a similar optimization to minimize total marginal GHG emissions instead of costs. This slightly changed the objective function, so that hourly marginal emissions intensity (E_h) was substituted for consumption cost (C_h) in Equation 2 while also applying a zero-value demand charge (DC_h). This process was meant to show how water utilities may change their operations given different objective functions outside of existing pricing signals. The same optimization process and constraints were applied in the GHG scenario as were applied in the pricing scenarios.

$$\min\left[\left(\sum_{h=1}^{H}(F_h * EI * C_h) + (X * \mathbb{1}_A)\right) + max_{h=1}^{H}|(F_h * EI * DC_h) + (X * \mathbb{1}_B)\right]$$

$$\mathbb{1}_A(F_h) = \begin{cases} 0\ if\ 0 \le F_h \le F_{max} \\ 1\ if\ F_h < 0\ or\ F_h > F_{max} \end{cases}$$

$$\mathbb{1}_A(V_h) = \begin{cases} 0\ if\ V_{min} \le V_h \le V_{max} \\ 1\ if\ V_h < V_{min}\ or\ V_h > V_{max} \end{cases}$$

$$\mathbb{1}_B(V_h) = \begin{cases} 0\ if\ V_{h=H} \ge V_{h=1} \\ 1\ if\ V_{h=H} < V_{h=1} \end{cases}$$

Equation 2

where EI = pump energy intensity (MWh/MG); C_h = energy cost ($/MWh) during hour h; E_h = emission intensity ($MTCO_2e$/MWh) during hour h; DC_h = peak energy demand charge ($/MW); and X = penalty charge (~$Infinite-1).

Statewide Energy Grid Evaluation Approach

To understand the energy demand flexibility of the water sector and evaluate optimum energy cost operations, multiple signals were assessed as unique scenarios. A baseline (scenario 1), that has a flat consumption rate and no demand charge, establishes the flexibility of specific water systems and the overall water sector when introduced to more complex motivational price signals (scenarios 2 through 8 below). The potential for energy flexibility was calculated as the difference between the simulated energy demand in scenario 1 and each of the price signals (scenarios 2 through 8). Table 2 summarizes the various rates under each scenario for reference.

Table 2: Summary of the Consumption and Demand Rates for Eight Electricity Rate and Emissions Structures

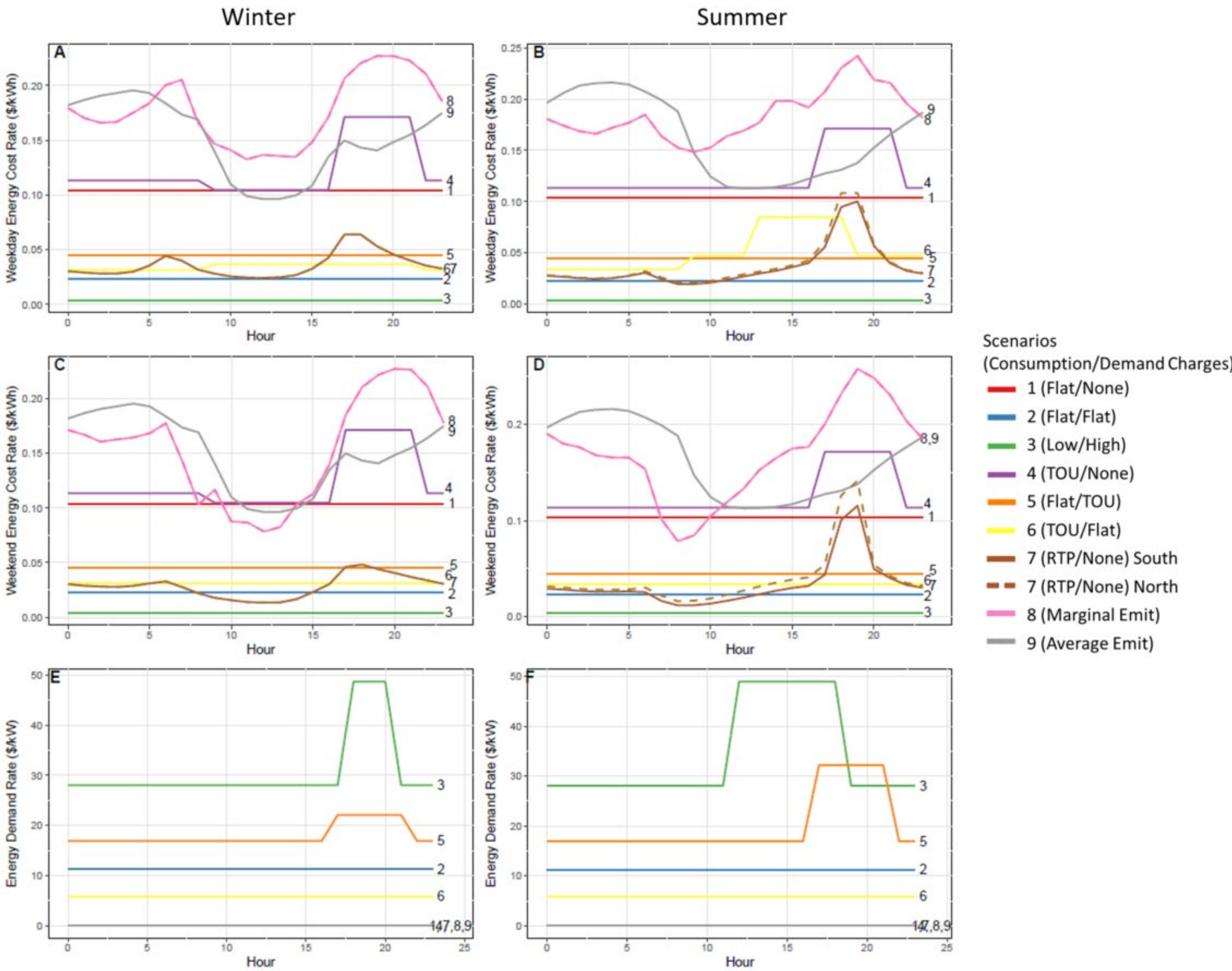
Scenario	Consumption Rate ($/kWh)	Demand Rate ($/kW)	Description
1	Flat	None	This represents the 'baseline', where the time and the rate at which a utility consumes energy do not affect the bill. Minimization of costs is applied only to the minimization of total energy demand and not to the time of energy use.
2	Flat	Flat	Neither consumption nor demand charge varies with time of day.
3	Flat (Low)	TOU (High)	There are very low constant consumption rates with a relatively high demand charge that increases during the afternoon in the summer and in the early evening in the winter.
4	TOU (Modern)	None	Modern TOU peak consumption hours are from 4:00 p.m. to 9:00 p.m., when the statewide net electricity grid experiences a ramping of demand.
5	Flat	TOU	This is similar in structure to scenario 3, but this scenario has relatively high flat consumption charges and lower time dependent demand charges.
6	TOU (Legacy)	Flat	Legacy TOU peak consumption hours are from 12:00 p.m. to 6:00 p.m. in the summer. These TOU structures are widely used but are being phased out and replaced with more modern TOU schedules (such as scenario 4).
7	TOU (RTP)	None	This represents the California ISO locational marginal pricing (LMP) for Northern or Southern California utilities.
8	TOU (Marginal Emissions)	None	The consumption charge reflects the marginal emissions intensity for Northern or Southern California water utilities.
9	TOU (Average Emissions)	None	The consumption charge reflects the average emissions intensity of the California electric grid, estimated for 2020 to 2030 (CEC, 2020).

Source: Rupiper et al., 2024

For real-time pricing (wholesale electricity prices) and emissions scenarios 7 and 8, which vary for every hour of the year and by location, the project team chose to represent the diversity of the signals without substantially increasing the complexity of the input data by grouping the water systems into Northern California and Southern California. These regions generally correspond to the service territories of PG&E in Northern California and SCE and SDG&E in Southern California. Any water systems outside of these service territories were assigned to one of these regions based on their geographic proximity to the region. For RTP, the project team used day-ahead market locational marginal pricing (LMP) data from the California ISO in 2020. Prices for the northern region were represented by the PG&E demand load aggregation point (DLAP) and prices for the southern region were represented by the average of SCE and SDG&E DLAPs. For the emissions optimization scenario, the project team used marginal operating emission rate data from California's Self Generation Incentive Program (SGIP), using the PG&E SGIP data for the northern region and an average of the SCE and SDG&E SGIP data for the southern region.

The scenarios considered in this analysis represent pricing schedules currently provided by SCE and SDG&E, with a variety of consumption and demand combinations and structures that are applicable to water utilities with significant pumping demands as well as two scenarios representing average and marginal electric grid GHG emission intensities. Figure 6 graphically displays the consumption and demand charges for each scenario for the summer and the winter by hour of day. For these scenarios, summer runs from June 1 until September 30. Subplots A and B in Figure 6 show the various consumption rates under each pricing scenario for each hour of the day on a weekday. Subplots C and D show the weekend rates, subplots E and F show the demand rates. For scenarios 7 and 8, the consumption rate varied for every hour of the year in the optimization but followed a similar pattern by season. In Figure 6, scenarios 7 and 8 are plotted as averages for the winter and the summer to demonstrate the typical pattern they followed, although any given hour used in the optimization may have varied from this pattern. Scenarios 8 and 9 emissions intensities were minimized as if they were consumption charges, using $MTCO_2e$/MWh marginal emissions intensity values as if it was a $/kWh consumption charge. At any given hour, marginal emissions varied between the northern region and the southern region but, on average, they were the same, which is why there is only one line for marginal emissions in Figure 6.

Figure 6: Energy Price Structures Within Energy Grid Model



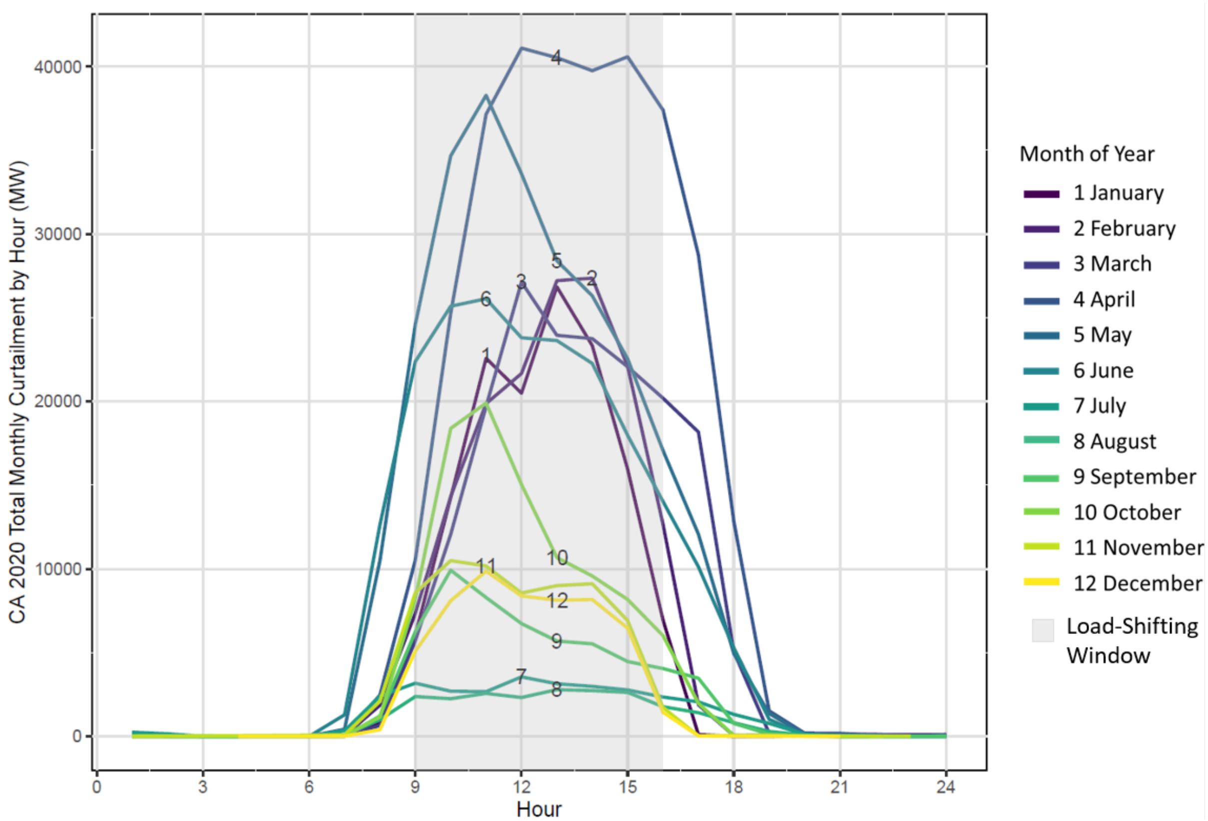
Energy pricing rate structures (consumption and demand) under each scenario by season, weekdays, and weekends. (Marginal Emissions, scenario 8, are plotted as $MTCO_2e/MWh/2$ for ease of plotting).

Source: Rupiper et al., 2024

Net Load Shifted

Between the hours of 8:00 a.m. and 6:00 p.m. there can be times where forecast renewable generation exceeds energy demand, resulting in curtailment of renewable resources, as shown in Figure 7 (CAISO, 2021a). The greatest curtailment in California occurs in the first half of the year, peaking in May with high solar availability and low energy demands, and lowest in August with high energy demands, resulting in less need for curtailment. To avoid curtailment and take advantage of low carbon, often inexpensive, energy sources, it may be desirable to shift energy demand to when curtailment is at its highest. Currently in California, the point of greatest curtailment of renewable resources and lowest net energy demand occurs between 9:00 a.m. and 4:00 p.m., after which net demand begins ramping up toward an evening peak between 7:00 p.m. and 8:00 p.m. This study quantified the magnitude of energy shifted into the curtailment window minus any energy shifted out of the 9:00 a.m. to 4:00 p.m. window as the net load shifted.

Figure 7: Total Renewable Curtailment by Hour and Month for California in 2020



Total solar and wind curtailment by hour of day and month in California for 2020 (data from CAISO, 2021a).

Source: Rupiper et al., 2024

Average Emission Intensity and Avoided Emissions

Shifting the energy load may impact the average emission intensity of the water distribution sector, given the variable GHG emissions of the electric grid at different times of the day due to the availability of renewable resources (Miller et al., 2022). Total GHG emissions and average emissions intensity were calculated as in Equation 3, by multiplying the energy profiles under each scenario by emissions factors according to the appropriate hour and month and then summing the emissions and dividing by the total energy consumption. Average emissions intensities highlight the fraction of the grid-wide emissions that can be attributed to the energy consumption (which comes from a variety of sources) of the water distribution sector.

The project team also considered marginal emissions intensities because they better represent the consequential impact of load shifting and avoided emissions. The team calculated avoided emissions under each scenario by multiplying the change in hourly electricity demand (scenarios 2 through 9 minus the baseline) by hourly marginal emissions factors. This accounts for the emissions intensity of the last unit of energy that would have been produced to meet demand. By reducing demand when marginal emissions intensities are high, the last units of energy are not required, and those emissions are avoided. Avoided emissions account for the impact of shifting water distribution demands on the electric grid (which changes the last unit of produced energy); that is how the water sector can change overall grid emissions.

$$Average\ Emission\ Intensity\ \left(\frac{Metric\ Ton\ CO2e}{MWh}\right) = \frac{\sum(Energy_t * EmissionFactor_t)}{Total\ Energy} \quad \textbf{Equation 3}$$

Net Demand Peak Reduction

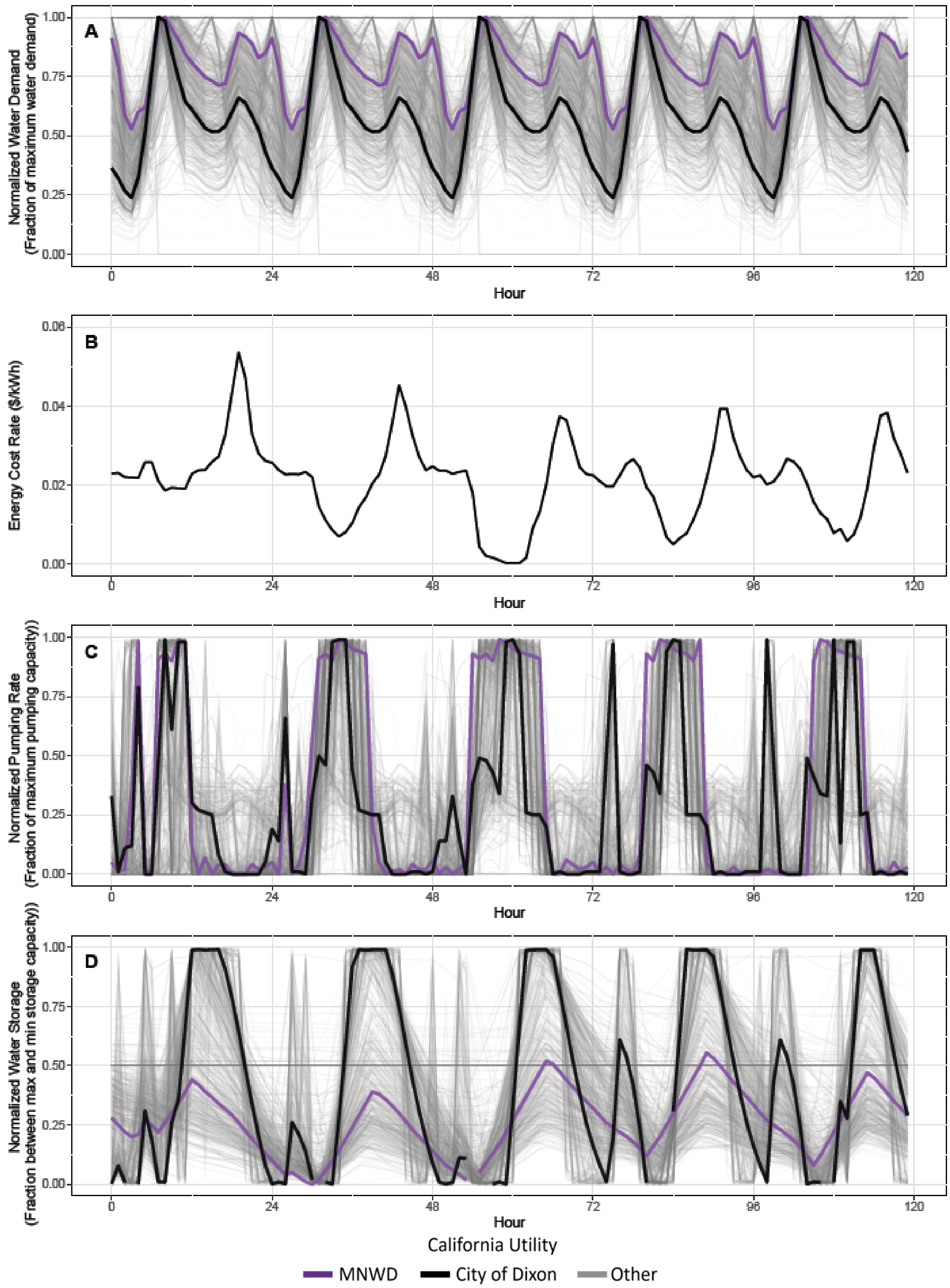
Net demand peak is the maximum net energy demand (total energy demand minus wind and solar generation) in a single interval each day. This quantity represents the total nonrenewable capacity that is required that day and can dictate the number and size of fossil-fuel-generated power plants required to meet energy demand in California (CEC, 2021). Reducing the net energy demand peak may mean greater grid reliability, as the grid can have a greater capacity to handle demands and reduce the likelihood of rolling blackouts or insufficient energy supplies during high demand periods. A reduction in the net demand peak may also mean reducing grid emissions, since peak demand is often served by less-efficient and more-emitting peaking power plants (Torriti, 2015). Regular peak energy demand has been shifting later in the day since 2011, with the summer total demand peak occurring, on average, around 6:00 p.m. in 2020 and the net peak occurring after 7:00 p.m. (CEC, 2021). This metric of impact is assessed at the statewide level by examining the overall water distribution sector net energy demand curve of the baseline relative to the different scenarios at 7:00 p.m.

