The Water-Energy Nexus at Water Supply and Its Implications on the Integrated Water and Energy Management

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Abstract
Water and energy are highly interdependent in the modern world, and hence, it is important to understand their constantly changing and nonlinear interconnections to inform the integrated management of water and energy. In this study, a hydrologic model, a water systems model, and an energy model were developed and integrated into a system dynamics modeling framework. This framework was then applied to a water supply system in the northeast US to capture its water-energy interactions under a set of future population, climate, and system operation scenarios. A hydrologic model was first used to simulate the system's hydrologic inflows and outflows under temperature and precipitation changes on a weekly-basis. A water systems model that combines the hydrologic model and management rules (e.g., water release and transfer) was then developed to dynamically simulate the system's water storage and water head. Outputs from the water systems model were used in the energy model to estimate hydropower generation. It was found that critical water-energy synergies and tradeoffs exist, and there is a possibility for integrated water and energy management to achieve better outcomes. This analysis also shows the importance of a holistic understanding of the systems as a whole, which would allow utility managers to make proactive long-term management decisions. The modeling framework is generalizable to other water supply systems with hydropower generation capacities to inform the integrated management of water and energy resources.

Keywords: Water-energy nexus; system dynamics modeling; water supply; hydrologic modeling; hydropower generation; climate change

Over the last decade, the traditional approach of managing water and energy separately is increasingly being challenged by the manifesting water-energy nexus (Cohen et al., 2004; DOE, 2006; EPA, 2013; Hussey and Pittock, 2012), which refers to the compounded interactions between water and energy resources emerged from the development of modern engineered systems. Municipal water supply relies heavily on energy for treatment and pumping (Mo et al., 2010; Mo et al., 2011), yet it could also constrain energy supply when competing with thermoelectric cooling, hydropower generation, and/or biofuel feedstock irrigation for the limited water resources (Cherubini et al., 2009; Searchinger et al., 2008). Power plant shutdowns happen when insufficient amount of water (especially during droughts) is available for cooling (DOE, 2014). On the other hand, water utilities are often paid by power companies to get off grid during peak hours to alleviate energy stress (Mo et al., 2016). The nexus, as it exists today, increases the vulnerability of both water and energy supplies facing future population, environment, and technology changes (DOE, 2014; Hussey and Pittock, 2012).

Water supply and treatment is often one of the biggest contributors to a city's energy budget (Mo et al., 2011). In the US, drinking water and wastewater systems consume around 3-4% of total electricity (Mo et al., 2010), adding over 45 Gg of greenhouse gases annually (EPA, 2017). Furthermore, energy could represent as much as 40% of the total operational cost (EPA, 2017) of a drinking water system. To reduce cost and improve sustainability, harnessing the hydropower potential from water systems has been increasingly discussed and applied in addition to water conservation and energy efficiency improvement practices (Corcoran et al., 2013; McNabola et al., 2012; Ramos et al., 2010). Dams have been used to manage source water storage, control flooding, and generate electricity to recover the water systems' energy cost. According to the US National Inventory of Dams, around 150 large water supply dams are currently also being used for hydropower generation (NID, 2016). Additionally, the potential of micro hydropower generation in US water systems is estimated to be on the order of hundreds of megawatts (Pabi et al., 2013). Unlike the facilities that are primarily used for hydropower production, hydropower facilities in drinking water systems are usually operated under the priority of water supply (Corcoran et al., 2013; Westphal, 2001). Hence, the amount of hydropower generation is often subject to changes in water demand, water availability, and individual management practices. The existence of such facilities presents a potential water availability and energy generation tradeoff, which could further influence the sustainability and resilience of the water supply systems.

