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Resilience Implications of Energy Storage in Urban Water Systems

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ABSTRACT

Additional water storage is modeled in concentrated and distributed configurations in a case study water distribution system model of Cleveland, Tennessee, U.S.A. This is done to understand: if there are energy generation capabilities from increased storage, and if new water demand modeled to represent a doubling population can be supported by additional water storage. Model outputs show that the distributed water storage configuration increases water system resiliency to population growth, meeting doubled water demand. The concentrated storage configuration cannot meet doubled water demand, due to the inability of the design to manage pressure and deliver water across the space-and-time continuum. Both scenarios are unable to meet water demands and maintain pressures while also generating energy. This research concludes that the primary motivation for adding additional water storage (e.g., for energy generation or to withstand chronic population growth) should determine additional tank locations and configurations.

KEYWORDS

Water-energy nexus, Energy storage, Urban water system resiliency.

INTRODUCTION

Communities across the United States (U.S.) are struggling to address the problematic new normal of aging infrastructure, increasing climate variability, economic volatility and deepening economic disparity between community groups. Many communities simply lack the resources to prepare and respond effectively to these threats [1]. To be resilient in the face of these acute and chronic challenges, urban infrastructure must be designed and managed to balance the three conditions of sustainability: environmental, societal and economic health [2].

To help cities do this, new tools have been developed in recent years to measure the sustainability of urban infrastructure over time [3]. Many framework and indicator sets attempt to resolve complex issues into variables [4], to assess the sustainability and resilience of urban infrastructure systems [5]. Frameworks often focus on interactions and feedback loops between aging infrastructure and surrounding environmental,

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economic and social-system conditions [6]. Ultimately, frameworks resolve into sets of sustainability criteria and indicators for the built environment [7]. One interaction that is consistently missing from these frameworks is that they typically approach urban infrastructure systems in a linear and unintegrated manner.

This is because while cities are systems of systems operating simultaneously, they are often managed separately. Barriers to integration are well defined in the literature and primarily include: fragmentation between management structures and lack of availability of standardized data sets and tools [8].

Systems integration is a generally desirable concept in municipal settings, because synchronous operation theoretically means considering multiple drivers for better operational practices. Energy and water systems are of particular interest, because social and economic structures are critically dependent upon them [9]. Additionally, the interactions of these two systems with other urban systems, like transportation right of ways, allow communities uninterrupted delivery of services [10].

Strategic integrating of water and energy systems can support community resilience, delivering more reliable and affordable services [11]. Cities administrations seek ways to meet increasing demands for water and energy from growing populations, while grappling with acute and chronic variables: flooding from extreme rainfall, drought and rising sea levels in coastal communities, for instance [12]. Systems integration is becoming increasingly attractive, in the form of distributed infrastructure that can insulate a city from resource disruption [13].

Actualizing the water-energy nexus motivates this research. The primary objective is to define chronic stresses scenarios in a municipal water system, measuring resiliency in terms of depth of failure. It examines how the addition of energy storage capacity in urban water distribution systems can be simulated to buffer demand from a doubling population. Exploring how energy and water system integration can increase community resilience is the primary knowledge contribution.

The paper proceeds as follows. First, the term resiliency is defined in terms of urban water system infrastructure. The literature review provides the background on what is known, as well as the foundation and theory for the research approach. The paper objectives are outlined, stating what is still unknown and what the research is designed to discover. The analysis and methods assess additional water storage originally added to a water distribution system for energy generation, to see if this storage can also have resiliency benefits by being able to service a doubling population. Conclusions are stated, and point to next steps for this area of research.

DEFINING URBAN WATER SYSTEM RESILIENCE

This paper discusses the term “resiliency” in terms of infrastructure [14]. This is because resiliency is an emerging field of practice and thus the term still has a variety of meanings in various contexts [15]. Further, this research explores resiliency as it relates to water and energy systems in an “emerging” city [16], a term that is also defined.

The National Infrastructure Advisory Council’s report on Critical Infrastructure [17] states: “Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to and/or rapidly recover from a potentially disruptive event”. According to this definition, infrastructure resilience is about delivering services regardless of disruption. This understanding of resilience is common in the water and energy sectors [18].

Resilience is often discussed in terms of acute risk and reliability, and resiliency to chronic stressors is still emerging from concept into operation in urban water systems [19]. Water managers consider it practically as how quickly system recovery can be achieved after a disruption. The older fields of risk management and emergency management focus on the ability to prevent acute failures from acute natural disasters and to maintain or stabilize an ideal system state. In contrast, resilience is emerging as a method, focusing on planning for uncontrollable factors, and identifying ways to manage long-term system adaptation to economic, environmental and social changes [20].

For researchers who study the behavior of these systems, the idea of resilience has broad implications. According to the U.S. Department of Energy (DOE) report Ensuring the Resiliency of our Future Water and Energy Systems [21], urban resilience is "The capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience". For the purposes of this research, this definition best defines resilience at the local level. It does not focus on disasters or attempt to neutralize all acute risk to infrastructure [22]. Local resilience focuses on vulnerability and capacity to cope in the face of chronic and significant disruptors, because those are the elements of risk a community can best control [23].

Energy and water systems are typically discussed in terms of reliability [24, 25]. The target through that lens is usually uninterrupted and/or perfect operation. Resiliency is the newer lens that examines the ability of local water and energy infrastructure systems to recover from failures over time. The goal is not perfect operation, but instead to maintain functionality from the customer's perspective [26, 27].

KEY LITERATURE REVIEW

Urban water systems must respond to and recover from significant threats and multiple changes with minimum damage to public health, the economy and the environment [28]. The urban water system faces challenges arising from densely populated areas, such as high use water demands and pollution from point and nonpoint sources [29]. Increasingly, these systems need to be designed not only for emergency service provision, but also for resilience to threats that emerge over time (e.g. population growth, climate changes, or lack of system preventative maintenance), which can lead to system failures if not proactively addressed [30].