Results From Statewide Simulation

Demand Shifts at the Utility Level Under Real-time Energy Pricing

On the individual utility level, demand changes in response to different pricing signals in the water sector might look something like Figure 8. Figure 8 plots the model results for individual water utilities in gray, highlighting two specific water systems with very different storage capacity and water demands. Plotted in purple is MNWD in Southern California with a max storage capacity of 71.1 MG and max daily water demand around 27,000 gallons per minute (gpm). Plotted in black is the City of Dixon in Northern California with a max storage capacity of 0.6 MG and max demand of 1,100 gpm for five days in May, starting on a Friday. Most utilities have water demand profiles, such as is shown in panel A of Figure 8, characterized by peaks in the morning and evening. To meet water demand, a utility has to draw water from its storage tanks, shown in panel D, which will be refilled by pumping water to the tank demanding energy, as shown in panel C. Under an optimized real-time pricing scheme (scenario 7), shown in panel B, the utility may choose to pump water when prices are low, even when the tanks have sufficient supply to meet demand. The RTP signal will encourage utilities, where possible given water storage and demand constraints, to shift their water pumping to times of day when energy costs are low, resulting in more pumping occurring in the early morning and the middle of the day, to avoid pumping during high rates in the evening when energy demand prices are higher.

Figure 8: Illustration of Optimized Operations for Select Water Systems Under the Energy Grid Model



Optimized operations for individual utilities for five days in May, starting on a Friday under real-time pricing scenario 7.

Source: Rupiper et al., 2024

In Figure 8, during the relatively high costs of energy near 7:00 p.m., MNWD optimization avoided pumping and used sizeable storage to meet water demand until energy costs decreased. On Sunday (hours 48 to 72), energy costs in the afternoon were at their lowest for the week, reaching as low as $0/kWh. In the simulation, MNWD took advantage of Sunday's low rates and used its storage to pump almost constantly throughout the afternoon until prices increased in the evening, when it was able to shut off the pumps and meet water demand by draining stored water. During this same period, the City of Dixon also increased its pumping but could not take advantage of the entire low pricing period given its limited storage. Panel D of Figure 8 shows the city filing its tanks to capacity when energy prices are low and draining them to their minimum when prices increased — indicating that its ability to load shift was limited by its storage volume. Where feasible, the project team observed this behavior in most utilities to varying degrees.

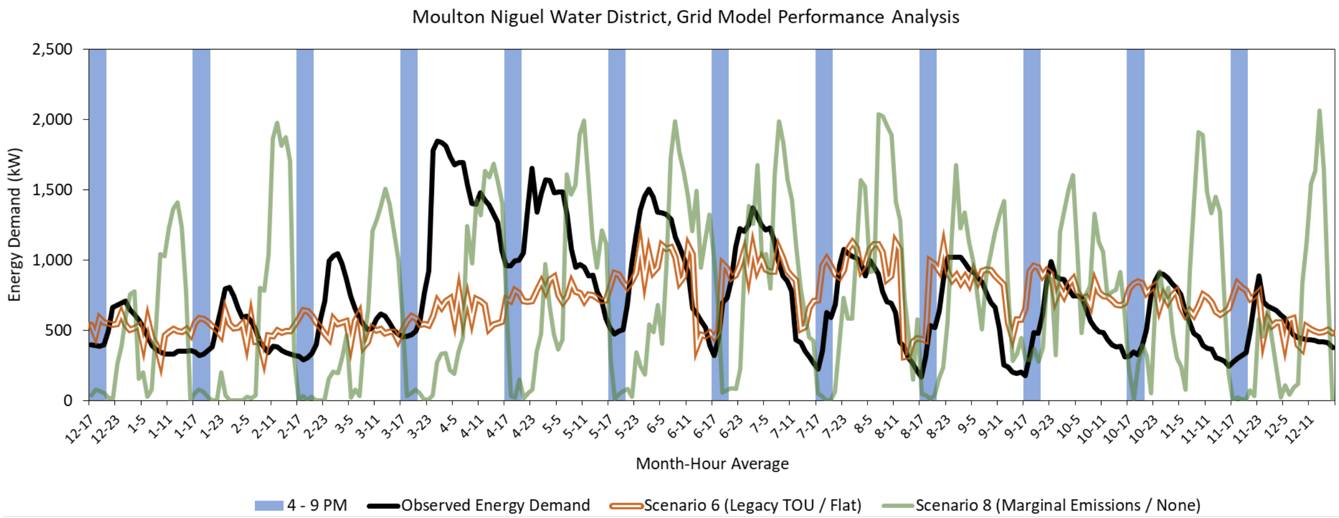
Local minima and maxima in rate structures can be especially impactful on utilities that do not have sufficient storage or pumping capacity to avoid pumping until the global or daily minimum prices are available. As seen in panels B and C of Figure 8, both MNWD and the City of Dixon pumped when a local low in the pricing scheme occurred. In the case of Dixon, it did not have adequate storage to meet demand for extended periods and was forced to pump whenever a local low energy price occurred, even when a lower price would be available in a few hours. In the case of MNWD, which has excess storage, it also occasionally had to pump during local minimum energy costs because it did not have adequate pumping to fill the storage tanks sufficiently before the daily low pricing period ended.

Not all utilities under all scenarios or in all months are able to fully shift when they pump, due to limited storage or pumping capacity, high water demands, or extended high pricing periods. In these instances, the utility may be forced to pump water even when energy prices are high, to meet water demand. Pumping despite high prices can be seen in Figure 8 for several utilities (thin gray lines), where their pumping rate in panel C remains high or even increases in order to deliver adequate water volumes to meet demand even when energy prices are elevated. In cases where a water system has no appreciable storage, utilities are forced to pump to exactly meet demand and therefore demonstrate no capacity for load-shifting. All utilities, regardless of their capacity for load-shifting, were included in the analysis to represent the water distribution sector in its entirety.

Comparison With the Pilot Site

While the energy grid model was designed to best reflect the statewide water distribution sector in aggregate, it is important that the resulting utility-scale simulation reasonably reflect the range and flexibility in energy demand expected of a single given water utility. Comparing the simulation results from the energy grid model under two energy tariff structures to the real, observed energy demand at the MNWD, it can be observed that the simulations reasonably reflected the capacity for load shifting at the utility by respecting the maximum annual energy demand, and they demonstrated similar capacities for load reduction in response to peak hour energy price periods (Figure 9). Note that the measurements obtained from MNWD include background energy demand from the buildings, lighting, and other equipment in addition to water distribution pumping.

Figure 9: Energy Grid Model Fit to the MNWD



Month-hour comparisons between the measured energy demand at the Moulton Niguel Water District and two scenarios from the energy grid model optimization results.

Source: Rupiper et al., 2024

Demand Shifts at the Statewide Level

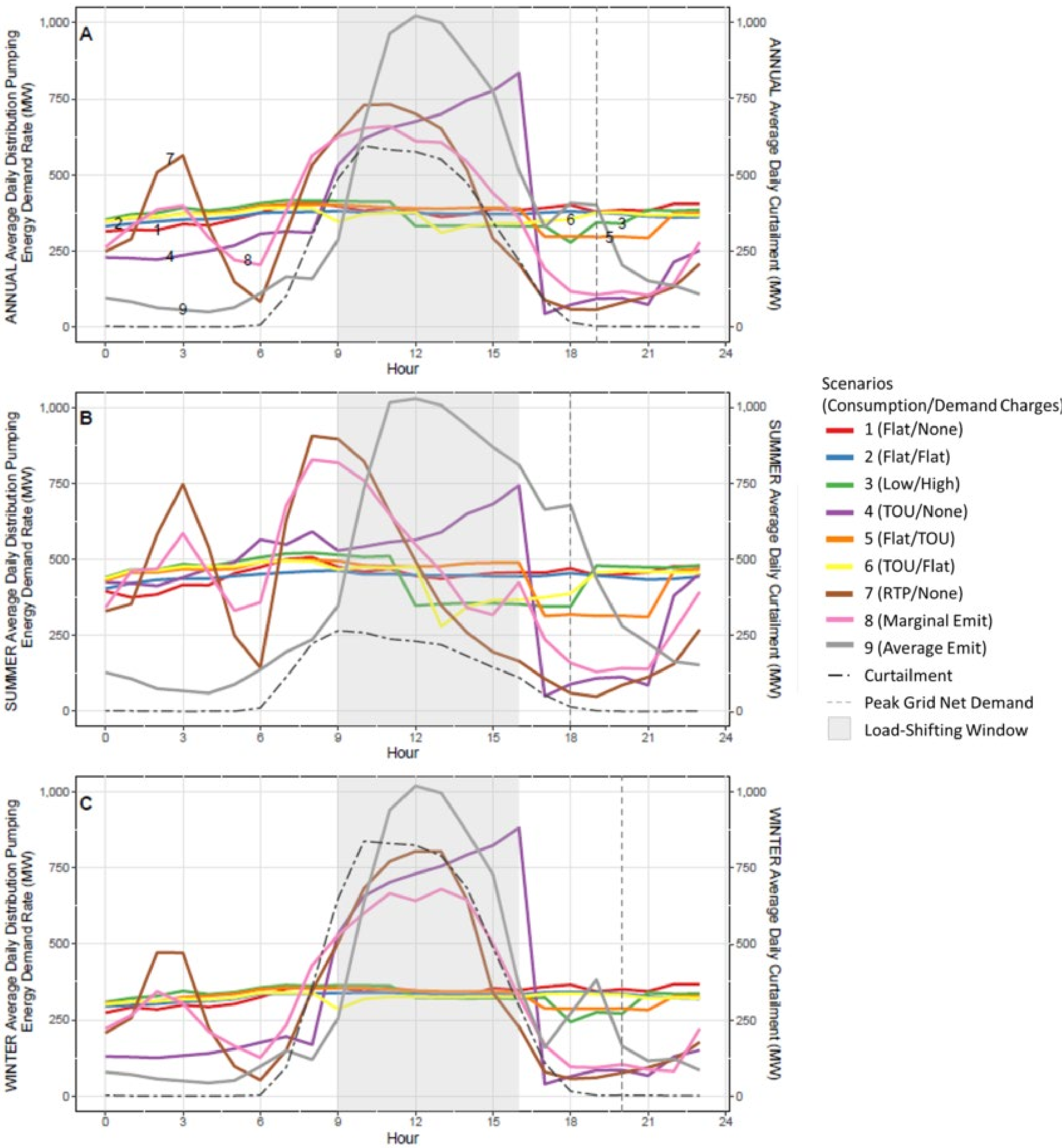
Aggregating the optimization model results for 702 Californian utilities across the eight scenarios yielded insight into the ability of the water sector as a whole to impact the California electric grid and statewide energy and emissions goals. Depending on the scenario, utilities behaved differently to minimize cost or minimize GHG emissions, resulting in alternative energy demand profiles, electric grid impacts, and load shifting potentials.

Net Load Shifted

Assuming a constant pricing signal (scenario 1) as the baseline for comparison, scenarios without demand charges, 4, 7, 8, and 9, resulted in the most significant shifts in energy loads into the curtailment window between 9:00 a.m. and 4:00 p.m. in aggregate over the entire year. Figure 10A plots the annual daily average energy demand in California by the water distribution sector by hour of day under each optimization scenario. Marked on the figure as a shaded gray area is the curtailment window, representing the hours when sizable quantities of energy are curtailed in California, along with a dashed line representing the actual curtailment values for 2020. Scenarios with demand charges, 2, 3, 5, and 6, all resulted in minimal or negative load shifting and relatively flat hourly consumption rates. Scenarios 4, 7, 8, and 9, without demand charges, all resulted in positive load shifting and much more dynamic energy consumption over a 24-hour period. These patterns held true for both the winter and the summer periods, as shown in panels B and C of Figure 10.

Quantifying the observed patterns in Figure 10, Table 3 lists the annual total energy consumed, annual net load shifted, GHG emission intensity, and avoided GHG emissions under each scenario. Optimized pumping for all scenarios resulted in similar annual total energy consumed, assuming a static pumping efficiency and equal water demands under all scenarios.

Figure 10: Optimized Statewide Water Distribution Pumping Under the Energy Grid Model



A) Aggregated annual daily average, B) summer daily average, and C) winter daily average water sector pumping energy demand by hour of day under eight optimization scenarios, California 2020 electric energy curtailment by hour of day, and 2020 California net peak demand hour.

Source: Rupiper et al., 2024

Table 3: Annual Total Energy Consumed, Shifted, Emissions, and Emission Intensity Under Eight Different Optimization Scenarios

Scenario (Consumption/ Demand Charges)	Annual Total Energy Consumed (MWh)[1]	Annual Net Load Shifted (MWh)[2]	Average GHG Emission Intensity ($MTCO_2e/MWh$)[3]	Annual Total Avoided Emissions ($MTCO_2e$)[4]
1 (Flat/None)	3,273,163	0.0	0.1552	0.0
2 (Flat/Flat)	3,214,285	-16,660	0.1560	21,859
3 (Low/High)	3,228,971	-37,354	0.1578	29,200
4 (TOU/None)	3,189,280	740,900	0.1416	149,178
5 (Flat/TOU)	3,202,021	30,195	0.1559	42,621
6 (TOU/Flat)	3,183,231	-80,584	0.1579	34,005
7 (RTP/None)	2,989,939	578,158	0.1518	289,574
8 (Mar. Emit/None)	3,134,091	535,682	0.1488	330,627
9 (Avg. Emit/None)	3,179,347	1,071,478	0.1263	128,256

1 Total energy consumption under all scenarios should be identical, given identical water demands. Small variations exist because each optimization scenario may have resulted in slightly different final water storage levels each month, resulting in slightly more or less total energy being demanded for pumping. The total energy consumed for pumping under all scenarios equates to approximately 1.2 percent of the total energy consumed in California in 2020.

2 Net load shifted is relative to scenario 1 as the baseline, considering the energy consumed between the hours of 9:00 a.m. and 4:00 p.m. Negative values indicate that a greater load was shifted into the load shift window than out.

3 Average GHG emission intensity, calculated as the annual sum of the energy demand in each hour, multiplied by the corresponding hourly average California electricity grid emissions rate, divided by the annual total energy consumed as reported in the first column.

4 Avoided emissions, calculated as the sum of the differences in energy demands between scenarios 2 through 8 and the baseline scenario 1, multiplied by the marginal emissions intensity of the California electric grid for every hour in 2020.

Source: Rupiper et al., 2024

Summing the energy demands for the 702 water distribution systems in the dataset resulted in an annual energy usage of approximately 3,200 GWh for distribution pumping, making up roughly 1.2 percent of the 272,576 GWh of total electrical energy consumed in California in 2020 (CEC, 2020). Operations that minimized average GHG emissions under scenario 9 resulted in the greatest annual net load shifted, with the ability to shift approximately one-third of its energy demand, approximately 1,070 GWh, followed by scenario 4 with a modern TOU energy consumption rate without a demand charge, scenario 7 real-time pricing without a demand charge, and scenario 8 marginal emissions. Scenario 6, which has a legacy TOU consumption charge, resulted in the greatest negative load-shifting potential since energy rates are highest in the second half of the curtailment window, encouraging consumption during other times of the day.

For those scenarios that were successful at motivating a positive shift, they all incentivized consumption during the middle of the day, with relatively low energy prices or emissions rates, and did not penalize periods of high consumption (that is, no demand charges), so that consumers were able to take full advantage of their pumping and storage capabilities. Additionally, the most successful scenarios had relatively higher costs or emissions rates during all other periods of the day to discourage consumption outside of the curtailment window.

Impact on Curtailment

The potential for the water sector to shift energy loads under different scenarios could result in reduced curtailment of renewable resources and an increased capacity for integration of renewable energy on the California grid. In Figure 10, California's average daily renewable energy curtailment for 2020 is plotted by hour of day relative to the energy demand by the water sector under the various scenarios. In 2020, the California ISO curtailed a total of 1,580 GWh of solar and wind energy (CAISO, 2021a). If net load shifted is considered as the potential to reduce curtailment of renewable energy, then statewide curtailment could be reduced by up to 68 percent under the optimized average emission scenario (scenario 9).

Total GHG Emissions, Average Emission Intensity, and Avoided Emissions

Shifting pumping to the middle of the day to take advantage of lower energy costs does not impact the total amount of energy being used but it may mean lower overall GHG emissions due to the prevalence of solar energy on the California electric grid in the middle of the day. Operating to minimize average GHG emissions under scenario 9 resulted in the lowest average emission intensity, where the majority of energy demand occurred in the middle of the day and emissions were reduced by 19 percent compared to the baseline. Other scenarios that were successful at performing load-shifting (scenarios 4, 7, and 8) also have reduced emissions over the baseline, since a greater portion of their energy consumption occurred during low emissions intensity periods. Table 3 reports the annual average GHG emission intensity estimated for each scenario. The greatest average GHG emissions were under scenario 3, which has the highest demand charge and the lowest consumption charges, and scenario 6, which has a legacy TOU consumption charge and a flat demand charge.

Shifting energy consumption to low emissions intensity periods will help reduce average GHG emissions, but that can be counteracted by high levels of consumption during periods of time when emissions intensities are high. The RTP scenario, which successfully performed load-shifting, did not see as much of a reduction in average GHG emissions as scenario 4 because of a local peak of consumption in the early morning around 3:00 a.m. (see Figure 10). During this early morning energy peak, emissions intensity on the California energy grid were at their highest (see Figure 7), undoing some of the emissions reductions achieved by shifting into the curtailment window in the middle of the day.

While average emissions estimations can be useful in understanding how the allocation of grid emissions to the water sector will change, they do not capture the impact of load-shifting in the water sector on grid-wide emissions, that is, avoided emissions. Operating to minimize marginal emissions, scenario 8, unsurprisingly, resulted in the greatest quantity of avoided GHG emissions, followed closely by RTP, scenario 7. Scenario 8, marginal emissions, avoided 330,000 $MTCO_2e$, which is equivalent to approximately 65 percent of the emissions currently attributed to the water distribution sector. Scenarios 4 and 9, both of which resulted in the greatest load shifting and average GHG reductions, avoided less than half of the emissions of scenarios 7 and 8. This was due to marginal emissions following a slightly different hourly pattern than the California grid as a whole; Figure 6 shows that the average grid emissions are lowest in the middle of the day but the marginal emissions are lowest in the morning, especially during the summer months.

Net Demand Peak Reduction

A few of the scenarios result in a sizable reduction in the contribution of the water sector to the grid-wide net demand peak. In 2020, the annual California grid-wide instantaneous peak demand occurred in August at 47,121 MW, with typical daily net peaks throughout the year around 30,000 MW (CAISO, 2021b). Potable water distribution pumping within the water sector contributes roughly 1 percent toward the state grid-wide net energy demand peak on any given day. Figure 10 plots a vertical line indicating the moment of peak net demand in California for 2020, just after 7:00 p.m., on average, over the year. The performance of each scenario relative to the baseline scenario 1 is visually apparent in Figure 10 as reduced consumption during this time and quantified in Table 4. RTP, modern TOU consumption, and marginal emissions (scenarios 7, 4, and 8) resulted in the largest reductions in the net demand peak: 85.1 percent, 75.6 percent, and 72.0 percent over baseline, respectively.