The water-energy nexus in drinking water systems has primarily been investigated via energy audits (DOE, 2006; Goldstein and Smith, 2002; Maupin et al., 2014; Sanders and Webber, 2012) and life cycle assessments (LCA) (Friedrich et al., 2009; Godskesen et al., 2010; Lyons et al., 2009; Mo et al., 2010; Mo et al., 2014; Mo et al., 2011; Rothausen and Conway, 2011; Stokes and Horvath, 2009; Valek et al., 2017). Energy audits characterize the operational energy consumption of water utilities at national, regional, or individual system scales, which are often based on highly aggregated survey data, and subject to data approximations and allocations. LCA quantifies both direct and indirect energy flows associated with the entire supply chain of water utilities, and hence offers a more comprehensive approach in quantifying the "true" energy embodiment beyond the physical boundary of the water supply systems. Both audits and LCAs, however, are limited in their capacities to include temporal details, system feedback, and stochastic properties, and hence are unable to provide understandings of future trends, and to support proactive and integrated water-energy decision making (Friedrich, 2002; Lyons et al., 2009; Mo et al., 2010; Mo and Zhang, 2016; Mo et al., 2011; Racoviceanu et al., 2007; Stokes and Horvath, 2009). A study in California employed a statistical approach, using Classification and Regression Tree algorithm to investigate the influence of reservoir operation and climate on water supply and hydropower generation (Yang, 2015). One drawback of statistical methods, however, is the limited insights they provide towards the underlying mechanisms of the water-energy tradeoffs. Process-based hydrologic and energy models have also been used by previous studies to investigate the impact of climate change on the water-energy nexus (Gaudard et al., 2018; Kern and Characklis, 2017; Tarroja et al., 2016; Tarroja et al., 2014; Turner et al., 2017; Voisin et al., 2016). Nevertheless, most of these studies approach the problem from an energy supply perspective, while the constraints from the water supply perspective were not discussed.

In light of the limitations of the current methods, a modeling framework that is based upon the concept of system dynamics (SD) modeling was developed at a watershed scale. SD is a powerful platform for modeling dynamic, coupled, and complex systems beyond traditional system boundaries (Ford, 1999; Forrester, 1961; Kelly et al., 2013; Sterman, 2000). It not only captures the dynamic behavior of water and energy that are critical for understanding sustainability and vulnerability, but also characterizes the dynamics of feedbacks, thresholds, and constraints to systems from external disturbances (e.g., management, demand, and climate changes). Although SD has been increasingly applied in environmental decision making (Anand et al., 2006; Chang et al., 2008; Feng et al., 2013; Kibira et al., 2009; Lauf et al., 2012), particularly in the area of water resource management (Ahmad and Simonovic, 2004; Fernández and Selma, 2004; Winz et al., 2009; Zhuang and Zhang, 2015), few efforts have applied such a framework to holistically understand the water-energy nexus (Zhuang and Zhang, 2015). In this study, we focused on characterizing water supply and hydropower interactions as an initial effort in developing the integrated water and energy management framework for an entire urban water cycle. A hydrologic model, a water systems model, and an energy generation model were developed and integrated using the SD modeling concept, and applied to a case study water system to capture its water-energy interactions under a set of future population, climate, and system operation scenarios. This model framework is applicable to other water supply systems with hydropower facilities to inform the integrated management of water and energy resources.

1 Case Study System Description

The Massachusetts Water Resources Authority (MWRA) is the primary water supplier of the Greater Boston area with a daily flow of around 950 ML and a serving population of around 2.2 million. The MWRA obtains its source water from two reservoirs: the Quabbin reservoir and the Wachusett reservoir (Figure 1; Table S-1 of the Supporting Information (SI)). The Quabbin aqueduct connects the two reservoirs, and allows water to transfer from Quabbin (higher quality) to Wachusett (lower quality) by gravity. The Quabbin-to-Wachusett water transfer helps keep the Wachusett water level at a range of 118.9-119.3 m to maintain water quality. The Ware River flows in between the two reservoirs and intersects with the Quabbin aqueduct. The Ware River water can be diverted to the Quabbin reservoir via the aqueduct to meet high summer water demand. However, the river diversion restricts other uses of the aqueduct (e.g., Quabbin-to-Wachusett water transfer).

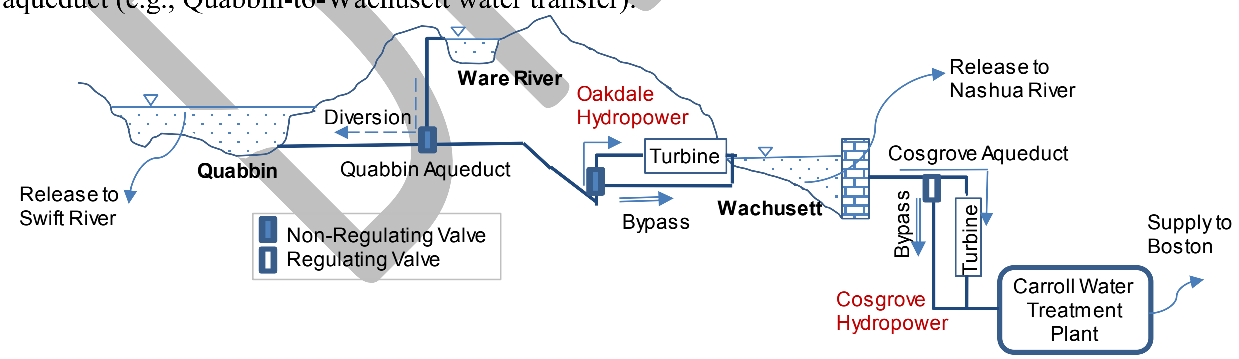


Figure 1 Schematic of the major system components at the Massachusetts Water Resources Authority (adapted from Westphal et al. 2001)