Resilience can be built into existing water systems by embedding redundancy and flexibility into system design, or by upgrading systems to address chronic stressors [31]. To design for resiliency, urban water system managers must know how much water is needed now, how much will be needed in the future, and how to obtain and manage it when considering water demand [32]. They also need to understand influencing parameters, like source availability, available storage, the rate of water demand growth and water system pressure needs to be able to deliver water to all users [33].

Water system planning models are often used to accommodate specific water demands at system nodes to test water system response capacity [34]. Modeled variables can serve as indicators of system resiliency. Energy storage within an urban water system is one tool in a portfolio of water system resiliency planning and modeling options. Examples of measures that can be increased or decreased as they prove feasible and cost-effective include:

- Building more water storage;
- Conjunctive use of surface water and ground water, with ground water recharge;
- Desalination, if the community is coastal;
- Rainwater harvesting/stormwater harvesting;
- Use of recycled water, including industrial process water and treated wastewater;
- Keeping water supply and management public or privatizing portions of it;
- Acquisition of water rights from agriculture;
- Better matching of water use to water quality [35].

Model results across studies and geographies can be inconsistent, but provide better planning information than nothing at all [36]. “Signposts” can be established within resiliency decision frameworks, to monitor the development of the scenarios and determine when adaptation measures are no longer common to all or most scenarios [37].

Like urban water systems, the electric system in the U.S. faces changing conditions and projected growth needs [38]. Addressing chronic stressors is also drawn from an arsenal of options, such as integrating more energy from renewable sources, and enhancing efficiency from non-renewable and distributed-energy processes [39]. Additions to the electric grid must maintain a robust electricity delivery system [40].

For the energy system, resilience means providing affordable energy services, minimizing disruption of those services and providing them without adversely impacting other systems [41]. While the first two parts of this definition are established components of energy assurance, the last is not [42]. A resilient energy system must go beyond infrastructure to reduce internal vulnerability, by including measures that increase community sustainability [43].

Local government planning entities should pursue policies that incentivize investment, research and innovation [44]. Energy storage can play a significant role in meeting these challenges by: improving the operating capabilities of the grid, lowering cost and ensuring high reliability, and deferring or reducing infrastructure investments [45]. While energy storage can serve to level the differences between energy demand and production, it can also improve emergency preparedness because of its ability to provide backup power and grid stabilization services [46].

Methods for predicting water and energy system resiliency

Literature that presents attempts to model water and energy systems in an integrated and comprehensive manner is rare. Examples of integrated modeling continue to be few and are far more specialized (system optimization, for instance) than resiliency modeling currently is. Water distribution systems are modeled as multiple nodes (such as reservoirs, storage tanks and hydraulic junctions) interconnected by physical links (pipes or pumps, for instance). The connectivity patterns of this network affect its reliability, efficiency and response to failures [47].

By modifying water and energy use projections, models can answer questions about how using water system storage tanks for pumped hydropower can play a role in urban resiliency. Modifying consumption patterns can account for variables like population growth, as the state of a water system can be defined by how much water is available for storage and how much for use [48]. Urban water systems obey laws of accumulation, conservation, and depletion: inflows increase the stock and outflows decrease it [49]. Non-physical, or perceived states, can be included as well, especially at the local level. Safety and reliability of the water supply are examples of perceived states [50].

Urban water systems are increasingly modeled for resilience. One study uses a quantitative approach for assessing how resilient water supply systems can be when faced with disruptions. It examines recovery robustness and timeframes in relationship to disruption frequency, and simulates resilience in water system performance and in supply scheduling to ascertain loss by scenario [51]. Another study investigates the performance of water distribution and urban drainage during simulated pipe failures. This study’s results indicate that flexibility in system design ensures continued service during failure scenarios. The study concludes that considering potential failure costs, resilient design strategies prove to be a sound investment strategy [52]. Models that can examine urban water system resilience can aggregate data on many different scales, from citywide to neighborhood and can be correlated with specific physical assets and parameters. Most models do not calculate water demand on a house-by-house basis [53].

Likewise, energy systems are also increasingly being modeled for resilience. One study groups energy models into 4 categories: energy systems simulation, energy systems optimization, power systems and electricity markets, and qualitative or mixed-methods scenarios. This study examines the challenges of these 4 analytic methods and the efforts being taken to address them [54]. For a complex system of systems like a city, advanced multidisciplinary approaches are needed to accurately model real conditions, while maintaining computational consistency, reliability and efficiency [55]. One study analyzes available models for distributed energy generation planning and design from the perspective of gathering their capabilities into an optimization framework. This framework builds on the main concept of a local energy management system and adopts multiple criteria for providing energy services through distributed generation [56].

How water and energy infrastructure system growth occurs in cities

Water and energy utilities make investments in water and energy system capacities to keep pace with increasing water and energy demands [57]. As a city fills in its growth boundaries with new population, water lines, pumps and storage tanks are added to create new pressure zones to meet new water demand. The existing local power grid also increases and more electricity is either created or purchased to meet new energy demands.

Infrastructure upgrades can often ensure access to supply [58]. Additionally, strengthening connections between neighboring water systems becomes an important investment, to allow more water to be purchased or sold as water demand shifts over time. In the face of water scarcity or influx, there is a growing recognition of the importance of investing now to meet future infrastructure needs [59].

Electrical demand management and energy efficiency measures are a first line of defense to manage increasing energy demands [60]. The ability to access a variety of energy sources in addition to the existing energy supply also increases in valuable with increasing electricity demands. Each of these become methods that can help avoid the need to budget for, permit and construct new power plants [61].