Table 4: Daily Peak Annual Averages Under the Energy Grid Model Scenarios

Scenario (Consumption/ Demand Charges)[1]	Annual Average Daily Peak Net Energy Demanded (MW)[1]	Change in Annual Average Daily Peak Net Energy Relative to Scenario 1 (MW)	Percent Change in Average Daily Peak Net Demand Relative to Scenario 1 (percent)
1 (Flat/None)	378.3	0.0	0.0
2 (Flat/Flat)	376.1	-2.1	-0.6
3 (Low/High)	342.5	-37.9	-9.3
4 (TOU/None)	92.5	-285.7	-75.6
5 (Flat/TOU)	295.3	-82.7	-21.8
6 (TOU/Flat)	375.2	-2.6	-0.7
7 (RTP/None)	56.3	-321.5	-85.1
8 (Marginal Emissions)	105.6	-272.1	-72.0
9 (Average Emissions)	399.2	21.4	5.7

1 Peak energy measured as energy demanded at the 7:00 p.m. hour (representing the net peak demand on the California grid in 2020).

Source: Rupiper et al., 2024

All scenarios with demand charges resulted in relatively flat energy consumption and low potential to load-shift or reduce peak demands. Demand charges discourage utilities from high levels of energy consumption at any given time, thus resulting in utilities maintaining a consistent level of consumption to minimize their overall demand. This is plainly seen in Figure 10, scenarios 2, 3, 5, and 6, all of which have demand charges, resulting in fairly consistent and flat energy demand profiles throughout the day, with the TOU demand scenarios 3 and 5 causing a slight drop in their consumption during periods of increased demand charges. Under the TOU demand rates that had increased demand costs during the peak period, utilities reduced their demand to avoid the additional costs, but this meant very little and, in some cases, it resulted in negative potential load-shifting during the curtailment window, only small reductions in the net demand peak, and increases in average GHG emissions.

Impact of Pricing Structure on Load Shifting

TOU consumption rates that did not have demand charges had much more dynamic energy demands that peaked in the middle of the day. This flexibility allowed this sector to reduce curtailment, reduce their contribution to peak demand, reduce average GHG emissions, and avoid GHG emissions. The capacity for demand shifts all depends on the TOU structure and the timing of the peaks and valleys of the consumption charges. Scenario 4 imposed its lowest costs during the daytime, with a steep price increase at 4:00 p.m., causing utilities to increase pumping just before 4:00 p.m. to avoid pumping during the high pricing period if at all possible. This resulted in an increase in demand leading up to the 4:00 p.m. period that was beneficial for reducing curtailment and average GHG emission and in a steep drop-off at 4:00 p.m., bringing down demand during the grid-wide peak. Similar to scenario 4, scenario 9 had its lowest prices during the middle of the day but, unlike scenario 4, it also had high prices during the nighttime period, causing more utilities to avoid pumping at night, thus creating the greatest load-shifting potential.

Local minima in a TOU rate structure can have a significant impact on energy consumption in the water sector. Scenarios 7 and 8 (RTP and marginal emissions) both experienced a peak in energy demand during the early morning because of a local minimum price around 3:00 a.m. (see Figure 6 and Figure 10). Water distributors that do not have adequate water stored to meet morning water demand may have to pump in the early morning during this relatively low price until the afternoon, when prices drop again. The morning local minima in scenarios 7 and 8 means that they do not shift as much into the load-shifting window and that they have higher average emissions, but it also means that they avoid the greatest quantity of marginal emissions. There is a similar effect of a local minimum in the average emissions scenario 9, which occurs between 6:00 p.m. and 7:00 p.m. in the winter. Water systems took advantage of this local minimum as a last chance to pump water before the high intensity nighttime period (see Figure 6 and Figure 10). However, this localized low price coincided with the moment of grid net peak demand, resulting in scenario 9 actually increasing demand during this time period relative to the baseline. Local minima in rate structures can be especially impactful on utilities that do not have sufficient storage or pumping capacity to avoid pumping until the global minimum prices are available.

Summary of the Results From the Energy Grid Model

As California increases its renewable energy portfolio to include more solar, energy generated during the middle of the day will more frequently exceed demand and by a greater margin unless demand for that energy can be shifted to when it is available. Potable distribution pumping in the water sector accounts for approximately 1.2 percent of the total electricity consumption in California annually and it has the capacity to shift when it uses that energy to help integrate more renewable resources onto the grid, reduce curtailment, decrease GHG emissions, and reduce net peak load. This study accounts for the operations of 702 water distribution systems in California with simulated water demand, pumping, and energy demands under eight different energy pricing and emissions minimization scenarios. From this simulation, it was found that the water sector has the flexibility to shift its energy demands by up to 1,071 GWh annually, to reduce curtailment in California by up to 68 percent, to reduce its contribution to peak net demand by up to 321 MW, and to avoid 330,627 $MTCO_2e$ of emissions.

The potential distribution system response depends on an individual system's combination of tank storage capacity, pumping capacity, and water demands, as well as on the applied energy tariff structure. Most systems had the ability to perform some load shifting, with the greatest potential at systems with high storage volumes, low water demands, and high pumping capacity. Energy tariffs with demand charges resulted in minimal and, in some cases, negative load-shifting compared to the baseline. The tariffs without demand charges and TOU consumption charges that aligned low pricing with the load-shifting window and higher prices outside the window, resulted in the most dynamic energy consumption, the greatest shifts in energy load, and the lowest GHG emissions. Depending on the objective, adjusting rate structures could encourage the water sector to shift the time when it demands energy, such that it could better assist California in meeting future energy and emissions targets.

CHAPTER 5: Deployment and Pilot Results

Hydraulic Model Development and DMS Deployment

The WaterWatch energy DMS was deployed at MNWD between January 1, 2021, and December 31, 2021. In preparation for this deployment, hydraulic models for the potable and recycled water distribution systems were built or modified and calibrated to allow for real-time forecasting in the DMS tool. In support of the water utility operations during the COVID pandemic, the tool was installed at MNWD as a stand-alone tablet with WaterWatch installed, which operators could use as convenient for educational purposes. Over the course of the year-long pilot, MNWD operators used the tool 31 times and were found to have reduced their energy demand by 4.05 percent for the five days following each interaction with the tool.

Hydraulic Model Development

MNWD has two distinct water distribution systems that run within its territory, a potable water distribution system that supplies drinking water to its customers and a reclaimed water distribution system that supplies non-potable water for irrigation and other non-potable uses. Hydraulic models were acquired for both distribution systems so the DMS could be used for operating either water network.

The MNWD potable water distribution system distributes water to approximately 55,000 customer sites and delivers over 24 MG of water daily. This system consists of 8 open pressure zones and 4 closed pressure zones that are served either by pump stations or pressure regulating stations. The primary elements of the potable water system include 700 miles of distribution pipelines ranging from 3 inches to 66 inches in diameter, 28 storage reservoirs, 23 active pump stations, 7 inactive pump stations, and 20 pressure regulating or flow regulating facilities. The potable water system shares 16 interconnections with water suppliers and adjacent water agencies, including the city of San Juan Capistrano, El Toro Water District, South Coast Water District, and Santa Margarita Water District. The MNWD potable water network was built starting in 1961, with new sections being added up to the present time. The potable system benefits from up-to-date geographic information system (GIS) files, pump station hydraulic efficiency reports, and modern SCADA equipment. These data were acquired from MNWD and used to build a new, custom hydraulic model of the potable water distribution system.

For irrigation and other non-potable water uses, MNWD serves more than 1,300 customer sites and delivers over 7 MG of water daily. To reduce the usage of comparably expensive imported potable drinking water to meet these customer demands, MNWD began production of reclaimed water for its customers in the late 1960s (MNWD, 2016c). Production of reclaimed water has continued to expand, fueled in part by the 2011 to 2017 California drought, as a cost-effective measure to improve water-efficiency while complying with California Governor Jerry Brown's obligations for long-term improvements to water use, reduction of water waste, and improved drought planning (Office of Governor Edmund G. Brown Jr., 2016). Today, by reusing over 70 percent of all wastewater produced in the district, MNWD is meeting over 25 percent of the district's overall water demand using reclaimed water (MNWD, 2016c).

MNWD's reclaimed water system consists of 6 open pressure zones and 10 closed pressure zones that are served by either pump stations or pressure regulating stations (MNWD, 2017). The primary elements of the reclaimed water system include 144 miles of distribution pipelines ranging from 4 inches to 30 inches in diameter, 11 storage reservoirs, 11 active pump stations, 1 inactive pump station, 19 pressure regulating facilities, and 1,338 active recycled service e-meters ranging from 0.5 inch to 10 inches in diameter (MNWD, 2017). The reclaimed water system shares four interconnections with the adjacent water agencies of Via Escolar, Via Noveno, Golden Lantern, and Santa Margarita Water District. The majority of the reclaimed water network in MNWD was built between 1990 and 2010, and it benefits from up-to-date GIS files, pump station hydraulic efficiency reports, and modern SCADA equipment (MNWD, 2017). In 2016, MNWD completed the development and calibration of a hydraulic model of its reclaimed water system that uses the commercial hydraulic modeling software InfoWater (IW) as part of a greater capital infrastructure improvement effort. This hydraulic model was provided by the MNWD for the purposes of this study.

Reclaimed Water Distribution System

The reclaimed water system hydraulic model provided by MNWD was developed as part of a capital infrastructure improvement effort. Typical hydraulic models not built for EWQMS require modifications before they can simulate energy load shifting. Therefore, to prepare the hydraulic model for the EWQMS optimizations, several modifications were made to aspects of the hydraulic model to increase its robustness and simulation speed.

Pattern data resolution was discovered to have a noticeable impact on the ability of the hydraulic model to successfully perform extended period simulations. Conversations with Innovyze technical support staff identified a known issue with the EPANET model regarding high-resolution pattern data that makes it more difficult for the hydraulic model to discover satisfactory hydraulics. To remedy this situation, the provided dataset was aggregated to a lower resolution of 1 hour. This action prevented excessive hydraulic balancing calculations and further increased the trial simulation rate.

Operating logic for the provided hydraulic model was developed to simulate existing operations under the availability of new infrastructure and therefore included some elements of operation that reflected existing energy rate structures at specific pump stations. As an example, the peak and shoulder periods of most current energy rate structures overlapped with the period of minimum carbon intensity of energy generation and could have prevented the discovery of low-carbon operating solutions. These operating logics were removed or altered where appropriate to better allow the optimization procedures to discover pumping periods that otherwise would conflict with the standard periods of an energy rate structure.

Potable Water Distribution System

MNWD had not developed a hydraulic model for the potable system prior to this project. Consequently, it was necessary to fully construct and calibrate a hydraulic model unique to the MNWD potable water distribution network, in order to analyze the system's ability to perform load shifting. Model development occurred in four stages: data acquisition, data processing, model construction, and model calibration.

Where possible, data used to create the hydraulic model were procured directly from MNWD. Geospatial data for the potable water distribution system was provided in the form of ArcGIS geodatabase and vector data shapefiles. Engineering drawings of the entire potable system were also supplied for further detailed reference. Pump and tank asset data were provided, including original pump curves and copies of the most recent efficiency tests. Customer usage data were provided for each customer in the potable system. MWND transferred a copy of its SCADA historian, a large SQL database, which included pressure, flow, and usage data throughout the system for the previous 5 years. Pressure-reducing station settings were provided by the operators for assets not connected to the SCADA system. MNWD provided annual water imports, exports, and water loss estimations for the last 5 years. Publicly available elevation data for this region were taken from the United States Geological Survey (USGS) National Elevation Database (NED) (USGS, 2017). Pump curves that were not available from MNWD records were taken from the National Resource Conservation Service (NRCS) pump curve database (NRCS, 2017).

In interviews with MNWD operation staff, five different operating scenarios were selected that typified MNWD normal operating conditions. Corresponding historical dates were selected that exhibited the system characteristics and operating procedures associated with the scenarios. The hydraulic model was developed and calibrated under the Normal Hot Weather (NHW) Scenario. The NHW Scenario represents the typical yearly period in need of energy load shifting or DR, and therefore it was prioritized for this project. The DMS uses the network structure of the model and extends this initial scenario for all operations with historical operational data.

The data acquired from MNWD for the potable water distribution system was provided at various levels of accuracy, completion, and compatible formatting, thereby requiring significant processing before incorporation into the hydraulic model. Data processing requirements and a high-level summary of the processing methodology are presented.

The potable hydraulic model was built using the IW hydraulic modeling software at MNWD's request. MNWD's existing Reclaimed Model was built using this same software. The hydraulic calculations and modeling performed by IW were based primarily on the methods developed by the United States Environmental Protection Agency's EPANET software (Rossman, 2000). EPANET's hydraulic modeling engine can report the hydraulic status of complex water distribution networks and has been leveraged in academic and commercial applications to determine pump station operations that satisfy the required system performance measurements, including tank curves, maximum velocities, total pump flow, and minimum pressure (Rossman, 2000).

Network Construction

To build the potable hydraulic network, locational information was obtained from original MNWD GIS data. Mainline service pipes (mains) were directly imported from GIS shapefiles using IW; these included critical information on diameter, age, and material type. Original OBJECTIDs were used as unique identifiers within the IW database (IWDB) to maintain continuity for MNWD. New pipes were necessary in some cases to simulate the system more accurately or fill in data gaps and are identified by the letter P before their IW ID. Minor losses were not included in these models because these values must be determined from field measurement and verification. Check valves and shutoff valves were incorporated into the associated pipe's characteristics for IW models.

Junctions were not imported from the original fittings' shapefile; instead, they were created as appended to pipes through the functionality of IW. IW recommends this as best practice in model construction to reduce the connectivity issues between pipes and nodes. Select junctions were assigned nonzero demand values to indicate the simulation of one or multiple water customer accounts. Other modeling nodes, such as tanks, pumps, valves, supply intakes, and export locations, were built into the model using the GIS shapefile data.

Pumps were drawn in the model to ensure network connectivity and match engineering drawings received from MNWD. The building footprint shapefile was used to place additional pumps at the correct scale and location. Pump asset data required for modeling purposes included make, model, size, diameter, pump curves, efficiency curves, net positive suction head curves, and variable speed designation. Pump asset data was provided by MNWD from its records. MNWD's potable water system is maintained by 23 pump stations. Three of these are master meter takeout pump stations drawing water supply into the system. Under normal operations, 11 additional stations are active, six of which are reservoir duty (open system) stations and 5 of which supply closed pressure zones. The rest of the pump stations are backup stations, which run on an as-needed basis. Critical asset data were not available for all pumps. In the cases where no recent pump test data or original pump curve was available, a pump curve was sourced from literature (NRCS, 2017). For these archival pump curves, the known impeller diameter and model number were used to determine the approximate pump curve, and pumps were assumed to be single stage.

Tanks in the potable system were modeled in IW as constant diameter cylindrical tanks. Diameters, minimum levels, and maximum levels were specified from MNWD records. Initial tank levels were determined for each scenario from SCADA historical records. For the purposes of this model, interties are locations throughout the potable system where water is either imported into the system or exported to nearby water utilities. Each intertie was modeled as a fixed head reservoir followed by a flow control valve. The reservoir head was calculated using pressure readings at the intertie locations, where data was available. If pressure readings were not available, the pressure was estimated by using pressure data from the nearest location and correcting for the hydraulic grade line between these two locations. Flow from each reservoir is controlled by a flow control valve. The flow through the valve is simulated by an imported water pattern developed from SCADA data. Several intertie locations have pump stations that lift water from the source pipe to the open pressure zones at a head, or pressure, appropriate to that region's hydraulic grade line.

In IW, control valves limit the pressure or flow at a specific location in the network. There are two types of control valves in the potable system: pressure reducing valves, which restrain downstream pressure to a specified setting, and flow control valves, which regulate the flow to a target setting. The setting can be static, or it can be time variant and expressed by a pattern. Flow control facilities in the potable system are modeled using flow control valves, simulated by a unique flow pattern developed from historical SCADA data for each scenario. Offline flow control valves were modeled by restricting the flow setting to zero with no associated flow pattern. The pressure reducing stations in the potable system are modeled by pressure reducing valves. Pressure reducing station settings for each scenario were provided by MNWD. Offline pressure reducing stations were modeled by closing the upstream pipe and leaving the pressure setting at zero.

Elevations for elements in the water distribution systems were provided by MNWD, but not all assets had elevation data. For consistency, the elevations given by MNWD were not incorporated into the model. All elements were assigned an elevation based on ground surface elevation data from the USGS National Elevation Dataset (NED) (USGS, 2017). Elevation data were imported into IW and then mapped onto the individual assets of the system. NED provides national elevation data at a resolution of approximately 10 square meters for tiles of 1x1 degree of the earth's surface. The MNWD potable water system falls within the NED tile for the north latitude of 34 degrees and the west longitude of 118 degrees. Typical modeling practice for hydraulic models is to assume that water distribution systems are generally located at a consistent depth below ground surface and that ground surface elevation in this resolution serves as a satisfactory estimate of elevation change in the system.

Water customer demands from MNWD records were aggregated into representative groups throughout the potable network following a skeletonization process of laterals, or smaller diameter pipes. Skeletonization is a methodology employed by hydraulic models to reduce the size and complexity of the model and to decrease simulation time, by aggregating individual meter demands at nodes placed in strategic positions on main pipes. Demand node placement balanced the need to minimize the additional number of nodes while preserving proximity to the original lateral location and hydraulic representation. Geospatially defined demand multipliers were imported into the model using advanced IW modeling tools, specifically the Demand Allocator. The Demand Allocator generates demand multipliers at nodes following the skeletonization using the closest pipe assignment methodology, applying a local search algorithm to determine the closest pipe within a defined search space. The demand is then allocated to the junction on the side of the pipe that is closest to the meter location. The Demand Allocator splits demands at a node by usage type and associates the appropriate demand curve to each user-specific demand multiplier. This allows for demands associated with different customer types to be modeled at the same node.

The model was tested and refined for connectivity errors and analyzed for duplicate pipes and nodes. Issues were resolved on a case-by-case basis to create an accurate recreation of the potable water system. Once the connectivity of the distribution system was achieved, pipe segments with missing diameters or material types were completed by analyzing nearby and bounding pipes. Hazen-Williams roughness coefficient values were assigned for each pipe based on the pipe and lining material.

Incorporating Operational Data

To calibrate the hydraulic model, it was necessary to incorporate operational data from the selected time frame (the NHW Scenario). These data come in the form of historical flow rates through pumps and valves collected through the MNWD SCADA system and operational rules are used to determine the activation or deactivation of pumps for certain pump stations.

Typical operations use Programmable Logic Controllers (PLCs) to handle, evaluate, and execute operational rules where appropriate. Water agencies design PLCs to include factors such as pressure, tank levels, asset status, pipe flow, time, and season to trigger responses by the PLC. MNWD provided pdfs of PLCs for all active pump stations. MNWD operates on a sophisticated SCADA system, which records tank levels, downstream pump pressures, intake pressures, downstream pump flows, and other measurements on which to base these operational rules. Pump operating logic was compiled from the PLCs and checked against MNWD operator knowledge. Complex pump calls involving delay timers and alternations between pumps within a station were simplified to the essential trends associated with the activation and deactivation of assets under typical operating conditions. MNWD operators clarified which pump stations operated based on their PLC programs and which followed operators' discretion to achieve specific tank levels or to provide reliability to net system water storage. Active open system pump stations pump calls are controlled by time of day, time of year, and the level of the tank the pumps are supplying. Deactivation occurs when pump station discharge pressure is above the target range. Active closed system pump stations are composed primarily of variable speed pumps (VSPs), which use a PID control to align with a target discharge pressure. There are no time-of-use restrictions on these pumps; deactivation is triggered by decreasing discharge flow.