Models bypass the realities of implementation, so potential outcomes can be observed without significant time and capital investments. They can be an attractive place to advise from, away from the complexities of real life and the headaches of fieldwork [62]. However, both theoretical and practical roles are necessary. To achieve flexible infrastructure systems, a practical approach must be taken that keeps the possible in mind, but does not sacrifice the celebration of incremental progress as it slowly manifests itself.

RESEARCH OBJECTIVES

It is evident from the literature review that:

- There are a variety of frameworks, tools, and methods to make urban water and energy systems more resilient;
- Significant research effort is going into predictive modeling for various aspects of urban water and energy system resiliency;
- Urban water and energy systems are still primarily being considered individually as opposed to in conjunction to one another.

Motivated and reinforced by these findings, the objectives of this research are to explore one facet of urban water and energy system resilience. By modeling increasing water storage in the context of an emerging city, this research identifies trade-offs between the two systems, if they were integrated, in the face of the chronic external variable of population growth.

Questions answered by this feasibility research include an exploration of how increased energy storage capacity can aid in water system resiliency to chronic stressors.

The tested hypothesis assumes that the addition of storage capacity in urban water systems can make water systems more flexible and resilient when faced with chronic external variables in modeled scenarios. To answer the motivating research questions and test the hypothesis, a case study city's water system is modeled with additional water storage in place. The model's ability to meet system requirements with double the water demand is examined, both with and without energy-generating capabilities.

Because of this research, the water-energy nexus is advanced by a greater understanding of what to consider when adding water storage to an urban water system. Motivators for adding storage, such as to generate energy, or to increase system resiliency, should be used to determine the correct amount, configuration and implementation schedule at the local level. Understanding what various system configurations can and cannot do is important as communities work to understand water and energy system integration possibilities.

ANALYSIS AND METHODS

Before examining methods, it is important to analyze relevant characteristics of the case study city and understand why it is emerging. The key driver of urban water systems dynamics in emerging cities is adaptation of infrastructure to rapid population growth [63]. Because there is more flexibility for growth, there is also room for innovation in decision-making, in types of infrastructure is used [64], in management structures, and in ultimate system goals [65]. Cleveland: TN has an industrial history and is home to 13 Fortune 500 manufacturers [66]. It is an emerging city, part of the "Megalopolis" of greater Atlanta: GA, Chattanooga: TN and Knoxville: TN areas [67].

The term "Emerging cities" has appeared in various urban planning publications for over 50 years [67], but it still does not have a strong public-facing definition. It can refer to various stages of capitalism in urban areas [68]. It can refer to cities that are being planned and built before occupants arrive [69]. It can refer to cities that are moving from third to first world [70]. Emerging cities may be part of the density and coalescence of cities along the U.S. eastern seaboard [71]. They can be facing the challenge of retaining identity, as opposed to being defined as a "Bedroom community", housing residents who commute daily to work in a larger neighboring city [72].

This paper adopts the definition of an emerging city as one that is currently relatively low in population (under 100,000) but rapidly increasing in size and infrastructure [73]. Cleveland is ripe for reinvention. Examining how to use storage in urban water systems to generate energy can be of use to a city like Cleveland. They face a great deal of growth and associated changes in the coming decades and will need an arsenal of smart urban growth tactics to continue to address these changes progressively over time.

By 2040, the State of Tennessee (TN) is projected to grow by 2 million people, becoming the 15th most inhabited state in the U.S. [74]. Cleveland's 2010 census data notes a population of 41,285 [75]. This region is expected to grow by 32,000 people by 2035, almost doubling over a 20-year period. The Metropolitan Planning Organization (MPO) area has grown steadily over 60 years and that growth is expected to continue. From a regional perspective, Bradley County has experienced higher than average growth rates.

Farmland has declined by more than 50%, giving way to subdivisions in northeast Bradley County [76]. Cleveland's development has traditionally occurred in dense concentric circles around downtown, with a spoke pattern of development occurring along valleys and ridge lines. A substantial amount of residential infill development has occurred in older neighborhoods. The location and intensity of growth in Cleveland are influenced by availability of land, utilities and the proximity to major roads. Based on MPO growth forecasts, the county population is expected to grow from 98,520 residents in 2010 to 131,212 residents by 2035, or a total increase of over 32,000 residents in 25 years. This is approximately the size of Cleveland's current population [77].

The electrical load will grow as population increases, forcing the electrical system to also grow. With few exceptions, Cleveland Utilities (CU) provides electrical power services to most users within municipal boundaries of the City of Cleveland. The Volunteer Energy Cooperative (VEC) service territory encompasses CU's service territory. Electrical power for both VEC and CU is generated and transmitted by the Tennessee Valley Authority (TVA). The CU system receives power via two delivery substations (161 kV/69 kV) and provides service to its roughly 31,000 customers via 14 distribution substations (69 kV/13 kV), 53.5 miles of 69 kV lines and 530 miles of 13 kV lines. CU has a history of proactive long-range planning, which includes regular updates to a 10-year capital plan. Rate and billing structures allow revenues to fund upgrades and expansions of the CU electric system [78].

Potable water service and sewer services within Cleveland's urban growth boundary are also provided by CU. The available pressures and flows provide a high level of fire protection for the city. CU obtains system water supply from 4 sources:

- Its own Wastewater Filtration Plant (WWTP), with an average day processing of around 8 Million Gallons per Day (MGD);
- An average day 9.7 MGD allocation from the Hiwassee Utility Commission (HUC) Water Treatment Plant, which is operated under contract by CU;
- CU-owned-and-operated 1.5 MGD Waterville Springs, and, when needed;
- Purchased wholesale water via contract from Eastside Utilities [78].