Three control approaches are available in IW, referred to here as Simple Rules, Complex Rules, and Variable Speed Drive Controls. Simple Rules are programmed directly into assets and are designed as straightforward if-then statements. Simple Rules are useful for activating pumps when pressure falls below the set point at the downstream junction. Complex Rules are programmed outside of the associated asset through an interactive user interface that allows for intricate if-then-else-and statements, which include capabilities not available to the Simple Rules. Complex Rules are evaluated at a lower frequency than Simple Rules in the simulation. The hydraulic modeling software executes Simple Rules as needed during a time step in the analysis until hydraulic feasibility is determined. Complex Rules are executed before the start of every time step. The relationship of complex and simple rules is critical to successful pump rule simulations, due to known limitation of IW due to the discovery of hydraulically infeasible solutions when logical issues are faced during the hydraulic engineering calculations. An example of this is if the simple controls include activation and deactivation for pressure set points. The hydraulic model must evaluate the pressure changes within the same iteration to determine hydraulic feasibility and, in the circumstance that a pump's activation will cause a pressure increase greater than the difference between the set points, the hydraulic solution may not be found. To mitigate this problem Simple Controls were used to perform activations, while Complex Rules were used to perform deactivations. Although Simple Rules are the closest match to PLC operations, MNWD's PLCs incorporate multiple timers that prevent instantaneous responses to set points, and the impact of these timers can be approximated with Complex Rules. The last control type, VSPs, were programmed using IW's Variable Speed Drive (VSD) Controls. VSPs are designed to dynamically alter their operations to achieve a target flow or pressure downstream of the pump. During normal operations, VSPs are used to sustain closed pressure zones.

There were several different cases for which it was necessary to directly incorporate time-series data from the MNWD SCADA database into the model. Potable intertie flowmeters, where water is imported or exported into the system, record time-series flow data. Flow control facilities located throughout the system also record time-series flow data. MNWD uses a time-partitioned SQL database to store its SCADA historical data; all recorded data of all data types are stored together in a single table per timeframe. Each record type is identified by a specified tag-id. There is a master list of tag-id definitions that allows users to easily query records associated with a particular tag-id. To use this data for calibration, the SCADA records were collected for the NHW. The appropriate tag-ids were identified in order to group and analyze flow recordings, pressure recordings, and pump operation status separately. These measurements are typically recorded every few minutes and stored in the SCADA historian. In order to incorporate these time-variant flow patterns into the model, average flow measurements were determined for the 30-minute hydraulic model time step and formatted as an IW pattern. During deployment of the DMS, these assets within the model were linked to the full SCADA historian, which is updated in regular intervals to allow for full hydraulic simulations using historical data.

Model Validation

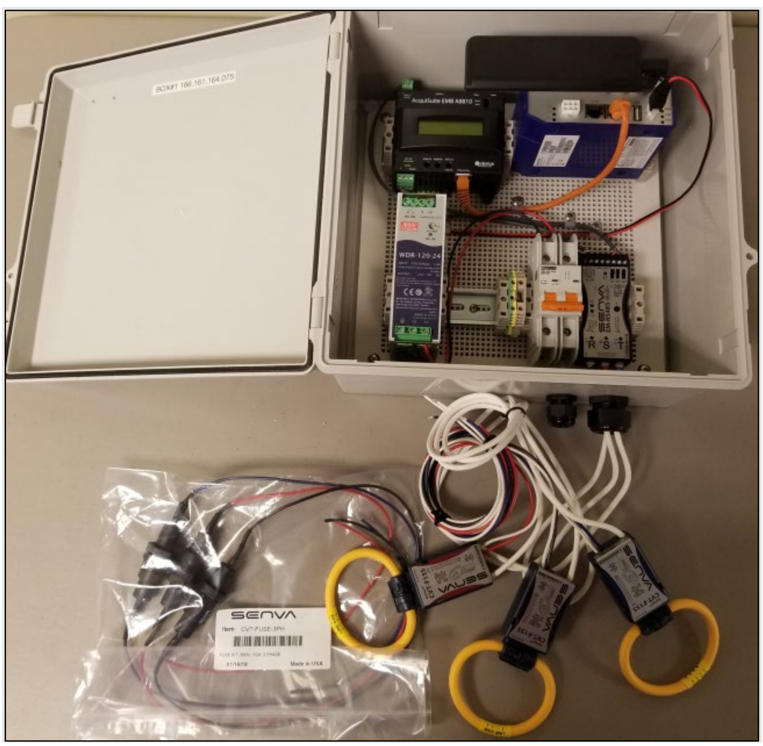
Once the model was fully constructed, it underwent a validation process in order to ensure proper simulation. Validation included a connectivity review, a hydraulic feasibility review, and an operational accuracy review. The validation process concluded with a functioning potable water distribution system ready for optimization and analysis. The first stage of model validation included confirming the status (open or closed) of pipes throughout the network to ensure logical and feasible hydraulic connectivity. Key examples included pipes and valves, which connected pressure zones throughout the system, which initially were not closed but were found to be hydraulically critical elements preventing the model from matching known SCADA data. During the design of the potable model, not all elevations or reservoir heights were known with absolute certainty and had to be adjusted as necessary to achieve a hydraulic grade line that intuitively modeled the system operations. In particular, minor adjustments to static intake heads, or elevations, and the minimum storage reservoir elevations were made to achieve water distributions from the intakes, which matched operations implied by the SCADA data. The last stage of model validation was to compare measured flow and energy data with modeled flow and energy data. This was performed in two passes, first for flow, or mass balancing, and secondly for pressure, or energy balancing. Mass balancing requires matching the height ranges and fill-drain cycles of reservoirs, as well as maintaining the typical operating flow range of pumping lift stations. Energy balancing requires matching the discharge pressures of water intakes and pumping lift stations, as well as matching known energy billing data to modeled energy demand.

Energy Interval Meters

To provide accurate energy data for the DMS, and to better perform measurement and verification of project performance and savings, sub-metering hardware was installed at participating and potentially controllable pumping facilities throughout the MNWD recycled and potable distribution systems. The energy meters, which use open-source software and fuse various available equipment for data gathering and logging purposes, were purchased and produced in entirety early in the project schedule. Due to deficiencies from an early project subcontractor, discussed in detail in the *Documentation of Helio Energy Systems Subcontractor Deficiencies* package, the data gathered by these meters would be stored at an external subcontractor's database, with limited access by the MNWD staff.

On April 8, 2019, after the removal of the subcontractor, UC Davis met with the MNWD instrumentation team to identify a path forward to enable installation of the energy sub-metering hardware in such a way as to deliver real-time energy data to the existing SCADA system of MNWD, to which MNWD and UC Davis had access and which was preferred for cost effectiveness, data security, and reliability. The selected approach connected the meters to an onsite data acquisition network owned and operated by MWND for the collection of other data at each facility, such as pump flow and discharge pressure (see Figure 11).

Figure 11: Energy Interval Meter Equipment, Per Pump Station



The equipment installed at each pump station to measure the energy demand per building.

Source: CWEE

The primary equipment used to measure energy demand at the MNWD pump stations included 1) the SENVA EM-RS 485 Protocol Energy Meter, and 2) the Obvius AcquiSuite A8810 Data

Logger. The SENVA energy meter is a three-channel meter that measures and reports the power demand of the entire building at the 15-minute resolution. The AcquiSuite data logger receives power demand measurements from the SENVA meter and stores them locally on a hard drive. Approximately once per month, the MNWD staff provided the observations from all pump stations to the UC Davis staff for review and analysis.

WaterWatch Software Installation and Deployment

The technology developed for this project, the WaterWatch software, is a local, on-premises software solution (not hosted in the cloud), designed and built by UC Davis that recommends operational decisions that enable a water distribution system to safely perform energy load shifting, ramping, and DR. This is achieved through combining water system hydraulic model functionality, real-time SCADA information, operations analytics, and optimization algorithms. The design guarantees valid operational recommendations by leveraging the engineering principles of hydraulic models with real-time, interactive overrides and controls from human operators. The critical objectives of the DMS were to:

- Forecast future water utility operations.
- Forecast future energy demand profiles and energy costs.
- Recommend optimized future water utility operations.
- Facilitate DR participation at the water utility.
- Empower utility operators to proactively explore and select new operations based on future energy rate structures or DR participation.

UC Davis produced the DMS with additional features and computational innovations using the C++ language in the Microsoft Universal Windows Platform environment for deployment on any modern Windows 10 and 11 machines, such as laptops, desktops, and tablets (see Figure 12). The completed DMS, marketed as "WaterWatch," is a robust application that leverages hydraulic models with real-time, multi-threaded computations for a highly interactive experience; it allows operators to review current and upcoming key performance indicators, review system assets in a modern blend of GIS features with three-dimensional maps, review upcoming operational recommendations and make critical overrides based on external knowledge, and compare operating scenarios based on user preferences.

The WaterWatch software was delivered to MNWD in February 2020 for the start of pilot operations just prior to the statewide public health orders stemming from the COVID-19 pandemic.

Figure 12: WaterWatch Installed on a Windows 10 Tablet

The WaterWatch software installed on a tablet, as experienced by the MNWD operations staff during the pilot.

Source: CWEE

Pilot Results

Adaption to COVID-19 Shelter-in-place Orders

In March 2020, statewide and county public health agencies employed shelter-in-place orders to reduce the spread and impact of COVID-19. MNWD, as a water utility with responsibilities to provide constant and safe drinking water, faced operational challenges to continue service while transitioning staff to remote work or practicing safe social distancing in a work environment not originally designed to accommodate the new public health requirements. At the same time, MNWD was performing the on-boarding of a new wastewater treatment plant that required immediate attention to ensure timely and effective system operation. These operational challenges spread the staff of MNWD too thinly to safely support the DMS pilot until such time as the MNWD operation staff reached a steady, balanced workload that allowed a reasonable time per week to interface with the DMS.

Ongoing conversations between MNWD and UC Davis continued monthly until MNWD determined that the operations staff had availability to safely operate the water system while maintaining remote work and safe social distancing, and also pilot the DMS technology. In February and March of 2021, MNWD and UC Davis discussed changes to the pilot design that would accommodate the safe operation of the DMS technology while requiring a minimum amount of staff time away from critical operations and still allow for remote work and social distancing. UC Davis proposed a design that leveraged the DMS as a "simulator," where operators could use the tool remotely; this approach would not require operators to interface with other staff and allowed the tool to be used during off-hours to further accommodate staff limitations. MNWD and UC Davis agreed to this approach and in April 2021 performed onboarding of the tablet and WaterWatch DMS to the MNWD firewall, such that the operations staff could safely use the tool from their home networks. In May 2021, the installation was completed with security compliance and operators received virtual, remote training.

WaterWatch Interactions

During the pilot period, WaterWatch was accessed by operators at MNWD a total of 31 times. Each time an operator interfaced with WaterWatch, the tool recorded the inputs and selections of the user and the date-time of that interaction. Once this information was extracted from the tool, the project team could reconstruct how often and for what mechanisms the tool was used. Example interactions included, but were not limited to:

- Switching between pages.
- Changing or overriding controls of an asset.
- Saving or loading a project file.
- Viewing time-series data.
- Interacting with the mapping tools.

Additionally, WaterWatch counted the number of left-clicks that the user performed within the tool every five seconds (see Figure 13). By analyzing the user interactions and the left-click counts, a continuous session with WaterWatch was identified if:

1. A WaterWatch project was loaded, and
2. WaterWatch was the top-most window in the Windows operating system, and
3. At least one left-click had been observed after the project was loaded.

The following parameters were used to determine whether MNWD operators ended a session with the tool:

1. WaterWatch was closed, or
2. 20 consecutive minutes without a valid left-click onto WaterWatch was observed (that is, the system timed out).

If the operator staff timed out, ended a session and returned on the same day, or clicked back into the application, this was considered a new session. Only one session in the pilot was started after resuming a previously timed-out session. The remaining 30 interactions with WaterWatch were observed to have ended when WaterWatch explicitly closed. Although the DMS was deployed for both the reclaimed and the potable water distribution systems, all of the observed sessions were for the potable water system; thus, it is unknown if there were spillover savings between systems.

Figure 13: Count of Left-Clicks During Use of WaterWatch

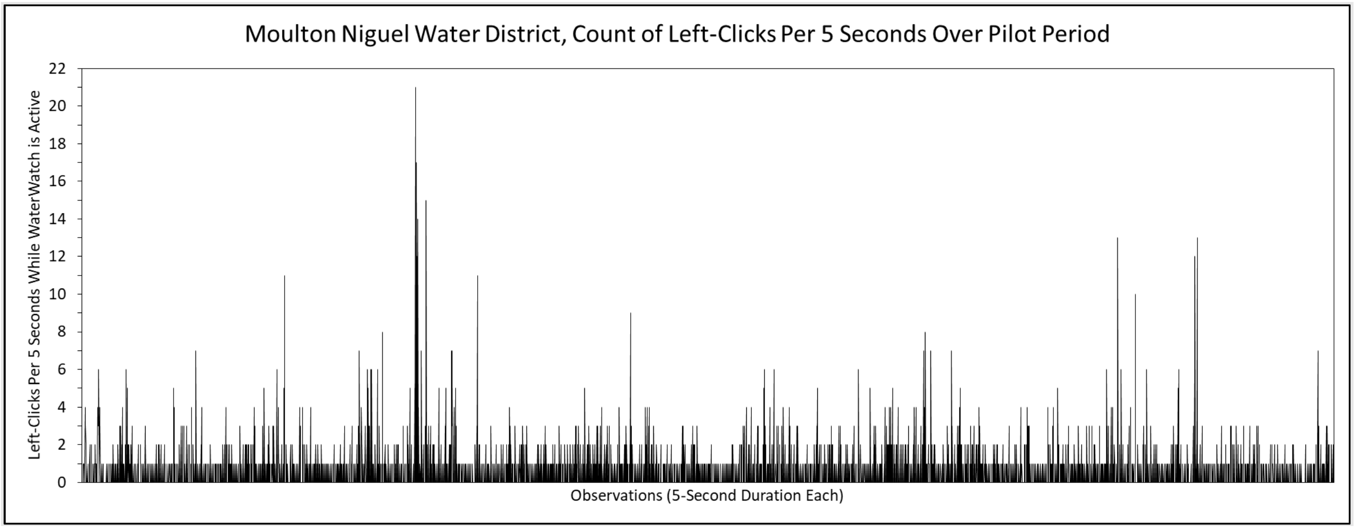


Illustration of the count of left-clicks onto WaterWatch every 5 seconds while a WaterWatch session was active. Sessions were considered to have started after a project was loaded and the first left-click was detected. Sessions were considered to have ended when WaterWatch was closed, or after 20 minutes without any left-clicks.

Source: Good, 2021

As shown in Table 5, the average duration of a session in WaterWatch was 1.57 hours, while the maximum observed duration was 8 hours. Within each session there could have been dozens to hundreds of individual actions taken, with an average of 132.77 actions per session. It appeared that the majority of interactions were accomplished at the start of each session, biasing the actions per hour to an average of 209.48, which reflects the influence of shorter sessions with a higher rate of interaction. On average, over all sessions, the user clicked on WaterWatch approximately once every 10 seconds.

Table 5: Annual Total Energy Consumed, Shifted, Emissions, and Emission Intensity Under Eight Different Optimization Scenarios

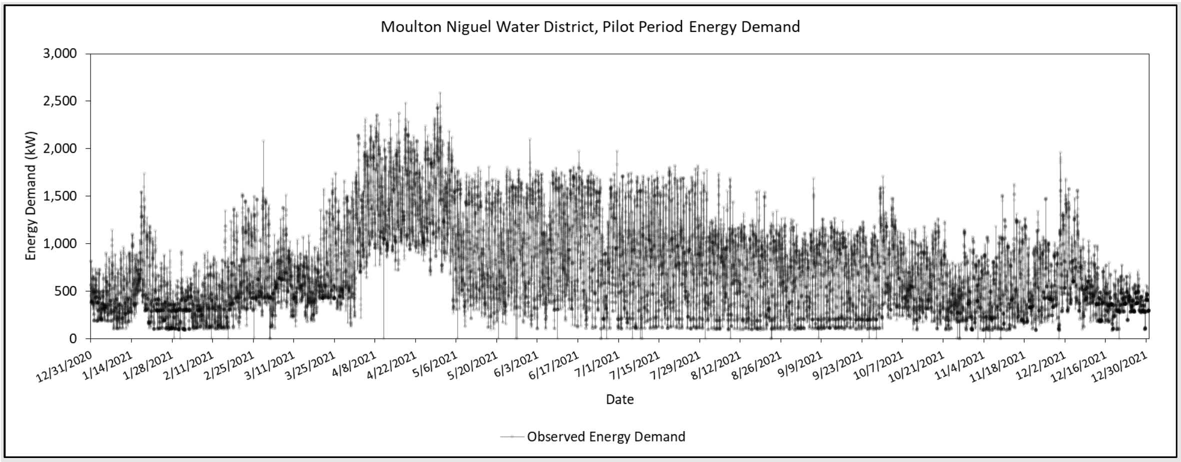
WaterWatch Interaction Summary	Average	Std. Dev.	Units
Session Duration	1.57	2.11	Hours
Actions per Session	132.77	187.31	Count
Actions per Hour	209.48	219.10	Count/Hour
Left-Clicks per 5 Seconds	0.54	1.25	Count/5 Seconds

Sessions were considered to have started after a project was loaded and the first left-click was detected. Sessions were considered to have ended when WaterWatch was closed, or 20 minutes without any left-clicks.
Source: CWEE

System Energy Consumption

Aggregating the energy demand of each pump station over the year-long pilot period, it can be observed that MNWD's energy demand was characterized by strong seasonal trends as well as diurnal variations (see Figure 14). The maximum observed energy demand from all pump stations exceeded 2.5 MW, with a typical monthly peak under 2 MW.

Figure 14: Annual Total System Energy Demand

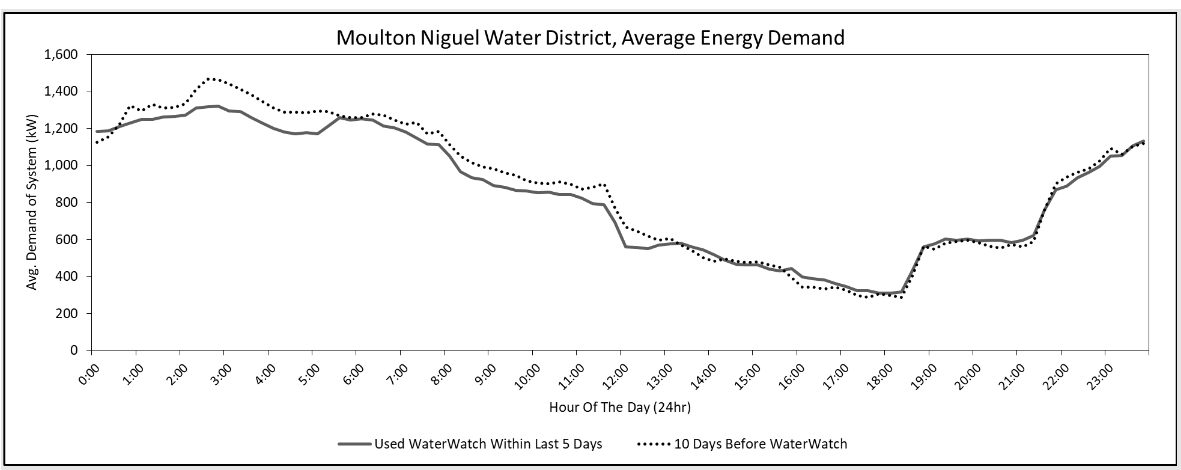


Aggregation of the energy demand of all pump stations at MNWD from January 2021 through December 2021.