Because this paper focuses on water storage within the potable water distribution system, it is simply noted here that the sewer system is prepared for growth. Beyond this, the wastewater side of the CU water system is not examined or discussed.

Analysis tools and scenario development

The U.S. Environmental Protection Agency (EPA) has created software that models pressurized, closed-water distribution-piping systems, which include pipes, nodes (junctions), pumps, valves and storage tanks or reservoirs. EPANET2 is a free and open-source toolkit, which is an important component to allow for ease of replicating of this study's methodologies in municipal water systems. Capabilities applicable to this study include determining pump energy usage, creating time-series graphs, and pumping and energy costs.

An EPANET2 model of the Cleveland: TN provides the baseline for water system behaviors. Model outputs are paired with external data throughout the research process, to produce answers in each research question. Approaches outlined in the literature review reinforce the development of this proof of concept.

Community energy data for the City of Cleveland is obtained and compared in Excel software (Microsoft Corp., Redmond: WA) to existing used and unused storage in the water model. When water model tank behaviors and their outputs are compared to aggregated community-wide electrical data, an order of magnitude is discovered that tempers expectations of peak-electrical-demand leveling and focuses attention upon the possibilities for peak-electrical-demand shaving. Cleveland electrical peaks are anywhere from 200,000-240,000 kWh per day. Peak electrical demand is defined as the hours of 1-9 PM Eastern Standard Time (EST), according to TVA guidelines [79]. 10% of that peak – not 10% of the entire community energy demand – is isolated and calculated to total 85,697 kWh over a 3-day period.

Scenarios are defined by the state of the existing water system, the magnitude and variability of water demand (manifested through population changes), and the magnitude and variability of energy demand. Concentrated and distributed water storage scenarios in the context of current (8 MGD/200,000 kWh per day) and future (16 MGD/400,000 kWh per day) water and energy demands are shown in Figure 1.

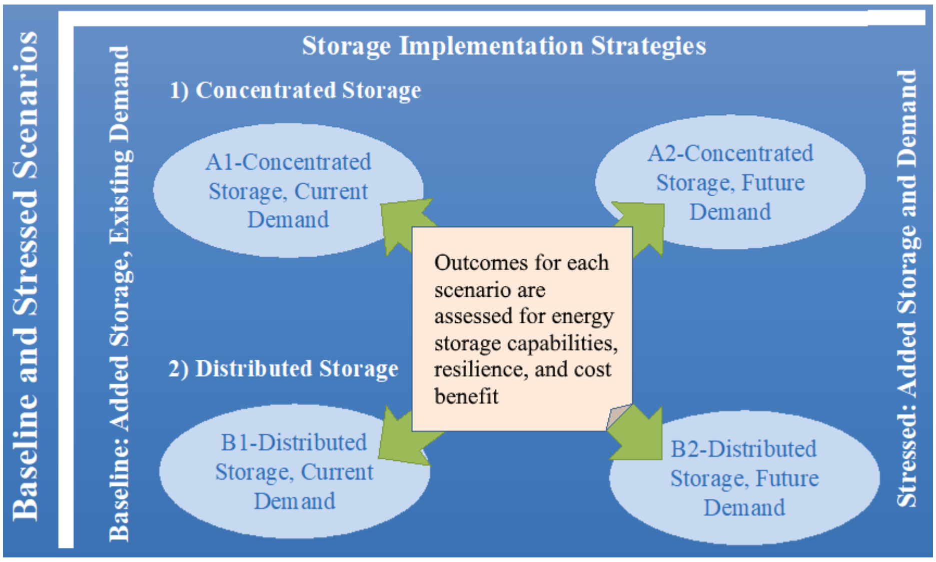


Figure 1. Method for analysis of storage implementation strategies

Population representing new water demand must be added within a water model in ways that most closely represent local development patterns. While Bradley County does have capacity for the forecasted growth, the City of Cleveland does not, unless there is redevelopment and infill development. For this reason, an infill approach to adding water demand is chosen for the A2 and B2 Cleveland scenarios.

Water demand projections can be added uniformly across the system by adding percent or multiplier increases to water demand patterns. This method tests incremental growth scenarios across a utility's service territory. Or, individual water demand increases can be added in the areas most likely to grow by adding links and nodes assigned specific water demands. While the water demand shape will be similar in either case, specific locations will influence water system variables, such as pumping requirements by elevation.

To determine if increased energy storage capacity aids in water system resiliency, additional energy storage capacity is modeled in an urban water system with increased population growth. Steps in this research process include:

- Determining a likely chronic stress scenario that the case study area could face, using population growth as the chronic stressor;
- Measuring the ability of the water system to meet water demand in associated failure scenarios, using the margin of water storage capacity above water demand;
- Comparing these scenario outcomes with and without energy generation.

How well the model responds to increases in population, with the addition of either concentrated or distributed storage, determines if adding water storage in various configurations enhances water system resiliency.

The A and B scenarios share 2 common methods: the energy calculation and the fire flow tests. To calculate generating potential for both scenarios, each tank's water demand [GPM], head [ft.], pressure [psi] and maximum height [ft.] is exported into Excel in 5-minute time steps for 3 24 hr days. Elevations are graphed for each tank to ensure the tank fills to maximum set levels during times of off-peak energy use and empties to minimum set levels during times of peak energy use. Then, flow, velocity [ft./sec)], unit head [ft./kg], friction factor, reaction rate and status (open/closed) for the associated General-Purpose Valve (GPV) is exported by 5-minute time step. Finally, horsepower is calculated for each GPV's hours of operation only (1-9 PM EST for each of the 3 days) using the following formula:

$$\text{Horsepower} = \frac{h_\text{A} Q(\text{SG})}{3{,}956} \tag{1}$$

where h_A is the head [ft.], Q is the flow [GPM], 328' is the difference in elevation between the upper and lower tanks and Specific Gravity (SG) is 1.