Source: CWEE

The project team sought to determine if the use of WaterWatch as a companion tool to the MNWD operating staff produced any real changes to energy use or energy intensity. Assuming that the use of WaterWatch would leave a short-term influence on the MNWD operating staff, the project team compared the 10 days before each session to the 5 days after each session. Figure 15 shows the average diurnal, or daily, energy use pattern from the MNWD distribution pumps between the period before and after the start of each WaterWatch session. Qualitatively, a small reduction can be observed in the first half of the day following the use of WaterWatch.

Figure 15: Hourly Total System Energy Demand

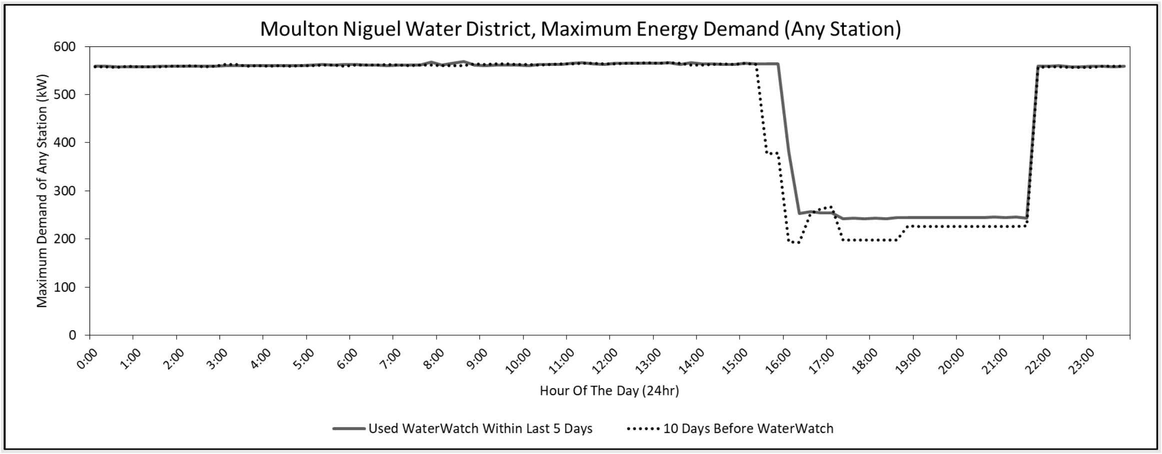


The hourly average of the total energy demand of all pump stations at MNWD from January 2021 through December 2021, isolating the 10 days prior to and the 5 days following each use of WaterWatch.

Source: CWEE

Taking the maximum energy demand of any pump station throughout the water system demonstrates that, while there is clearly some volatility, the conditions between the periods before and after the use of WaterWatch were functionally similar and do not display a change to their energy rate structure during the pilot period (Figure 16).

Figure 16: Maximum Hourly Pumping Station Energy Demand

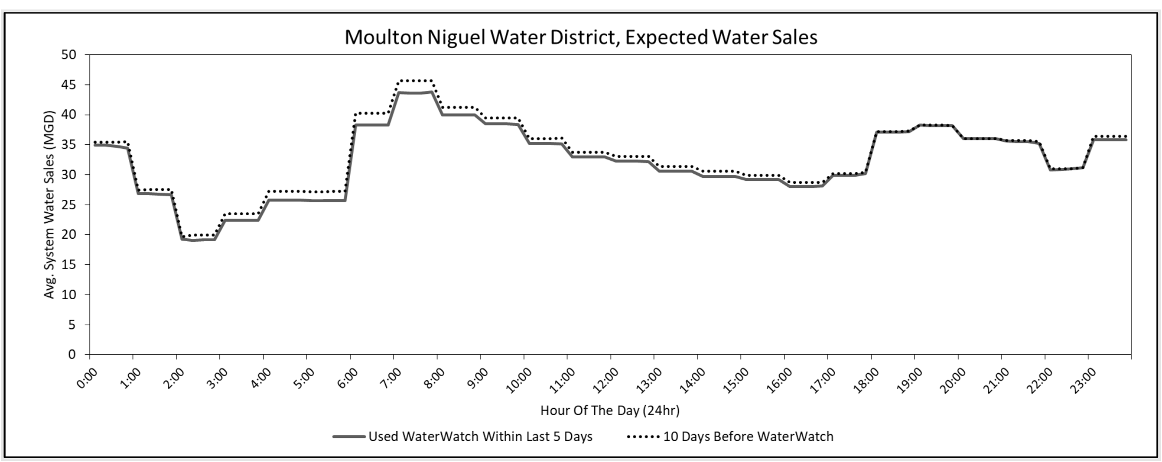


The hourly average of the maximum energy demand of any one pump station within MNWD between January 2021 through December 2021, isolating the 10 days prior to and the 5 days following each use of WaterWatch.

Source: CWEE

It was critical to identify whether any changes to energy use could be attributed to changes in water consumption on a monthly and diurnal basis. To control for these factors, the project team used the hourly water demand data for the MNWD water system developed for the energy grid model (see Chapter 4). Comparing these estimated hourly water sales with the 10 days prior to and the 5 days following the use of WaterWatch, it can be observed that there was a small reduction in the water sales in the first half of the day (Figure 17).

Figure 17: Estimated Hourly Water Sales



The hourly average of the expected hourly water sales at MNWD from January 2021 through December 2021, isolating the 10 days prior to and the 5 days following each use of WaterWatch.

Source: CWEE

Using the estimated hourly water sales and the high-resolution energy consumption data, an instantaneous estimate for the energy intensity of the water system can be generated, describing how the diurnal and seasonal changes to water sales directly impact the amount of energy required to deliver water to customers (Figure 18). The maximum observed instantaneous (that is, hourly) energy intensity was over 4.0 MWh/MG, whereas the annual average energy intensity was 0.673 MWh/MG. This demonstrates the real capacity for energy load shifting at MNWD due to the flexibility of its existing pump and storage equipment.

Figure 18: Estimated Annual Energy Intensity for Water Delivery

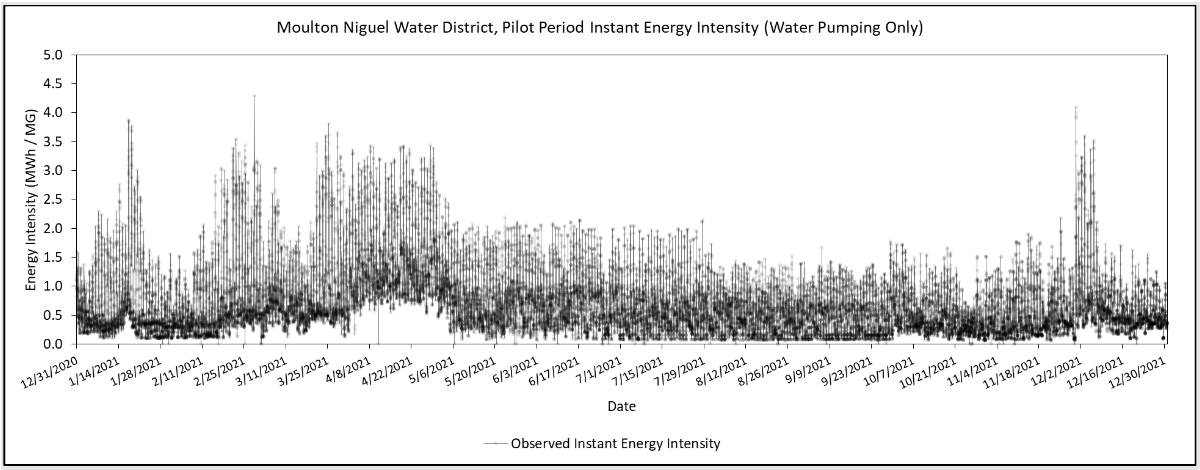
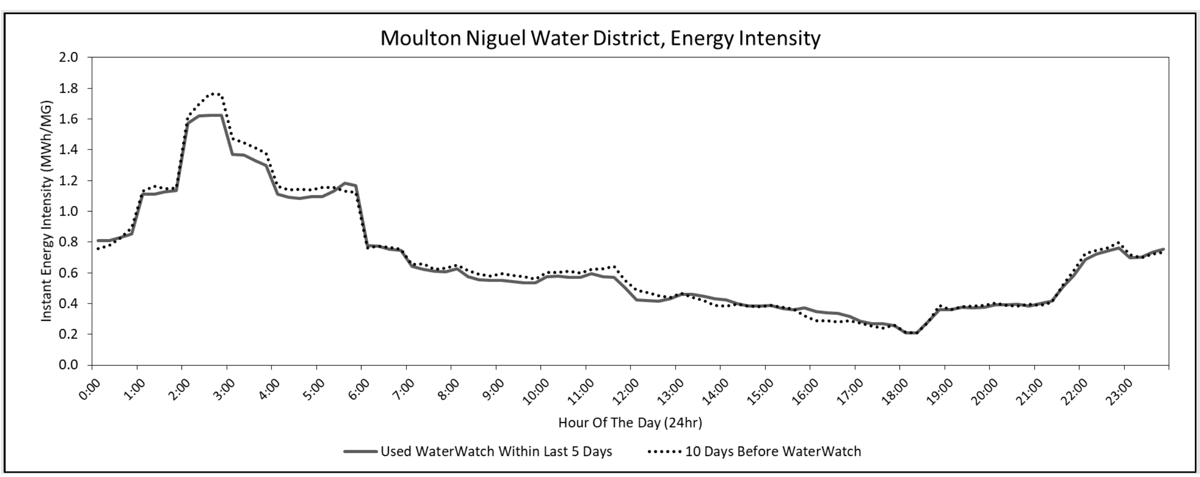


Illustration of the instantaneous energy intensity of water pumping required to serve water demand at each hour of the year, from January 2021 through December 2021.

Source: CWEE

Comparing the period before to the period after the sessions with WaterWatch using the energy intensities, it can be observed that there was a small reduction to the daily peak energy intensity between 2:00 a.m. and 3:00 a.m. (Figure 19).

Figure 19: Estimated Hourly Energy Intensity for Water Delivery



The hourly average of the instantaneous energy intensity of water pumping required to serve water demand at MNWD from January 2021 through December 2021, isolating the 10 days prior to and the 5 days following each use of WaterWatch.

Source: CWEE

WaterWatch Performance

Out of the entire year of the pilot, an approximate total of 1,624 hours was deemed to be within the 5 days following each session. To evaluate whether the WaterWatch sessions had a statistically significant, or quantifiable, impact on the energy use and energy intensity at MNWD during those days, an ordinary least-squares linear regression was performed, with four control configurations with progressively tighter and more strict controls. These configurations included:

1. Control for the exact day-of-the-year. This approach is the least accurate and the results typically provide an order-of-magnitude approximation of the real savings.
2. Control for the month of the year. This approach attempts to explain the changes to energy usage as a function of long-term seasonal trends.
3. Configuration 2 **and** control for the hour of the day. This approach attempts to explain the changes to energy usage as a function of long-term seasonal trends as well as daily, diurnal patterns.
4. Configuration 3 **and** control for the hourly water sales. This approach attempts to explain the changes to energy usage as a function of long-term seasonal trends, daily trends, and the direct hourly water sales.

Configuration 1 (Table 6), using the exact date control, results in highly statistically significant (greater than [>] 99.9 percent confidence) estimates for the reduction to energy demand due to the WaterWatch sessions by 145 kW during the 5 days after a session took place, in comparison to the 10 days prior to each session.

Table 6: Statistical Regression Results, Configuration 1

Dependent Variable (Units)	Power Demand (kW)	Energy Intensity (MWh/MG)	Energy Consumption (kWh/15 min)
Average	728.5–883.2[1]	0.673–0.676[1]	182.1–220.8[1]
Constant	547.713*** (43.64)	0.664*** (0.03)	136.928*** (10.91)
Used WaterWatch Within Previous 5 Days	**-145.634***** (26.5)	-0.008 (0.02)	**-36.408***** (6.62)
Percent Impact	-16.49 percent	N/A	-16.49 percent
Control for Water Sales	-	-	-
Control for Hour of Day	-	-	-
Control for Month of Year	-	-	-
Control for Exact Date	Yes	Yes	Yes

1 The range includes the annual average and the average from all observations used in the regression.
*** denotes significance at the 0.1 percent level.

Results of the ordinary least-squares linear regression with control configuration 1.

Source: CWEE

Configuration 2 (Table 7), using the seasonally motivated month control, results in highly statistically significant (>99.9 percent confidence) estimates for the reduction to energy demand and energy intensity due to the WaterWatch sessions by 39 kW and 0.025 MWh/MG, respectively, during the 5 days after a session took place, in comparison to the 10 days prior to each session.

Table 7: Statistical Regression Results, Configuration 2

Dependent Variable (Units)	Power Demand (kW)	Energy Intensity (MWh/MG)	Energy Consumption (kWh/15 min)
Average	728.5–883.2[1]	0.673–0.676[1]	182.1–220.8[1]
Constant	450.091*** (6.79)	0.598*** (0)	112.523*** (1.7)
Used WaterWatch Within Previous 5 Days	**-39.562***** (6.62)	**-0.025***** (0)	**-9.891***** (1.65)
Percent Impact	-4.48 percent	-3.70 percent	-4.48 percent
Control for Water Sales	-	-	-
Control for Hour of Day	-	-	-
Control for Month of Year	Yes	Yes	Yes
Control for Exact Date	-	-	-

1 The range includes the annual average and the average from all observations used in the regression.
*** denotes significance at the 0.1 percent level.

Results of the ordinary least-squares linear regression with control configuration 2.

Source: CWEE

Configuration 3 (Table 8), introducing the daily diurnal control, results in highly statistically significant (>99.9 percent confidence) estimates for the reduction to energy demand and energy intensity due to the WaterWatch sessions by 35 kW and 0.027 MWh/MG, respectively, during the 5 days after a session took place, in comparison to the 10 days prior to each session.

Table 8: Statistical Regression Results, Configuration 3

Dependent Variable (Units)	Power Demand (kW)	Energy Intensity (MWh/MG)	Energy Consumption (kWh/15 min)
Average	728.5–883.2[1]	0.673–0.676[1]	182.1–220.8[1]
Constant	401.864*** (8.65)	0.591*** (0.01)	100.466*** (2.16)
Used WaterWatch Within Previous 5 Days	**-35.582***** (4.95)	**-0.027***** (0)	**-8.896***** (1.24)
Percent Impact	-4.03 percent	-3.99 percent	-4.03 percent
Control for Water Sales	-	-	-

Dependent Variable (Units)	Power Demand (kW)	Energy Intensity (MWh/MG)	Energy Consumption (kWh/15 min)
Control for Hour of Day	Yes	Yes	Yes
Control for Month of Year	Yes	Yes	Yes
Control for Exact Date	-	-	-

1 The range includes the annual average and the average from all observations used in the regression.
*** denotes significance at the 0.1 percent level.

Results of the ordinary least-squares linear regression with control configuration 3.

Source: CWEE

Lastly, configuration 4 (Table 9) introduces the hourly water sales control and results in highly statistically significant (>99.9 percent confidence) estimates for the reduction to energy demand and energy intensity due to the WaterWatch sessions by 35 kW and 0.025 MWh/MG, respectively, during the 5 days after a session took place, in comparison to the 10 days prior to each session.

Table 9: Statistical Regression Results, Configuration 4

Dependent Variable (Units)	Power Demand (kW)	Energy Intensity (MWh/MG)	Energy Consumption (kWh/15 min)
Average	728.5–883.2[1]	0.673–0.676[1]	182.1–220.8[1]
Constant	405.202*** (14.1)	1.038*** (0.01)	101.301*** (3.53)
Used WaterWatch Within Previous 5 Days	**-35.570***** (4.95)	**-0.025***** (0)	**-8.892***** (1.24)
Percent Impact	-4.03 percent	-3.70 percent	-4.03 percent
Control for Water Sales	Yes	Yes	Yes
Control for Hour of Day	Yes	Yes	Yes
Control for Month of Year	Yes	Yes	Yes
Control for Exact Date	-	-	-

1 The range includes the annual average and the average from all observations used in the regression.
*** denotes significance at the 0.1 percent level.

Results of the ordinary least-squares linear regression with control configuration 4.

Source: CWEE

The four configuration results appear to narrow in on a consistent result, using the most complex and complete regression configuration; the reported result from this pilot is that the influence of WaterWatch on MNWD operating staff resulted in direct, achieved savings of 4.03 percent in energy demand and 3.7 percent in energy intensity for the 5 days following each use of WaterWatch.

These results were generated using an expected influence period of 5 days following each use of the WaterWatch tools. Shorter influence periods unacceptably reduced the samples available for the regression, whereas increasing the influence period to 10 days or more reduced the significance of the savings below standard requirements. It is therefore expected that the real period of influence was between 1 to 10 days following each use of WaterWatch.

Review of Benefits and Impact on California

Using the final coefficients for the achieved savings in energy demand and energy intensity at the MNWD pilot from using the WaterWatch tools for educational purposes (see Table 9), it is estimated that, over the estimated 1,624.25 hours of influence from the sessions, MNWD directly saved 57.77 MWh in energy consumption (see Table 10). If MNWD used WaterWatch throughout the year on a weekly basis, it is expected that the utility might save 311.58 MWh annually through direct performance gains discovered by operators following use of Water-Watch. Using the results of the energy grid model to estimate the size and scope of water distribution in California, it is anticipated that, if every public water agency in California leveraged WaterWatch on an approximately weekly basis, there would be an aggregate annual savings of 131,815 MWh.

Table 10: Benefits from Using WaterWatch for Education

Parameter (Units)	Condition	Value
Consumption (MWh)	Achieved Savings (MNWD)	57.77 (MWh)[1]
Consumption (MWh)	Expected Annual Savings (MNWD)	311.58 (MWh)[2]
Consumption (MWh)	Expected Annual Savings (California)[5]	131,815 (MWh)[3]
Energy Intensity (MWh/MG)	Achieved Savings (MNWD)	0.025 (MWh/MG)[1]
Emissions ($MTCO_2e$)	Achieved Savings (MNWD)	8.97 ($MTCO_2e$)[1,4]
Emissions ($MTCO_2e$)	Expected Annual Savings (MNWD)	48.36 ($MTCO_2e$)[2,4]
Emissions ($MTCO_2e$)	Expected Annual Savings (California)[5]	20,457.69 ($MTCO_2e$)[3,4]

1 Statistically significant savings detected during the 1,624.25 hours that WaterWatch was in active use using the coefficient of reduction from the final statistical analysis.
2 Assumes that the coefficient of reduction from the final statistical analysis was applied to all hours of the year.
3 Assumes that the water distribution sector's energy use agrees with scenario 1 of the energy grid model results.
4 Assumes that the average emission intensity of the water sector agrees with scenario 1 of the energy grid model results (0.1552 $MTCO_2e$/MWh).
5 Assumes the same list of public water utilities as those studied in the energy grid model.

Resource savings achieved during the pilot, as well as the expected resource savings if the approach taken during the pilot were extended to the entire year, and if the approach were extended to all public water utilities in California evaluated by the energy grid model.

Source: CWEE

MNWD demonstrated a small reduction to its energy intensity, which appeared to have taken place during its daily peak energy demand. It is unclear if this change would scale to additional water systems. Assuming an energy intensity of 0.1552 $MTCO_2e$/MWh, it is expected that California could achieve a savings of 8.97 $MTCO_2e$ and a reduction of 20,457 $MTCO_2e$ annually if all utilities used WaterWatch approximately weekly.

The average duration of any session with WaterWatch was approximately 1.5 hours, which includes all sessions with the tool over the pilot period. Assuming that operators continue with weekly sessions, it is expected that each water utility would invest approximately 80 hours annually from one operator to achieve these reported savings. It is unknown from this pilot whether these savings are additive with additional operators using and accessing the tool. Additionally, it is unknown from this pilot how many sessions, if any, are required before the savings become permanently achieved without requiring additional sessions. Lastly, it is unknown from this pilot how these savings would change if the operations staff used the WaterWatch recommendations and results directly instead of simply using it as an educational tool.