This is converted into kW for each peak-hour 5-minute time step by multiplying h_A by 0.7457 (the conversion from h_A to kW) and then by converting kW to kWh by multiplying kW by 0.08 (representing the 5-minute time step).

Additionally, both A and B scenarios are stress-tested with fire flow runs, which is when additional water demand is required incrementally during a run by the water distribution system model – as if supplying hydrant flows to extinguish blazes. The EPANET model must be able to meet normal water demands as well as water to put out fire demands. In fire scenarios, 20 psi is the standard minimum pressure that must be maintained throughout the system. A properly functioning model should be able to supply peak water demands, as well as accommodating additional fire flows with stable pressure. At time zero of the fire(s), nodes will still demand the same amount of water, motivating tanks to drain faster, and pumps to come on with more frequency.

A1 and A2 scenario methods: concentrated storage, future water demand

The design steps, assumptions and model modifications used to create the concentrated storage model under future water demand conditions are as follows:

- A verified model export of the Cleveland: TN water distribution system is the baseline for A1 scenario. To increase storage capacity and test for energy generation abilities, nine 3.5 million-gallon storage tanks are added in the southern portion of the water system. This storage capacity is chosen to be able to generate at least 10% of the community's peak electrical demand. The location is chosen because it is zoned industrial, has the necessary elevation (100 meters between the upper and lower tanks) and is located desirably close (1.08 miles) to a 69 kV electrical substation;
- Each tank configuration consists of upper and lower reservoirs connected by 36" pipes in a loop. Flow from the upper tank to the lower tank generates energy using a GPV to simulate a turbine during peak electrical demand times (1 PM to 9 PM EST). Water from the lower tank is pumped during off-peak energy demand times (9 PM to 1 PM EST) to refill the upper tank. These tanks function as electricity generators, not to meet water demand or to stabilize water system pressures. Potential energy generation is calculated in kWh to see how much peak community energy demand can be shaved using these tanks as a district-scale generating system;
- Using the A1 scenario model as a baseline for the A2 scenario model, the primary change from A1 scenario to A2 scenario is to double the water demand at each node within the model. A new pattern is created by exporting the existing peak water demand patterns, adding a multiplier of 2 to each, and importing them back into EPANET to replace the various Peak water Demand (PD) patterns;
- The Flow-Control Valve (FCV) is doubled in size at the water system's intake, to allow twice as much water to be pulled from the source. Increasing pipe sizes to allow for additional water purchase and withdrawal is something that CU contemplates in future upgrades to the water system, so this method reflects steps that would be taken to address a doubling population;

- Model warnings caused by negative pressures and loss of ability to meet additional water demand must be resolved. The A2 model fails with both the doubled population and the existing power generating controls added during A1 scenario design (Table 1). These controls command the additional storage to be drained during peak and filled during off-peak electrical hours. With these controls still in effect, the tank farm will serve only as pumped storage capacity for electricity generation, but will not meet water demand or maintain pressure. The tank farm needs to be allowed to respond to pressure and water demands, so these model rules are disabled;

Table 1. A1 scenario concentrated storage GPV and pump controls

CU model A1 scenario concentrated storage GPV and pump model controls		
Generating loop component	Setting	Model run time (hrs.)
LINK TANKFARM1_GPV	Open	at time 13.00
LINK TANKFARM1_GPV	Closed	at time 21.00
LINK TANKFARM1_GPV	Open	at time 37.00
LINK TANKFARM1_GPV	Closed	at time 45.00
LINK TANKFARM1_GPV	Open	at time 61.00
LINK TANKFARM1_GPV	Closed	at time 69.00
LINK TANKFARM1_PUMP	Open	at time 21.00
LINK TANKFARM1_PUMP	Closed	at time 37.00
LINK TANKFARM1_PUMP	Open	at time 45.00
LINK TANKFARM1_PUMP	Closed	at time 61.00

- Tank farm generating loops put in place in A1 for peak demand energy generation are also disabled, so that stored water can meet new water demand. Even with the model energy-generating controls disabled, the model continues to fail to meet pressure and water demands throughout the system. Negative pressures abound;
- Negative pressures are searched for at individual nodes throughout the model and resolved through slight elevation changes or nearby pump curve expansions;
- Pump curves are adjusted at individual pumps throughout the water distribution system, to try to eliminate negative pressures. The doubled water demand pattern is ultimately removed, replaced by the original water demand patterns. Water demand is then added to several nodes (representing subdivisions) in the southern half of the CU system, to see if concentrated storage can meet doubled water demand if it is within the same water pressure zone.

B1 and B2 scenario methods: distributed storage, future water demand

- B1 scenario is designed from a verified water model export of Cleveland: TN. To increase storage capacity and test for energy generation abilities, each existing water tank is doubled in height. Tanks are located in all development zones;
- Each B1 tank configuration consists of the doubled upper reservoir and a half-sized lower reservoir 100 meters apart, connected by 36” pipes in a loop. Flow from the upper tank to the lower tank generates energy using a GPV to simulate a turbine during peak electrical demand times. Water from the lower tank is then pumped during off-peak energy demand times to refill the upper tank. The additional storage added in B1 is used for energy generation, not to meet water demand or stabilize water system pressures. Potential energy generation is calculated to see how much peak community energy demand can be shaved using these tanks as a district-scale generating system;