CHAPTER 6: Technology and Knowledge Transfer

This chapter outlines the knowledge dissemination activities undertaken during the project period and any outstanding future activities to disseminate the knowledge gained, experimental results, and lessons learned to the public and key decision makers.

Through the pilot of the DMS technology at MNWD and the investigation into the capacity for energy load shifting from water distribution activities in California, the project team developed new knowledge in several areas and disseminated the knowledge across the project duration. The knowledge gained included barriers to energy load shifting in the water sector, innovations to hydraulic modeling and real-time data management for water systems, advanced policy-based optimizations, characterization of the challenges facing the energy sector in California, characterization of water system operational flexibility, and operational considerations for using DMS tools for real-time decision support at water distribution systems.

Because the categories of knowledge included technical, social, and regulatory components, each with a diverse audience, several dissemination methods were used to ensure successful communication. These include articles in peer-reviewed journals, presentations at conferences and university events, a webinar, factsheets, and online resources. These published resources will be made available on CWEE's website and will continue to be distributed at conferences and delivered to audience-specific events, such as industry sustainability activities and showcases. CWEE intends to continue with knowledge transfer beyond the duration of the project, through additional peer-reviewed journals and presentations at related conferences or events.

The intended audiences of the pilot project include hydraulic model developers, retail water systems, wholesale water systems and regulators with an interest in water system operation and optimization, energy suppliers and energy grid managers with an interest in energy tariffs and joint water-energy projects, and the general public. Additional audiences for project results and performance data include academics with an emphasis on the optimization and analysis of water distribution systems, as well as policy makers who work in water efficiency and energy efficiency.

The project team disseminated the project results to diverse audiences through journal articles, conference talk, event presentations, the development of print and online resources, and commercial availability of the DMS tool.

Six target audience categories were planned to receive project knowledge, including:

1. **Industry:** Including developers and programmers of hydraulic modeling design analysis tools.
2. **Academia:** Research facilities, staff, and students with an emphasis on the optimization and analysis of water distribution networks.

3. **Retail Water Systems:** Including those with an interest in short-term analysis or curiosity, all the way to those seeking real-time decision support.
4. **Wholesale Water Systems and State Regulators:** Those with an interest in cataloguing and accessing operation or network data about water systems.
5. **Energy Suppliers and Grid Managers:** Those with an interest in managing electric grid concerns and developing energy rate tariffs that reflect grid goals and those interested in working on joint water-energy projects.
6. **Policy Makers:** Those creating water policy decisions and new regulations around water sourcing, water systems operation, and water efficiency in the state.
7. **General Public:** All individuals potentially impacted by water system operators who modify their operations (for example, pressure reliability and water age) by using the DMS.

The following is a list of the useful knowledge that was gained from the project and transferred to the target audiences by:

- Communicating the value and potential of using WaterWatch Software.
- Determining energy and GHG savings using the WaterWatch Software at the pilot site.
- Showcasing how WaterWatch Software can be used as a collaboration tool across teams at a water utility.
- Communicating the barriers when creating a software for water system dissemination.
- Conveying barriers and considerations for implementation of next-generation software at water utilities.
- Providing tangible actions and a roadmap for a water utility to harness its data, allowing for full collaboration across departments toward operational goals.
- Describing the case study of software user experience at a water utility.
- Communicating considerations when creating an energy rate tariff for water distribution systems that incentivize load shifting and desired grid impact.
- Determining the electric load-shifting capability of the water distribution sector in California.

Technology and Knowledge Transfer Activities

Due to the large and diverse target audiences and the quantity of knowledge to be communicated, many dissemination methods were used to ensure that all the knowledge gained from this project was communicated appropriately. Transmission methods include several journal articles that will be published in peer-reviewed journals, presentations at conferences, webinars, university events, factsheets, handouts, and a software application. The published articles were made available on the CWEE's website (https://cwee.ucdavis.edu/publications/), published in peer-reviewed journals, and delivered to audience-specific events.

Journal Articles

Two peer-reviewed academic journal articles were accepted and published during the project period. These articles are available broadly in an open access journal. The citations are listed here:

Linz, D., E. Musabandesu, B. Ahmadi, R. Good, and F. Loge. 2020. "Multi-threaded simulation optimization platform for reducing energy use in large-scale water distribution networks with high dimensions." Proceedings of the 2020 Winter Simulation Conference, Virtual. Institute of Electrical and Electronic Engineers (IEEE). December 14–18, 2020. Available at https://doi.org/10.1109/WSC48552.2020.9383920.

Li, Y., E. Musabandesu, T. Fujiwara, F.J. Loge, and K. Ma. 2021. "A Visual Analytics System for Water Distribution System Optimization." 2021 IEEE Visualization Conference (VIS). New Orleans, Louisiana, October 24–29, 2021. 126–130. Available at https://doi.ieee computersociety.org/10.1109/VIS49827.2021.9623272.

Rupiper, A., R. Good, G. Miller, and F. Loge. 2024. "Mitigating renewables curtailment and carbon emissions in California through water sector demand flexibility." *Journal of Cleaner Production*, 437, 140373. Available at https://doi.org/10.1016/j.jclepro.2023. 140373.

Two peer-reviewed academic journal articles are in progress:

Musabandesu, E., R. Good, J. Herman, and F. Loge. In progress. "Reformulating Water Distribution System Operation Optimization for Energy Demand Management with Hierarchal Control Policies."

Musabandesu, E., Y. Li, T. Fujiwara, K.L. Ma, and F. Loge. In progress. "Opening the Black Box of Water Distribution System Optimization: Visualizing Fitness Function Structure for Human-Guided Optimization."

Presentations at Conferences and Events

Researchers have spoken at several conferences, events, and site visits. Table 11 summarizes the primary presentations given during the project period.

Table 11: Presentations and Seminars

Date	Event	Title	Presenter
April 2018	UC Davis Energy Efficiency Institutes Affiliates Forum (Poster)	Reducing Electricity Grid Imbalances Through Energy Demand Management of Water Delivery Infrastructure	Robert Good
May 2018	UC Davis Energy Efficiency Institute Energy Bites Seminar	Energy Demand Management Systems for Potable Water Systems: A case study	Robert Good
December 2018	California Water Efficiency Partnership (CalWEP) Plenary	Introducing an Energy Demand Management System	Kendra Olmos

Date	Event	Title	Presenter
May 2019	CalWEP Peer-to-Peer	Water Conservation Leads to Energy and Carbon Savings: Why are Water Utilities Not Receiving Credit?	Kendra Olmos
August 2019	UC Davis Energy Exchange Webinar Series (Webinar)	Ensure Effective Water Delivery and Optimize Energy Use: Enabling Data Driven Choices With Smart Software	Erin Musabandesu
October 2019	WaterSmart Innovations Conference and Exposition, Las Vegas, Nevada	Utilizing Policy Optimization for Pump Operations at Water Distribution Systems to Enable Energy Load Shifting	Erin Musabandesu
December 2019	UC Davis Energy Efficiency Institute Board of Advisors Meeting	Advancing Demand Response in the Water Sector	Frank Loge
October 2020	AWWA California/Nevada Annual Fall Conference (Virtual)	Utilizing Policy Optimization for Pump Operations at Water Distribution Systems to Enable Energy Load Shifting	Erin Musabandesu and Frank Loge
December 2020	Virtual Meeting With Sonoma Water	WaterWatch Demonstration 1	Robert Good and Frank Loge
December 2020	Winter Simulation Conference – Virtual	Multi-threaded Simulation Optimization Platform for Reducing Energy Use in Large-Scale Water Distribution Networks With High Dimensions	David Linz
January 2021	Virtual Meeting with Sonoma Water	WaterWatch Demonstration 2	Robert Good and Frank Loge
February 2021	UC Davis Center for Water-Energy Efficiency	WaterWatch Software Focus Group	Robert Good and Frank Loge
March 2021	Virtual Meeting With San Diego Water Authority	WaterWatch Demonstration	Robert Good and Frank Loge
June 2021	UC Davis Energy Efficiency Institute Board Meeting	WaterWatch Software: Decision Support for Water Distribution System Operations	Kendra Olmos and Robert Good

Date	Event	Title	Presenter
November 2021	UC Davis Energy Efficiency Institute Affiliates Forum (Webinar)	WaterWatch Software: A Planning and Management Tool for the Whole Team	Robert Good
December 2021	UC Davis Energy Efficiency Institute Board of Advisors Meeting	How the California Water Distribution Sector Can Shift Energy Demands, Reduce GHG Emissions, and Increase Renewable Energy Integration Statewide	Amanda Rupiper

Source: CWEE

Marketing Materials for WaterWatch

Throughout the project period and software development, CWEE has generated several marketing materials related to the WaterWatch software. Below is a list of the primary materials generated to date.

- WaterWatch Brochure: https://cwee.ucdavis.edu/wp-content/uploads/WaterWatch-Brochure_052021.pdf
- WaterWatch Software Frequently Asked Questions: https://cwee.ucdavis.edu/water watch/#FAQ
- WaterWatch User Manual
- WaterWatch Software Minimum User Requirements
- WaterWatch Software User Group Support Plan
- WaterWatch Software Demonstration Presentation (custom tailored to each utility)

CHAPTER 7: Production Readiness

Historically, water utilities are conservative in adopting new technologies that lack multiple full-scale pilots or demonstrations. The adoption of WaterWatch is no exception. A Production Readiness Plan was prepared to outline the potential avenues that UC Davis CWEE may take to further the adoption and commercialization of the innovative software. This includes the original Support Program Plan, details on the current barriers to implementation, and options for spinning up a new company to seek capital and move WaterWatch development and pilot testing forward to ensure that the product is made available to the water system broadly.

Production Readiness Plan

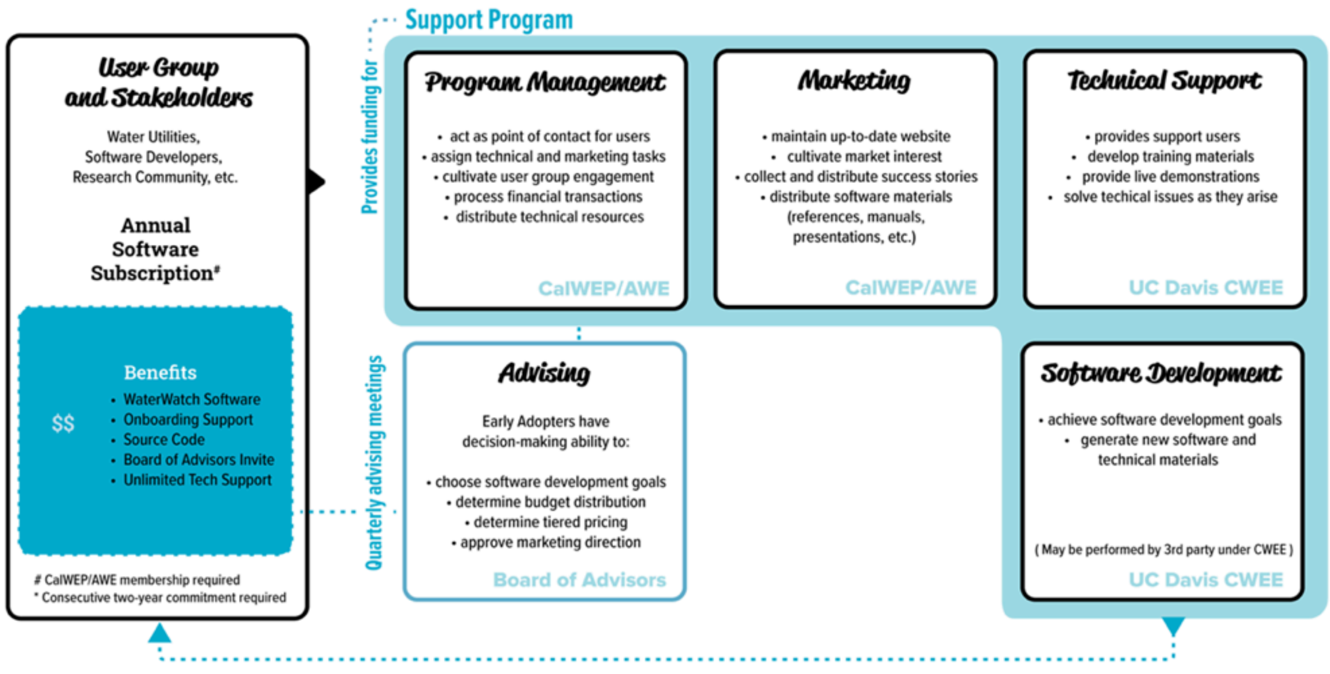
The California Water Efficiency Partnership (CalWEP), with support from its parent organization, the Alliance for Water Efficiency (AWE), and in collaboration with UC Davis CWEE, designed a program for CWEE to provide support for and enable widespread adoption of the software following completion of the CEC grant period. This included the development of a user group that would adopt the technology early after its development and serve as the first technology users to provide feedback on the software and produce use cases that will generate trust and interest from other water utilities throughout the state to facilitate future adoption.

The Support Program goals were 1) expanding stakeholder engagement, 2) broadening the user base, 3) providing ongoing technical support, and 4) responding to feedback for software and feature development. Tiered annual subscriptions to fund the not-for-profit activities are outlined in Figure 20.

The Support Program would continually develop and support the integration of WaterWatch software within the water distribution systems across the country. CalWEP and the AWE would oversee program management, develop educational materials and webinars, and market the software suite in order to grow the user base, thereby increasing the number of collaborative opportunities available to existing users. UC Davis CWEE would focus on providing technical support and ongoing software development.

Subscribers would not only have access to the software, but they would also be part of the overall initiative to further expand on the environment and its software offerings, including the development of additional WaterWatch features. Early adopters would be invited to join the board of advisors to steer product development, approve industry marketing direction, and advise on tiered rate pricing. Membership in CalWEP/AWE would be required.

Figure 20: Support Program Design



Illustrated design of the Support Program to enable the growth and distribution of WaterWatch.

Source: CWEE

Annual subscription rates would be informed by market interest, costs to the organizations running the program, market pricing for similar products, and grants available to subsidize the cost, among other factors. Funding generated would be split into base annual costs to fund program operation, as shown in Figure 20, and the remaining funding would go toward software development.

Barriers to Commercialization

The project team experienced several barriers to implementation and adoption of the software that made it challenging to obtain users prior to the end if the grant project period. Many are barriers that UC Davis CWEE is working on overcoming through an expansion of the research efforts. Others are challenges that will need to be overcome with time, or with the use of additional funding. Major barriers and their potential future solutions include:

1. <u>Hydraulic Model Availability</u>: The most critical user requirement of WaterWatch, and of all DMS tools that seek to generate safe recommendations, is a complete and updated water distribution system hydraulic model one that is calibrated sufficiently to represent current conditions of the system. While future management of distribution systems and water and energy efficiency will be driven by advanced intelligence, including hydraulic models, California water utilities as a whole have not advanced to using current hydraulic models. Though some do have the models or are working on having them built, it is CWEE's experience that these models are typically not built or calibrated sufficiently to enable trustworthy operation decision making. One major

barrier to new and updated models being of high quality is a lack of industry-wide standards in how to calibrate hydraulic models consistently and measurably.

   a. Solutions: UC Davis CWEE is an expert in building hydraulic models and has developed a method for accurately calibrating models. CWEE is actively seeking funding avenues to support research into developing a hydraulic model calibration handbook that can be used by utilities and consulting engineers to build accurate models. Any water utility that wants to pilot or adopt WaterWatch will need to have its hydraulic model evaluated and upgraded to meet the standards needed to fully use the software. As part of any system onboarding process, UC Davis CWEE will need to help facilitate this evaluation and upgrade the model, either by consulting with the utility on how to make the changes or by CWEE performing the work.

2. SCADA Data Availability: Another critical user input for obtaining the full benefits of the software is water system SCADA data — at a minimum, tank levels and pump status or flow. While many utilities have SCADA data, many do not, or the data is not accessible due to lack of support for automatic data access.

   a. Solution: If a utility is interested in using WaterWatch, it can still be onboarded and explore the software without SCADA data, but its use will be limited to simulations and recommendations that cannot be made up-to-date with current field measurements. For those entities wanting to improve their water system management and operations, an investment in SCADA will be needed to advance their water system into the 21st century. Ideally, the incoming federal infrastructure plan investment will have funding to help water utilities modernize with SCADA systems. Other current federal and state opportunities also exist for water utilities to seek grant funding for infrastructure improvements.

3. Utility Interest: Most water utilities are not early adopters and will wait for multiple technology proofs of concept to be implemented before even considering adoption of a new technology.

   a. Solution: As UC Davis CWEE can publish and market the pilot results of implementing WaterWatch at MNWD, it will be easier to generate interest from other utilities. Interest will grow as more early adopters test the software.

4. Energy Rate Issues: Currently, as demonstrated by the energy grid model results, the specific energy tariff rates applied at water utilities play an enormous role in determining the flexibility of a water system, and they may prevent use of the full pumping and storage resources accessible to the water system. UC Davis CWEE has supported research on the issues surrounding the gap of rate structures or on programs that will support and incentivize water utilities to participate in load shifting. Furthermore, performing live testing of WaterWatch for energy management is also a challenge, as water utilities could be penalized in the form of increased energy bills when testing out a new technology that specifically seeks to modify the time of energy

use. In particular, this concern was voiced while converting the MNWD pilot to an offline education program.

a. Solutions: CWEE developed a tool in WaterWatch that allows for the evaluation of using different energy rate structures as a means to pick the best available existing tariff within each energy supplier's territory in California. Also, as a next step to increase the water sector's ability to engage in energy demand management, UC Davis CWEE is working with SCE on understanding the existing barriers and needs unique to the water sector in regard to energy rates. A proposal is in review that will help SCE to fully characterize how time-based market mechanisms are being used by water utility companies within the SCE territory, identify any additional barriers to energy load shifting under the current incentives, and examine what rate structure characteristics may enable greater energy management, including more dynamic response from the water sector. The next step would be to have SCE develop a new rate for testing and pilot the new rate at several utilities. Additionally, UC Davis CWEE worked with MNWD, SCE, and SDG&E to begin setting up the ability to test WaterWatch without rate penalties if done during the off-peak seasons. MNWD hopes to perform a live pilot of WaterWatch in coordination with SCE and SDG&E. Finally, the team is working with Orange County Power to get approval from the CPUC to create an energy rate structure that is custom for the water sector; this may prove to be a more rapid route of moving forward if the SCE effort fails to materialize quickly.

5. Lack of Funding: The biggest current barrier to furthering the implementation and commercialization of the software is lack of funding. The CEC award was sufficient to develop the product and to onboard and perform pilot testing at one site. This was critical in developing the minimum viable product and proving market viability. To engage the user group and generate proven results at multiple locations, such that more utilities will want to adopt the technology, the project will need further funding.

    a. Solution: UC Davis CWEE has been cultivating relationships with funders and actively seeking grant and private funding opportunities to fund pilot implementation projects with WaterWatch. Applications are currently being developed for funding from the California Department of Water Resources, SCE, and Commonwealth Edison (in Illinois) to fund onboarding a water utility, making improvements to its hydraulic model, and performing a pilot. The team is also leveraging a current project to onboard an eligible water utility that will then have an opportunity to pilot the software. However, the more likely method of infusing funding into the WaterWatch software effort is through investor capital (discussed below).