- Water demand is doubled by importing the new water demand patterns created for the A2 model into the B2 model;
- The FCV at the primary water supply source is doubled in the B2 model, to allow twice as much water to be pulled from the source;
- The head at the corresponding supply pumps is raised and pipe diameters increased as needed (guided by model run warnings);
- Model warnings caused by negative pressures and loss of ability to meet additional water demand are resolved by increasing pump curves at various locations throughout the model to meet new water demand (meaning that CU would have to upgrade pumps throughout the system);
- Existing energy generating tank rules written into the B1 model are disabled, so that the tanks can respond at any point to meet water demand and pressure needs, within a system representing double water demands. Generating loops below each tank are disconnected, so that the additional storage previously used for energy generation can meet new water demand and pressure needs;
- Fire flows are run at 2-hour intervals at all nodes throughout the system to stress test water demand response;
- Maximum and minimum tank elevations during model runs are examined using the graphing function in EPANET2. This allows for observation of each tank's behavior over time, to ensure they are recharging and not being slowly emptied.

RESULTS AND DISCUSSION

The baseline A1 scenario concentrated storage model (normal water system demand with the tank farm generating electricity) can complete a run that includes fire-flow water demand, while maintaining pressure and meeting water demand throughout the system. Because tank farm water is not needed to meet water demand or to maintain pressures, instead only being used to generate energy at peak electrical demand, there is peak-electrical-demand shaving potential. The tank farm configuration can generate enough energy to offset 89,175 kWh, slightly over 10% of Cleveland's total July peak electrical demand.

However, the A2 model (doubled water system demand with the tank farm generating electricity) consistently either crashed or had negative pressures beginning at hour 30 that are unresolvable without entirely rebuilding the distributed CU water system model. Within the currently designed system, too many model modifications are needed to maintain a level of certainty that the model still represents reality. A model should reflect realistic possibilities in system operations, even after modifications occur.

After hundreds of hours spent learning the details of what normal operation looks like within the CU system, learning how to modify the model to make it smarter without violating the rules of flow within a water distribution system and learning to carefully make any reasonable, necessary system modifications, it is apparent that this scenario will not run with balanced flow or accurately represent system conditions. The initial 9 increased pump curves result in other pump curves needing to be increased. Increasing all model pump curves still does not correct negative pressures. Three times, the model fails at time 0 after working through all the previous pump errors. Other times, the model status report shows hundreds of negative node pressures, crashing the system's water balance at hour 30 within a 3-day model run.

While the concentrated storage design is better at generating electricity (as seen in A1 scenario), it does not ensure a water system that is resilient to a doubling population. Because the tank farm is in one place (southeast Cleveland), the additional storage it provides to generate electricity will not also be able to meet the water supply needs of a doubled and distributed population. Water from its tanks cannot answer pressure needs throughout the system, or meet additional water demands from nodes in other water pressure zones beyond the first day. The tank farm may be able to meet concentrated water demands if high growth occurs in south Cleveland, but it will need to be redesigned to space the tanks out in a manner that allows them to create and service their own pressure zones. If the tanks are used to meet water demand and to maintain system pressure, any energy generation gained in A1 will be sacrificed to service this new use.

Additional storage is required elsewhere throughout the A2 model for this scenario to satisfy new water demand, due to pressure zones throughout the system. This outcome ultimately makes sense. Supplying water demand is only one function of a tank in an urban water system. Tanks must be located close to the water demand they are meeting and be able to maintain pressures while supplying that water demand when required. The best way to do this is distribute tanks to delineate pressure zones, each with a primary tank controlling the pressures within that zone.

B1 and B2 scenario results: distributed storage, future water demand

B1 scenario can complete a run and meet stress-testing fire flows. Pressures are maintained and water demand is met. Tank turbines can also generate 5% of peak community electrical demand, or 44,704 kWh. While the B1 distributed storage scenario is not as successful as the A1 concentrated storage scenario in meeting energy generation needs, the B2 scenario is far more successful than the A2 scenario at adding water system resiliency when faced with the prospect of a doubling population. This finding is not surprising, given that recent literature also is documenting that distributed storage water storage supports system resiliency [80].

Because the distributed model has doubled the height of each tank, doubling the population and using all the additional storage to meet increased water demand (as opposed to using it to generate electricity) is possible. If additional storage is used to meet new water demands only (and not to generate electricity), the model can run without error and with an acceptable flow balance even when fire is also instigated (Figure 2).

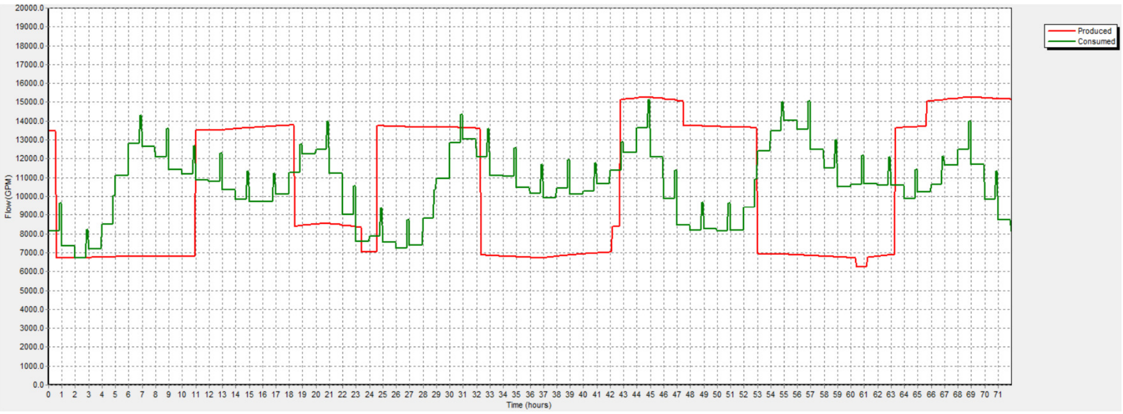
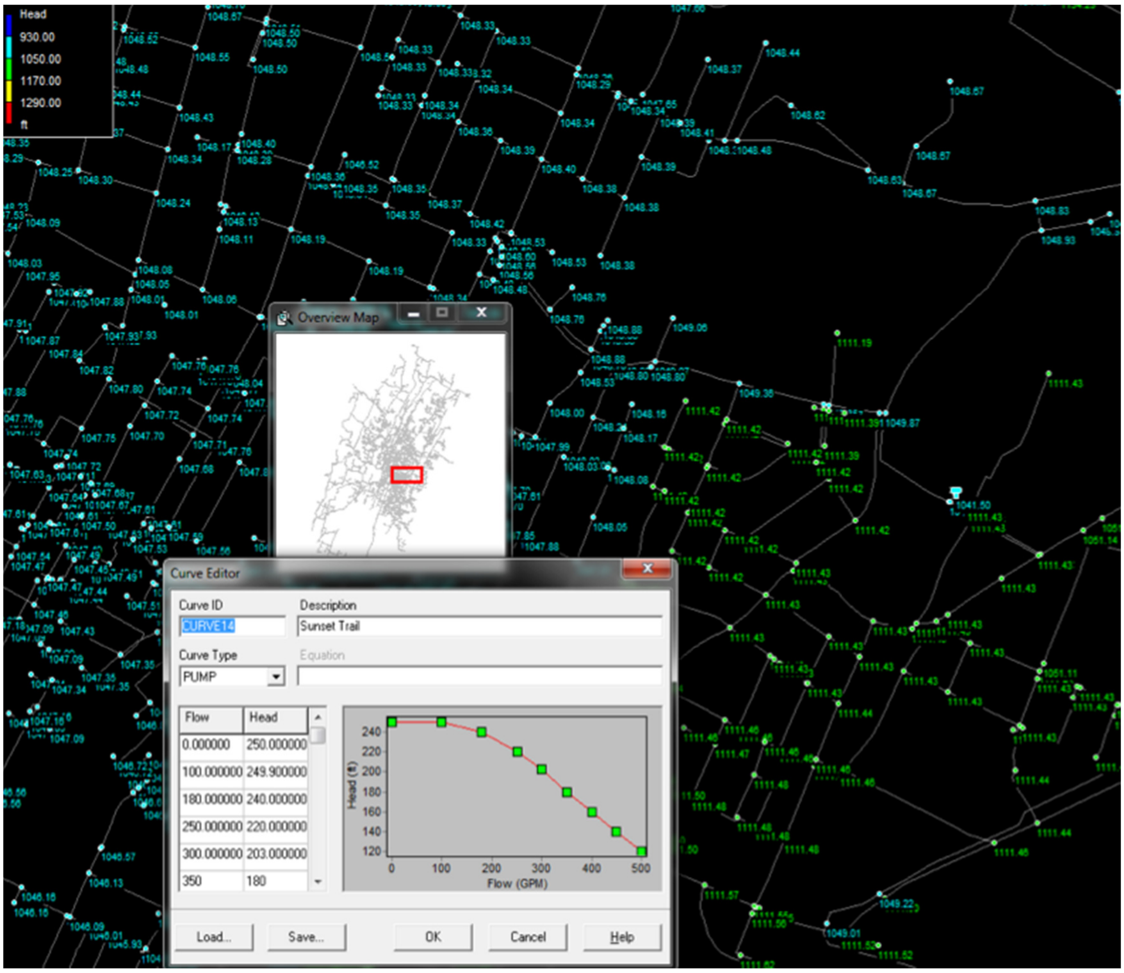


Figure 2. B1 scenario: water system balance with fire flow

However, pump sizes must be upgraded at each major pump throughout the system and any energy generation gained in B1 scenario is sacrificed. This is because all additional storage added in B1 is now going to meet the increased water demand added in B2 and cannot also then also be used to generate electricity. To meet doubled water demands and to also generate electricity, storage capacity would need to be doubled again, creating 3 times the amount the system began with. This is not realistic from a cost standpoint.

To ensure a B2 scenario model run that accurately reflects possible water system operations, many failed model runs are overcome. For instance, when the doubled water demand patterns are first introduced, the model failed comprehensively at time 0. Increasing 10 pump curves throughout the system to handle increased flow and head resulted in more failed runs, with negative pressures being the most common error (Figure 3).



Curve ID: CURVE14
Description: Sunset Trail
Curve Type: PUMP
Equation:

Flow	Head
0.000000	250.000000
100.000000	249.900000
180.000000	240.000000
250.000000	220.000000
300.000000	203.000000
350	180

Figure 3. Example of a model error correction: pump curve extension

It is not until the FCV settings and the corresponding pipe and pump sizes are upgraded at the water treatment plant that the model will run without error. Head graphs of each tank are examined to observe tank behaviors under these new constraints. All tanks maintain their desired elevations and water system operating preferences are also maintained. Therefore, the system can operate under B2 scenario parameters with double water demand, while providing fire flow to the entire system every 2 hours (Figure 4).

Cities are faced with tradeoffs as they test ways to make their water and energy systems more resilient: do they want to add water storage to generate energy to meet increased electrical demand, or do they want to add water storage to meet increased water demand? The desired outcomes must shape additional storage decisions and designs.

Predictive modeling designed to integrate various aspects of urban water and energy system resiliency is an area poised for development. Water and energy will not be considered in tandem until it is significantly less complicated to assess them together. The use of several different software programs leaves visual comparisons between water and energy hugely lacking. If the story of the two systems within the same community cannot be told in a cohesive manner, the motivators for taking proactive planning and implementation measures to integrate energy and water systems will remain hidden to the practitioner.