Commercialization of WaterWatch

Due to the barriers experienced while attempting to build momentum with WaterWatch, and a lack of current support from early adopter water utilities, the Support Plan cannot yet be implemented without seed funding to mobilize utility participation. As CWEE continues to market WaterWatch and make one-on-one connections with water utilities, the option exists to implement the Support Plan in the future, if CWEE could onboard three to five utilities concurrently. It is estimated that, with an amount in the $300,000 to $500,000 range, CWEE could 1) update and calibrate the hydraulic model of three to five interested utilities, 2) gain utility interest in performing a pilot at no cost to it and offer an incentive amount to cover its labor cost in participating in a pilot, and 3) be able to maintain the software and make bug fixes and improvements as utilities are piloting the software. Unfortunately, no state or federal grant opportunities have arisen that would be suitable for funding this type of effort. The next step to production readiness and commercialization is to seek startup funding, of which there are many opportunities.

All opportunities for seeking an infusion of capital for a commercialization opportunity must be sought out by a for-profit entity. Since UC Davis is a nonprofit, CWEE cannot apply directly to the many programs that help start-up technology companies. Therefore, the first step is for CWEE to spin out a private company for WaterWatch. To do this, CWEE must first develop a patent for the innovations within WaterWatch and then proceed with an internal process through the university to release the patent for the pursuit. CWEE has begun this process and is in the middle of developing the patent application and securing trademark and copyright licenses. CWEE projects that, once the patent application is completed, there will be strong pursuit of the investor programs thereafter.

There are a number of start-up investment programs that CWEE could apply for. A summary of the most promising programs found to be of interest are listed below. The most likely initial success is expected to be with the UC Venture Capitalist Program and the CalSEED Program.

1. UC Davis Venture Capital: This program (https://research.ucdavis.edu/offices/vc/) will help guide UC Davis inventors with technologies developed on campus through developing new viable ventures outside the university. It has a Smart Toolkit for Accelerated Research Translation Program to provide tools in forming and growing a successful company. It also provides guidance and support to navigate the federal Small Business Innovation Research (SBIR) Program.
2. SBIR and STTR Programs: The Small Business Innovation Research and the Small Business Technology Transfer programs are government-run programs (https://www.sbir.gov/about) that engage selected small businesses with federal research and development programs. The program has multiple offerings each year offered by a number of agencies, such as the Department of Energy and the National Science Foundation. The programs are challenging to navigate, which makes the UC Davis Venture Capital program desirable.
3. ImagineH2O: This program (https://www.imagineh2o.org/) is a technology accelerator program for water-related innovations. It has several challenge competition programs that help launch startup companies through financial awards, mentorships, showcases, and other tools for success.
4. Isle Utilities: This organization (https://www.isleutilities.com/) serves to promote and connect technology companies with end users through its many global technology

forums. It does not provide direct investment funding but it can be a tool to introduce WaterWatch to interested parties that could fund a pilot program.

5. CalSEED: This CEC-funded program (https://calseed.fund/about/) advances energy innovation through grants to promising technology startups.
6. New Energy Nexus: This organization (https://newenergynexus.com/programs) has a number of startup support programs to help launch energy-related technologies, including accelerators, seed funding, and pilot programs.

Funded or Planned Expansion Projects

UC Davis CWEE is dedicated to further the validation and commercialization of WaterWatch software. It will continue efforts to seek grant and private funding for pilot and development projects. Meanwhile, it will also work on finalizing the patent application and getting a release from UC Davis to spin WaterWatch into a stand-alone company that can seek investment funding. However, WaterWatch will still remain owned by UC Davis and CWEE will be able to use and develop the product in-house. Project efforts involving research with WaterWatch will still be run out of CWEE.

WaterWatch software has clear potential, as detailed in the final project report, the final measurement and verification report, and in reference to the overall potential of California water utilities to aid in grid stabilization as defined in our final grid model report. Additionally, the satisfaction of the product by the first user, MNWD, and its commitment to continue using WaterWatch is a testament to the value of the product. MNWD agreed to award a small development contract to UC Davis CWEE to add a new functional module to the software beginning in early 2022. The hope is that the promising value and impact the WaterWatch software has to offer both the water sector and the energy sector will create new grant funding opportunities at the state level, in addition to CWEE's planned efforts to develop an independent company.

User Group Roster

The project team met with several water systems to advertise the availability and features of WaterWatch and to identify which water systems would be interested in partnering with the project team in the future (Table 12).

Table 12: User Group Roster

Water System	Classification
Moulton Niguel Water District	Active User with Interest in Continued Use
California Water Service	Potential User with Interest in WaterWatch
East Bay Municipal Water District	Potential User with Interest in WaterWatch
Irvine Ranch Water District	Potential User with Interest in WaterWatch
Marin Municipal Water District	Potential User with Interest in WaterWatch
Santa Clarita Valley Water	Potential User with Interest in WaterWatch

Water System	Classification
Western Municipal Water District	Potential User with Interest in WaterWatch
Alameda County Water District	Prospective User
Anaheim, City of	Prospective User
Antelope Valley-East Kern Water Agency	Prospective User
Carlsbad, Municipal Water District	Prospective User
City of Orange	Prospective User
City of Stockton	Prospective User
Corona, City of	Prospective User
Eastern Municipal Water District	Prospective User
El Dorado Irrigation District, Main	Prospective User
Elsinore Valley Municipal Water District	Prospective User
Escondido, City of	Prospective User
Fairfield, City of	Prospective User
Fullerton, City of	Prospective User
Garden Grove, City of	Prospective User
Glendale — City, Water Department	Prospective User
Huntington Beach, City of	Prospective User
Jurupa Community Service District	Prospective User
Long Beach — City, Water Department	Prospective User
Oceanside, City of	Prospective User
Olivenhain Municipal Water District	Prospective User
Ontario Municipal Utilities Company	Prospective User
Pasadena — City, Water Department	Prospective User
Placer County Water Agency, Foothill	Prospective User
Pomona — City, Water Department	Prospective User
Rancho California Water District	Prospective User
Redding, City of	Prospective User
Redlands City Municipal Utilities Department, Water Division	Prospective User
Riverside, City Of	Prospective User
Roseville, City of	Prospective User
Sacramento, City of	Prospective User
San Bernardino City	Prospective User

Water System	Classification
San Diego, City Of	Prospective User
San Francisco Public Utilities Commission	Prospective User
San Jose Water Company	Prospective User
Santa Ana, City of	Prospective User
Santa Margarita Water District	Prospective User
Suburban Water Systems, San Jose	Prospective User
Upland, City of	Prospective User
Valencia Water Company	Prospective User
Victorville Water District	Prospective User
Vista Irrigation District	Prospective User
Walnut Valley Water District	Prospective User
West Valley Water District	Prospective User
Yorba Linda Water District	Prospective User

Source: CWEE

CHAPTER 8: Conclusion

This project sought to better quantify and exploit opportunities for energy demand management at water distribution systems in the California water sector. This was accomplished through the development and pilot of a novel DMS and by the development of a statewide energy grid model to evaluate the capacity for and benefits of energy load shifting in water systems across the state.

The project team developed a novel, high-performance DMS — branded as WaterWatch — to enable analytics on hydraulic models and other unstructured data in real-time to generate safe, optimized, and validated recommendations for energy load shifting and water system operations at any water system. WaterWatch was connected to calibrated hydraulic models for the recycled and potable water distribution systems operated by MNWD, which provides water, recycled water, and wastewater services to more than 170,000 customers in Southern California.

WaterWatch was piloted for 12 months at MNWD, reporting a total of 31 interactions, with operating staff averaging 1.57 hours per interaction. During piloting, operating staff were tasked with continuing regular system operations while examining the accuracy and reliability of WaterWatch. Ultimately, it was found that WaterWatch directly led to a reduction to the average energy demand of the water system by 35.57 kW for the 5 days following each periodic use of the software, which translates to approximately 4.03 percent less energy consumption (see Table 9). Additionally, it was found that the energy intensity of water delivery was reduced for the same period by 0.025 MWh/MG, or 3.7 percent. It is estimated that WaterWatch influenced the energy demand at MNWD for 1,624.25 hours of the year-long pilot. It is anticipated that, had MNWD used WaterWatch weekly, the net savings would have accumulated to 311.58 MWh annually, or 48.36 $MTCO_2e$ of avoided indirect carbon emissions (see Table 10).

To estimate the broader potential impact of water distribution systems like MNWD adopting a DMS and participating in dynamic load shifting, CWEE simulated water demands and load shifting of all public water distribution systems in California by developing a statewide energy grid model. The water demand, pumping, and energy demands of 702 water distribution systems were simulated under nine different energy pricing and emissions minimization scenarios. It was found that the potable water distribution sector accounted for at least 1.2 percent of the total electricity used in California and had the flexibility to shift its energy demands by up to 1,071 GWh annually, to reduce curtailment in California by up to 68 percent, or to reduce its contribution to peak net demand by up to 321 MW and avoid 330,627 $MTCO_2e$ of emissions. The scenarios that led to the greatest load shifting and emissions reductions included TOU energy rates that incentivize consumption during the middle of the day, whereas scenarios with demand charges prevented load shifting and resulted in flat energy consumption profiles throughout the day.

Leveraging the results from the statewide energy grid model to estimate the scale of water distribution activities, it was approximated that, if WaterWatch were extended to water systems throughout California, energy consumption could be reduced by 131.8 GWh annually when using WaterWatch as an educational tool alongside existing operating staff, or 20,457 $MTCO_2e$ of emissions (see Table 10). It is not yet known how much greater these savings could become if water systems actively employed the recommendations and optimizations produced by WaterWatch beyond educational purposes.

Recommendations

CWEE hopes that this research highlights the important role the water distribution sector can play in addressing the needs of the energy sector. If existing pumping and water storage assets were leveraged throughout California, CWEE estimates that new energy rates and technologies to motivate and enable energy load shifting could unlock up to 1.07 terawatt-hours of energy consumption available for shifting and alignment annually (see Table 3). This research identified the two primary barriers to unlocking this potential: 1) the demand charges within energy tariff structures, and 2) the availability of high-quality hydraulic models of water distribution systems.

Removal of Energy Demand Charges from Water Distribution System Energy Rates

The potential distribution system response depends on an individual system's combination of tank storage capacity, pumping capacity, and water demands, as well as the applied energy tariff structure. Most systems had the ability to perform some load shifting, with the greatest potential at systems with high storage volumes, low water demands, and high pumping capacity. Energy tariffs with demand charges resulted in minimal and, in some cases, negative load shifting compared to the baseline. The tariffs without demand charges and TOU consumption charges that aligned low pricing with the load shifting window and higher prices outside the window resulted in the most dynamic energy consumption, the greatest shifts in energy load, and the lowest GHG emissions. Depending on the objective, adjusting rate structures could encourage the water sector to shift the time when it demands energy, such that it could better assist California in meeting future energy and emissions targets.

Improved Standards for the Design and Calibration of Hydraulic Models

Early in the research that preceded the design and development of WaterWatch, CWEE identified that a key component of any tool that would generate recommendations for alternative operations at a water system was a complete, calibrated hydraulic model of the water network. However, CWEE has since learned from commercialization efforts that California water utilities, as a whole, have not advanced to having accurate hydraulic models. While many entities either have models or are procuring them, CWEE has found that the vast majority of models are typically not built and/or calibrated sufficiently to use for trustworthy operational decision making. A key component of this gap is that there does not yet exist adequate mechanisms to measure and confirm the accuracy and quality of hydraulic models upon delivery. Moving forward, it is critical that water systems have the ability to measurably review the quality of their procured hydraulic models for various applications, including steady-state analysis, time-series analysis, and real-time operations.

Suggestions for Further Research

In the process of compiling this research, several opportunities or concepts arose that warrant further investigation but fell outside the scope of this project. Given time and resources these topics should be further explored:

- Optimized Energy Rate Designs for the Water Sector
  - The energy grid model developed for this project leveraged an optimization and modeling approach that allowed for the examination of arbitrary, highly complex energy rate designs, which can take any form or design. CWEE hypothesizes that this energy grid model could be used to generate new energy rate structures for the water sector, which maximizes energy load shifting, equity, and cost effectiveness while incorporating revenue requirements of the energy sector. While this project identified that demand charges present a clear barrier to water systems performing energy load shifting, it may not be necessary to entirely eliminate demand charges. An investigation using these grid modeling tools may identify the best future roles that demand and consumption charges could play in harmonizing the water and energy sectors.
- Optimized Capital Improvement Investments through Hydraulic Simulations
  - The WaterWatch software introduced a highly robust optimization tool for water distribution systems that can be used to build, simulate, and compare entire hydraulic models dynamically. This feature, currently used to generate new control logics, could be leveraged to examine the selection of capital improvement assets such as reservoirs, pumps, or even new water sources.
- Real-time Leak Detection
  - In a single, shared environment, the WaterWatch software can understand and use SCADA measurements, water customer billing data, hydraulic model information, and much more. It is known that deviations from hydraulic modeling results to real SCADA measurements can be employed to perform real-time calibration. CWEE hypothesized that the same concept can be extended to water customer billing data; by using the hydraulic model's design with SCADA data to identify and measure water inflows and outflows to all pressure zones, deviations can be discovered from water customer billing information at the time-scale of the customer meter (bi-monthly, monthly, or hourly). Typically, this activity would be incredibly intensive for a data analyst due to the range of measurements, which do not align in time, but WaterWatch has already solved that barrier and is particularly well-suited to this type of unstructured time-series analysis.

- Integrating Multiple WaterWatch Projects
    - Communication between retail water distribution systems with wholesale water transmission systems often requires multiple daily phone calls or emails to identify the desired flowrate and water purchases. Optimizations and decision support software deployed at any one water system is likely to be content with an increase to operational complexity by requiring the water system to potentially change water purchase decisions rapidly or unexpectedly. In these circumstances, CWEE hypothesizes that a potential solution is to deploy WaterWatch for both the retail and the wholesale water systems and enable interconnected communication and optimizations between the two water networks.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
API	Application Programming Interface
AWE	Alliance for Water Efficiency
AWWA	American Water Works Association
BIP	base interruptible program
California ISO	California Independent System Operator
CalWEP	California Water-Efficiency Partnership
CBP	capacity bidding program
CEC	California Energy Commission
CPP	critical peak pricing
CPUC	California Public Utilities Commission
CWEE	Center for Water-Energy Efficiency (University of California, Davis)
DLAP	demand load aggregation point
DMA	district metered area
DMS	demand management software
DR	demand response
EPANET	Environmental Protection Agency's Model for Water Distribution Piping Systems
EPIC	Electric Program Investment Charge
EWQMS	energy and water quality management system
FRD	facility-related demand
FSL	firm service level
GHG	greenhouse gas
GIS	geographic information system
gpm	gallons per minute
GS	General Service
GWh	gigawatt-hour
IOU	investor-owned utility
IRWD	Irvine Ranch Water District
IW	InfoWater
IWDB	InfoWater database
kW	kilowatt
kWh	kilowatt-hour
LMP	locational marginal pricing

Term	Definition
MG	million gallons
MIDAS	Market Informed Demand Automation Server
MNWD	Moulton Niguel Water District
$MTCO_2e$	metric tons of carbon dioxide equivalent
MW	megawatt
MWh	megawatt-hour
NED	National Elevation Database
NHW	Normal Hot Weather
NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resource Conservation Service
OASIS	Open Access Same-Time Information System
OBMC	optional binding mandatory curtailment
PA	agricultural and pumping
PG&E	Pacific Gas and Electric Company
PID	proportional, integrative, derivative
PLC	Programmable Logic Controller
RTP	real-time pricing
SBIR	Small Business Innovation Research
SCADA	Supervisory, Control, and Data Acquisition
SCE	Southern California Edison Company
SDG&E	San Diego Gas & Electric Company
SGIP	Self-Generation Incentive Program
SLRP	scheduled load reduction program
SQL	structured query language
TOU	time-of-use
TRD	time-related demand
UC Davis	University of California, Davis
USGS	United States Geological Survey
VSD	variable speed drive
VSP	variable speed pump
WaterWatch	demand management software for water systems by UC Davis CWEE
WDN	water distribution network

References

Action, J.P., R.E. Park, B.M. Mitchell, and M.E. Vaiana. 1983. *Time-of-Day Electricity Rates for the United States*. The Rand Corporation. Publication Number: R-3086-HF. Available at https://www.rand.org/content/dam/rand/pubs/reports/2007/R3086.pdf.

Alvisi, S., and M. Franchini. 2016. "A Methodology for Pumping Control Based on Time Variable Trigger Levels." *Procedia Engineering*, 162, 365–372. Available at https://doi.org/10.1016/j.proeng.2016.11.076.

Aneke, M., and M. Wang. 2016. "Energy storage technologies and real life applications – A state of the art review." *Applied Energy*, 179, 350–377. Available at https://doi.org/10.1016/j.apenergy.2016.06.097.

Ashley, C., L. Holmes, G. Wikler, and EnerNOC Utility Solutions. 2013. "Using More Energy Can Be a Good Thing: C&I Loads as a Balancing Resource for Intermittent Renewable Energy." American Council for an Energy-Efficient Economy, Summer Study on Energy Efficiency in Industry. Available at https://www.aceee.org/files/proceedings/2013/data/papers/3_090.pdf.

Beyer, D. 2017. Personal communication. May 12.

Beyer, D., J. Young, E. White, and S. Bunn. 2005. "Implementing an Energy Management System for Distribution Pumping." American Water Works Association, Annual Conference and Exposition (ACE). San Francisco, California, June 12–16, 2005. Available at https://api.semanticscholar.org/CorpusID:61905279.

Blinco, L.J., A.R. Simpson, M.F. Lambert, and A. Marchi. 2016. "Comparison of Pumping Regimes for Water Distribution Systems to Minimize Cost and Greenhouse Gases." *Journal of Water Resources Planning and Management,* 142(6), 04016010. Available at https://doi.org/10.1061/(ASCE)WR.1943-5452.0000633.

Bonvin, G., S. Demassey, and A. Lodi. 2021. "Pump Scheduling in Drinking Water Distribution Networks with an LP/NLP-Based Branch and Bound." *Optimization and Engineering*, 22, 1275–1313. Available at https://hal-mines-paristech.archives-ouvertes.fr/hal-02158535.

Boulos, P.F., L.B. Jacobsen, J.E. Heath, and S. Kamojjala. 2014. "Real-time modeling of water distribution systems: A case study." *Journal American Water Works Association*, 106(9), E391–E401. Available at https://doi.org/10.5942/jawwa.2014.106.0076.

Boulos, P.F., K.E. Lansey, and B.W. Karney. 2006. *Comprehensive Water Distribution Systems Analysis Handbook for Engineers and Planners*, 2nd Edition. Pasadena, California: MWH Soft, Incorporated. ISBN: 0974568953. 1–490.

CAISO (California Independent System Operator). 2016. "FAST FACTS: What the duck curve tells us about managing a green grid." California Independent System Operator. Available at https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf.

CAISO. 2017. "Over-supply/Over-generation." California Independent System Operator, Operating Procedure No. 2390. Available at https://www.caiso.com/Documents/2390.pdf.

CAISO. 2021a. "Production and Curtailments Data – 2020." California Independent System Operator. Available at https://www.caiso.com/about/our-business/managing-the-evolving-grid.

CAISO. 2021b. "Today's Outlook: Current and forecasted demand." California Independent System Operator. Available at https://www.caiso.com/todays-outlook#section-net-demand-trend. Accessed September 11, 2021.

Candelieri, A., R. Perego, and F. Archetti. 2018. "Bayesian Optimization of Pump Operations in Water Distribution Systems." *Journal of Global Optimization*, 71(1), 213–35. Available at https://doi.org/10.1007/s10898-018-0641-2.

CEC (California Energy Commission). 2020. "2020 Total System Electric Generation." California Energy Commission. Available at https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2021-total-system-electric-generation/2020.

CEC. 2021 (May). "A Peek at Net Peek." California Energy Commission. Available at https://www.energy.ca.gov/data-reports/energy-insights/peek-net-peak.

Cherchi, C., M. Badruzzaman, J. Oppenheimer, C.M. Bros, and J.G. Jacangelo. 2015. "Energy and water quality management systems for water utility's operations: A review." *Journal of Environmental Management*, 153, 108–120. Available at https://doi.org/10.1016/j.jenvman.2015.01.051.

Coelho, B., and A. Andrade-Campos. 2014. "Efficiency achievement in water supply systems—A review." *Renewable and Sustainable Energy Reviews*, 30, 59–84. Available at https://doi.org/10.1016/j.rser.2013.09.010.

CPUC (California Public Utilities Commission). 2015 (Dec 28). "Order Instituting Rulemaking to Access Peak Electricity Usage Patterns and Consider Appropriate Time Periods for Future Time-of-Use Rates and Energy Resource Contract Payments." California Public Utilities Commission, Rulemaking 15-12-012. Available at https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M157/K412/157412121.pdf.

De León. 2018 (Sep 10). "SB 100 - California Renewables Portfolio Standard Program: emissions of greenhouse gases." California State Legislature, Senate Bill 100, Chapter 312, Statutes of 2018. Available at https://legiscan.com/CA/text/SB100/id/1819458.

Denholm, P., and M. Hand. 2011. "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity." *Energy Policy*, 39(3), 1817–1830. Available at https://doi.org/10.1016/j.enpol.2011.01.019.

Denholm, P., M. O'Connell, G. Brinkman, and J. Jorgenson. 2015. *Overgeneration from Solar Energy in California. A Field Guide to the Duck Chart*. National Renewable Energy Laboratory, United States Department of Energy Office of Energy Efficiency and

Renewable Energy. Technical Report Number: NREL/TP-6A20-65023. Available at https://doi.org/10.2172/1226167.

Eiben, A.E., P.E. Raue, and Z. Ruttkay. 1994. "Genetic Algorithms with Multi-Parent Recombination." In the Third Conference on Parallel Problem Solving from Nature, International Conference on Evolutionary Computation. Jerusalem, Israel, October 9–14, 1994. 78–87. Available at https://doi.org/10.1007/3-540-58484-6_252.

EPRI (Electric Power Research Institute). 2021. "Water-Energy Intensity Modeling Application for Electric Power and Water Supply Utilities: Final Report and User Documentation." Palo Alto, CA. 10013029.

Fantozzi, M., I. Popescu, T. Farnham, F. Archetti, P. Mogre, E. Tsouchnika, C. Chiesa, A. Tsertou, M. Castro Gama, and M. Bimpas. 2014. "ICT for Efficient Water Resources Management: The ICeWater Energy Management and Control Approach." *Procedia Engineering*, 70, 633–40. Available at https://doi.org/10.1016/j.proeng.2014.02.069.

Faruqui, A., and S. Sergici. 2013. "Arcturus: International Evidence on Dynamic Pricing." *The Electricity Journal*, 26(7), 55–65. Available at https://doi.org/10.1016/j.tej.2013.07.007.

GEI Consultants and Navigant Consulting, Inc. 2010 (Aug 31). *Embedded Energy in Water Studies, Study 1: Statewide and Regional Water-Energy Relationship*. California Public Utilities Commission. Available at https://files.cpuc.ca.gov/gopher-data/energy%20efficiency/Water%20Studies%201/Study%201%20-%20FINAL.pdf.

Goldman, F.E., and L.W. Mays. 2004. "Chapter 5: Water Distribution System Operation: Application of Simulated Annealing." *Water Resources Systems Management Tools*, 1st Edition. New York City, New York: McGraw Hill. ISBN: 0071443819. 1–320. Available at https://www.public.asu.edu/~lwmays/Ch05_mays_144381-9.pdf.

Good, Robert. November 9, 2021. "WaterWatch Software: A Planning and Management Tool for the Whole Team." Webinar. University of California, Davis. Available at https://cwee.ucdavis.edu/waterwatch/.

Hooke, R., and T.A. Jeeves. 1961. "`Direct Search' Solution of Numerical and Statistical Problems." *Journal of the Association for Computing Machinery (JACM)*, 8(2), 212–229. Available at https://doi.org/10.1145/321062.321069.

IRWD (Irvine Ranch Water District). 2021 (Apr). "Draft Water Industry Energy Tariff Research Paper." In Irvine Ranch Water District Engineering and Operations Committee, Irvine Ranch Water District. 47–51. Available at https://www.irwd.com/images/pdf/about-us/committee-meetings/engineering-and-operations/2021/04_20_21_eng-ops_agenda.pdf.

Jentgen, L., S. Conrad, R. Riddle, E. Von Sacken, K. Stone, W. Grayman, and S. Ranade. 2004. *Implementing a Prototype Energy and Water Quality Management System*. London, UK: IWA Publishing. ISBN: 1843398575. 1–192.

Jowitt, P.W., and G. Germanopoulos. 1992. "Optimal Pump Scheduling in Water-Supply Networks." *Journal of Water Resources Planning and Management*, 118(4), 406–422. Available at https://doi.org/10.1061/(ASCE)0733-9496(1992)118:4(406).

Kang, D. 2014. "Real-Time Optimal Control of Water Distribution Systems." *Procedia Engineering*, 70, 917–923. Available at https://doi.org/10.1016/j.proeng.2014.02.102.

Kennedy, J., and R. Eberhart. 1995. "Particle Swarm Optimization." In Proceedings of ICNN'95 - International Conference on Neural Networks. Institute of Electrical and Electronic Engineers (IEEE). Perth, WA, Australia, November 27–December 1, 1995. 1942–1948. Available at https://doi.org/10.1109/ICNN.1995.488968.

Klein, G., M. Krebs, V. Hall, T. O'Brien, and B. Blevins. 2005. *California's Water-Energy Relationship*. California Energy Commission. Publication Number: CEC-700-2005-011-SF. Available at http://large.stanford.edu/courses/2012/ph240/spearrin1/docs/CEC-700-2005-011-SF.PDF.

Klise, K.A., R. Murray, and L.T.N. Walker. 2015. *Systems Measures of Water Distribution System Resilience.* Sandia National Laboratories, Albuquerque, New Mexico. Technical Report Number: SAND2015-20746R. Available at https://doi.org/10.2172/1177373.

Lekov, A., L. Thompson, A. McKane, K. Song, and M.A. Piette. 2009 (Apr). *Opportunities for Energy Efficiency and Open Automated Demand Response in Wastewater Treatment Facilities in California – Phase I Report*. Lawrence Berkeley National Laboratory, Environment Energy Technologies Division. Publication Number: LBNL-2572E. Available at https://eta-publications.lbl.gov/sites/default/files/lbnl-2572e.pdf.

Li, Y., E. Musabandesu, T. Fujiwara, F.J. Loge, and K. Ma. 2021. "A Visual Analytics System for Water Distribution System Optimization." 2021 IEEE Visualization Conference (VIS). New Orleans, Louisiana, October 24–29, 2021. 126–130. Available at https://doi.ieee computersociety.org/10.1109/VIS49827.2021.9623272.

Liang, X. 2017 (Nov 8). "Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources." *IEEE Transactions on Industry Applications,* 53(2), 855–866. Available at https://doi.org/10.1109/TIA.2016.2626253.

Limaye, D.R., and S. Jaywant. 2019. "Development of Indicators from the World Bank IBNET Database." Washington, DC: World Bank.

Linz, D., E. Musabandesu, B. Ahmadi, R. Good, and F. Loge. 2020. "Multi-threaded simulation optimization platform for reducing energy use in large-scale water distribution networks with high dimensions." Proceedings of the 2020 Winter Simulation Conference, Virtual. Institute of Electrical and Electronic Engineers (IEEE). December 14–18, 2020. Available at https://doi.org/10.1109/WSC48552.2020.9383920.

Makaremi, Y., A. Haghighi, and H.R. Ghafouri. 2017. "Optimization of Pump Scheduling Program in Water Supply Systems Using a Self-Adaptive NSGA-II; a Review of Theory to Real Application." *Water Resources Management*, 31(4), 1283–1304. Available at https://doi.org/10.1007/s11269-017-1577-x.

Mala-Jetmarova, H., N. Sultanova, and D. Savic. 2017. "Lost in optimisation of water distribution systems? A literature review of system operation." *Environmental Modelling & Software*, 93, 209–254. Available at https://doi.org/10.1016/j.envsoft.2017.02.009.

Marchi, A., A.R. Simpson, and M.F. Lambert. 2017. "Pump Operation Optimization Using Rule-Based Controls." *Procedia Engineering*, 186, 210–217. Available at https://doi.org/10.1016/j.proeng.2017.03.229.

Menke, R., E. Abraham, P. Parpas, and I. Stoianov. 2016. "Demonstrating demand response from water distribution system through pump scheduling." *Applied Energy*, 170, 377–387. Available at https://doi.org/10.1016/j.apenergy.2016.02.136.

Miller, G., K. Novan, and A. Jenn. 2022 (Apr 8). "Hourly accounting of carbon emissions from electricity consumption." *Environmental Research Letters*, 17(4), 044073. Available at https://doi.org/10.1088/1748-9326/ac6147.

MNWD (Moulton Niguel Water District). 2016a. "Moulton Niguel Water District Boundary Map with Cities Served." Moulton Niguel Water District. Available at https://www.mnwd.com/servicearea/.

MNWD. 2016b. "Where Does Our Water Come From?" Moulton Niguel Water District. Available at https://www.mnwd.com/watersupply/.

MNWD. 2016c. "MNWD's Recycled Water Program." Moulton Niguel Water District. Available at https://www.mnwd.com/wp-content/uploads/2016/10/Nov-FINAL.pdf.

MNWD. 2017. "Comprehensive Annual Financial Report for the Fiscal Year Ended June 30, 2017." Moulton Niguel Water District. Available at https://ocauditor.gov/wp-content/uploads/2018/02/Moulton-Niguel-Water-District-CAFR-2017.pdf.

Mohajeryami, S., M. Doostan, A. Asadinejad, and P. Schwarz. 2017. "Error Analysis of Customer Baseline Load (CBL) Ccalculation Methods for Residential Customers." *IEEE Transactions on Industry Applications*, 53(1), 5–14. Available at https://doi.org/10.1109/TIA.2016.2613985.

Musabandesu, E., and F. Loge. 2021. "Load shifting at wastewater treatment plants: A case study for participating as an energy demand resource." *Journal of Cleaner Production*, 282, 124454. Available at https://doi.org/10.1016/j.jclepro.2020.124454.

Musabandesu, E., R. Good, J. Herman, and F. Loge. In progress. "Reformulating Water Distribution System Operation Optimization for Energy Demand Management with Hierarchal Control Policies."

Musabandesu, E., Y. Li, T. Fujiwara, K.L. Ma, and F. Loge. In progress. "Opening the Black Box of Water Distribution System Optimization: Visualizing Fitness Function Structure for Human-Guided Optimization."

Navigant Consulting, Inc. 2006. *Refining Estimates of Water-Related Energy Use in California*. California Energy Commission, Public Interest Energy Research Program. Publication Number: CEC-500-2006-118. Available at https://www.sandiegocounty.gov/content/da m/sdc/pds/ceqa/Soitec-Documents/Final-EIR-Files/references/rtcref/ch3.1.3/2014-12-19_CEC2006.pdf.

NRCS (National Resource Conservation Service). 2017. "Pump Curves." National Resource Conservation Service. Available at https://www.wcc.nrcs.usda.gov/ftpref/wntsc/Pump%20Curves/.

Office of Governor Edmund G. Brown Jr. 2016 (May 9). "Governor Brown issues Order to Continue Water Savings as Drought Persists." Office of the Governor, State of California. Available at https://archive.gov.ca.gov/archive/gov39/2016/05/09/news19408/index.html.

Ormsbee, L.E., and S.L. Reddy. 1995. "Nonlinear Heuristic for Pump Operations." *Journal of Water Resources Planning and Management*, 121(4), 302–309. Available at https://doi.org/10.1061/(ASCE)0733-9496(1995)121:4(302).

Olsen, D., S. Goli, D. Faulkner, and A. McKane. 2012. "Opportunities for automated demand response in wastewater treatment facilities in California – Southeast Water Pollution Control Plant Case Study." Lawrence Berkeley National Laboratory. Publication Number: LBNL-6056E. Retrieved from https://industrialapplications.lbl.gov/sites/default/files/LBNL-6056E.pdf.

Park, L., C. Minasian, J. Wells, and M. Vu. 2019 (Oct 25). *Water Sector Over-Generation Mitigation and Flexible Demand Response, Phase 2 Program Recommendations*. Water Energy Innovations for Southern California Edison. Available at https://waterenergyinnovations.com/wp-content/uploads/2020/03/20191025-FINAL-Overgen-Ph2-Report-COMPLETE-2-Sided-Print.pdf.

Paschke, M., K. Spencer, N. Waniarcha, A.R. Simpson, and T. Widdop. 2001 (Jan). "Genetic Algorithms for Optimising Pumping Operations." 19th Federal Convention, Australian Water Association. Canberra, Australia, January 2001. Available at https://www.researchgate.net/publication/270582992_Genetic_algorithms_for_optimising_pumping_operations.

Paterakis, N.G., O. Erdinç, and J.P.S. Catalão. 2017. "An overview of Demand Response: Key-elements and international experience." *Renewable and Sustainable Energy Reviews*, 69, 871–891. Available at https://doi.org/10.1016/j.rser.2016.11.167.

Quintiliani, C., and E. Creaço. 2019. "Using Additional Time Slots for Improving Pump Control Optimization Based on Trigger Levels." *Water Resources Management*, 33(9), 3175–3186. Available at https://doi.org/10.1007/s11269-019-02297-6.

Robinson, L., J. Edwards, and L. Willnow. 2012. *Computer modeling of Water Distribution Systems*, 3rd Edition. Denver, Colorado: American Water Works Association. ISBN: 1583218645. 1–231.

Rossman, L.A. 2000 (Sep). *EPANET 2 Users Manual*. United States Environmental Protection Agency Office of Research and Development, Water Supply and Water Resources

Division, National Risk Management Research Laboratory. Publication Number: EPA/600/R-00/057. Available at https://nepis.epa.gov/Adobe/PDF/P1007WWU.pdf.

Rupiper, A., R. Good, G. Miller, and F. Loge. 2024. "Mitigating renewables curtailment and carbon emissions in California through water sector demand flexibility." *Journal of Cleaner Production*, 437, 140373. Available at https://doi.org/10.1016/j.jclepro.2023.140373.

Santhosh, A., A.M. Farid, and K. Youcef-Toumi. 2014. "The impact of storage facility capacity and ramping capabilities on the supply side economic dispatch of the energy-water nexus." *Energy*, 66, 363–377. Available at https://doi.org/10.1016/j.energy.2014.01.031.

Savic, D.A., J.B. Boxall, B. Ulanicki, Z. Kapelan, C. Makropoulos, R. Fenner, K. Soga, I.W. Marshall, C. Maksimovic, I. Postlethwaite, R. Ashley, and N. Graham. 2012. "Project Neptune: Improved Operation of Water Distribution Networks." *Water Distribution Systems Analysis 2008*, 1–16. Available at https://doi.org/10.1061/41024(340)47.

SCE (Southern California Edison). 2021. "Energy Solutions for Your Business." Southern California Edison. Available at https://www.sce.com/business. Accessed May 1, 2021.

Schäfer, M., O. Gretzschel, T.G. Schmitt, and H. Knerr. 2015. "Wastewater Treatment Plants as System Service Provider for Renewable Energy Storage and Control Energy in Virtual Power Plants – A Potential Analysis." *Energy Procedia*, 73, 87–93. Available at https://doi.org/10.1016/j.egypro.2015.07.566.

Sherwood, J., A. Chitkara, D. Cross-Call, and B. Li. 2016. *A Review of Alternative Rate Designs: Industry Experience with Time-Based and Demand Charge Rates for Mass-Market Customers.* Rocky Mountain Institute. Available at https://web.archive.org/web/20160512013545/http://www.rmi.org/alternative_rate_designs.

Song, T., Y. Li, X.-P. Zhang, J. Li, C. Wu, Q. Wu, and B. Wang. 2018. "A Cluster-Based Baseline Load Calculation Approach for Individual Industrial and Commercial Customer." *Energies*, 12 (1), 64. Available at https://doi.org/10.3390/en12010064.

Sterling, M.J.H., and B. Coulbeck. 1975. "Technical Note. A Dynamic Programming Solution to Optimization of Pumping Costs." *Proceedings of the Institution of Civil Engineers*, 59(4), 813–818. Available at https://doi.org/10.1680/iicep.1975.3642.

SWRCB (State Water Resources Control Board). 2018. "Electronic Annual Report." State Water Resources Control Board. Available at https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/ear.html.

Torriti, J. 2015. *Peak Energy Demand and Demand Side Response*, 1st Edition. New York City, New York: Routledge. ISBN: 9781315781099. 1–188. Available at https://doi.org/10.4324/9781315781099.

U.S. EIA (United States Energy Information Administration). 2021. "California's Curtailments of Solar Electricity Generation Continue to Increase." United States Energy Information Administration. Available at https://www.eia.gov/todayinenergy/detail.php?id=49276.

USGS (United States Geological Survey). 2017. "National Map Downloader – Elevation." United States Geological Survey. Available at https://apps.nationalmap.gov/downloader/.

Van Zyl, J.E., D.A. Savic, and G.A. Walters. 2004. "Operational Optimization of Water Distribution Systems Using a Hybrid Genetic Algorithm." *Journal of Water Resources Planning and Management*, 130(2), 160–170. Available at https://doi.org/10.1061/(ASCE)0733-9496(2004)130:2(160).

Verzijlbergh, R.A., L.J. De Vries, G.P.J. Dijkema, and P.M. Herder. 2017. "Institutional challenges caused by the integration of renewable energy sources in the European electricity sector." *Renewable and Sustainable Energy Reviews*, 75, 660–667. Available at https://doi.org/10.1016/j.rser.2016.11.039.

Water Energy Innovations. 2019 (May 7). *Water Sector Over-Generation Mitigation and Flexible Demand Response*. Prepared for Southern California Edison. Available at https://waterenergyinnovations.com/wp-content/uploads/2020/02/20190507-FINAL-Overgen-Ph1-Assess-COMPLETE.pdf.

Williams, A.A. 1996. "Pumps as turbines for low cost micro hydro power." *Renewable Energy*, 9(1-4), 1227–1234. Available at https://doi.org/10.1016/0960-1481(96)88498-9.

Wimmler, C., G. Hejazi, E. de Oliveira Fernandes, C. Moreira, and S. Connors. 2017. "Impacts of load shifting on renewable energy integration." Energy Procedia, 107, 248–252. Available at https://doi.org/10.1016/j.egypro.2016.12.142.

Wu, Y.Z., M.E. Tryby, E. Todini, T.M. Walski, W.R. Hartell, and K.L. Culin. 2008 (Aug 29). "System and method for modeling and simulating water distribution and collection systems including variable speed pumps." National Institutes of Health, National Library of Medicine, National Center for Biotechnology Information. Patent Number: US-8265911-B1. Available at https://pubchem.ncbi.nlm.nih.gov/patent/US-8265911-B1.

Younghein, M., and E. Martinot. 2015. *Beyond 33 percent Renewables: Grid Integration Policy for a Low Carbon Future*. California Public Utilities Commission, Staff White Paper. Available at https://www.cpuc.ca.gov/-/media/cpuc-website/files/uploadedfiles/cpuc_website/content/utilities_and_industries/energy/reports_and_white_papers/beyond33percentrenewables-gridintegrationpolicy-final.pdf.