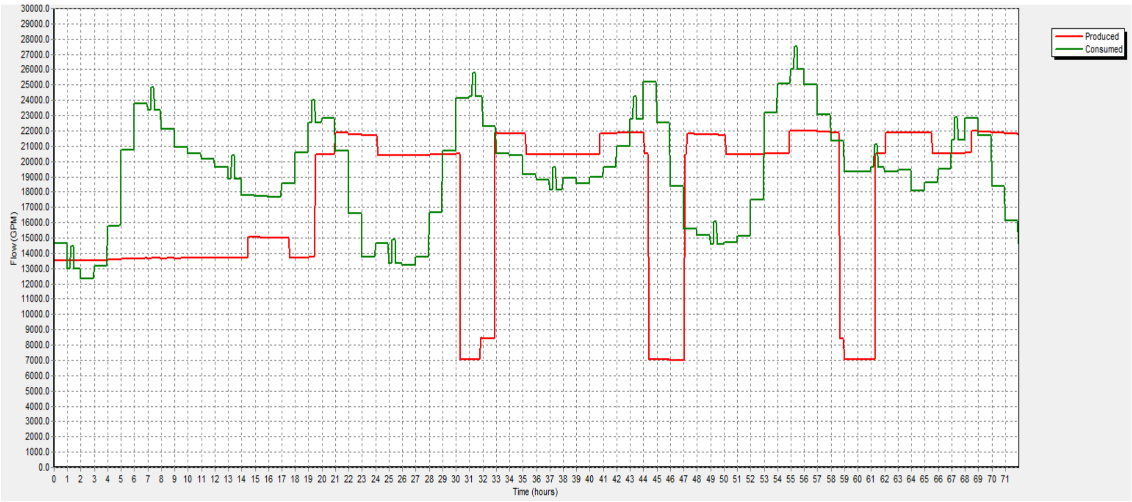


Figure 4. B1 scenario: water system balance with fire flow

CONCLUSIONS

The tested hypothesis assumes that the addition of energy storage capacity can make water systems more flexible and resilient when faced with chronic and uncontrollable external variables in modeled scenarios. To test the hypothesis, a city's water system is modeled with additional storage. The ability to meet double the water demand is examined, both with and without energy generating capabilities. New storage added in the A1 and B1 model scenarios is designated for energy generation only. Stored water in the upper tanks is released at peak electrical demand times. Released water generates electricity through a GPV, collects in the lower tank and is pumped to recharge the upper tank during off-peak electrical times. This water is not used to meet community water demand or to maintain water system pressures.

A rapidly growing population is simulated in the A2 and B2 scenarios by doubling water demand at each node with the water system model. This is done to understand how the increased storage originally added for energy generation can help a community address the chronic stress of growth. These scenarios are designed to reflect Cleveland's growth projections of primarily infill and redevelopment. Doubling population in the model means that the storage added in A1 and B1 scenarios for energy generation must instead be used to meet new water demand and water system pressure requirements in A2 and B2 scenarios. Generating electricity requires unused storage. Storage would need to double again to meet this increased water demand and to also continue to generate electricity. Communities must be clear on their goals for any storage additions.

Not only is energy generation sacrificed, but pumps must also be upgraded throughout the system in A2 and B2 scenarios to meet new water demand. The stressed A2 scenario (tank farm with increased water demands) will not function to meet new water demands of that magnitude. A tank farm scenario cannot meet doubled water demand throughout a full water distribution system, due to not being able to transfer water throughout the system at the time that it is required. It also cannot maintain water system pressures. To make the A2 concentrated storage scenario meet doubled water demand, the whole system would have to be rebuilt, even with intake pipes, pumps and valves preemptively upgraded as a model presupposition.

The stressed B2 scenario (distributed increased storage with increased water demands) will meet doubled water demands. In terms of water system resiliency, distributed storage is better than concentrated storage. As a system grows, managing pressure and meeting water demand throughout is more easily done over time, as tanks are placed within new developments. Isolating storage, while better for hydropower generation, makes less sense through the resiliency lens. However, in both population-stressed scenarios, energy generation must be sacrificed to attempt to meet doubled water demands.

It is reasonable to assume that with doubled water demand comes a similar increase in electric demand. As neither stressed scenario can meet new water demand, maintain system pressure and generate electricity all at once, it becomes clear that without significant water system growth (specifically for energy generation), the community electrical load cannot be reduced by energy generation within the urban water system. However, if a community adopted an energy consumption offset mentality towards the provision of water and energy services, there could be opportunities for water and energy system integration at the neighborhood scale. For instance, a water tank pressurizing a small area could not only meet water demand and maintain water system pressure for that area, but it could also be designed with in-line pipe turbines to capture tank outflows and convert them into enough energy generation to service that tank's associated pumping station during peak electrical demand. With peak-demand energy pricing, pumping costs could be minimized or covered by the addition of turbines.

While this research explores water system support of the electrical system from a community-wide lens, future research should focus on distributed energy within urban water systems at the neighborhood scale for increased resiliency. Reducing the scope of study will allow for a clearer understanding of how energy generation from pumped storage within an urban water system can work to make that system more resilient, while also producing electricity in small amounts to offset water system energy consumption operating costs. A separate study assesses the economic implications of these storage configuration scenarios. Findings from that economic analysis also support neighborhood-scale implementation. Investments in smaller energy-generation systems designed to reduce a specific and targeted energy load have shorter payback periods, reducing the upfront capital requirements and the timeframe to realize a return on investment. If the water-energy nexus is to advance in urban settings, the goals of system integration, as well as the economic, environmental and social implications of these goals must factor into any engineering analysis.

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