The MWRA currently has two active hydropower stations: the Oakdale station and the Cosgrove station (Figure 1). The Oakdale station sits on the Quabbin aqueduct and generates electricity from the Quabbin-to-Wachusett water transfer. It has an installed capacity of 12.6 MW and a hydraulic capacity of around 13 m^3/s. A non-regulating valve is installed at the station inflow. When transferred water is below the Oakdale's hydraulic capacity, water will be used for power generation. Otherwise, all water will bypass the station without power generation. The Oakdale station currently sells around 50 TJ of electricity/year to the grid. The Cosgrove station generates electricity when water is transferred from the Wachusett reservoir to the Carroll Water Treatment Plant. It has an installed capacity of around 1.2 MW and a maximum hydraulic capacity of around 9.5 m^3/s. Unlike the Oakdale station, regulating valves are installed at the Cosgrove station. Hence, the station is able to run at full capacity even when the maximum hydraulic capacity is exceeded by only allowing the excess water to bypass. The Cosgrove station sells around 11 TJ of electricity/year to the grid.

2 Methods

The modeling framework applied in this study has three interlinked components (Figure 2). A hydrologic model was first developed to simulate the watershed runoffs entering the water system based upon temperature and precipitation inputs. Outputs from the hydrological model were then used in a water systems model to simulate reservoir water storage/level changes based upon water management decisions (e.g., water transfer and diversion). The simulated water levels and operation parameters will collectively feed into an energy generation model to dynamically simulate the hydropower generation at the Oakdale and Cosgrove stations. A weekly time step is adopted throughout the entire modeling process, which aligns with the MWRA's general decision making interval of water management. Microsoft Excel was used for model development and validation.

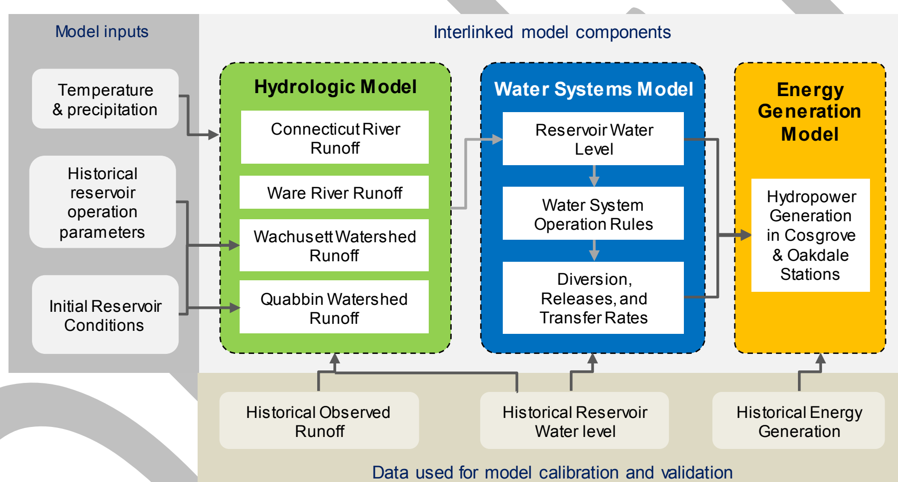


Figure 2 Overview of the modeling framework applied in understanding the water supply and hydropower generation interactions at the Massachusetts Water Resources Authority

2.1 Hydrologic Model

Runoffs in the four hydrologic components related to the MWRA system (the Quabbin and Wachusett watersheds, the Connecticut River, and the Ware River) were simulated using a modified version of the abcd hydrologic model (Westphal, 2001). This model was selected based upon its limited data requirement (only maximum and minimum air temperature and precipitation are used as inputs), reliable simulation outcomes demonstrated by previous studies (Alley, 1984; Vandewiele and Xu, 1992; Westphal, 2001), and easy-to-use spreadsheet format. In the modified model, four physically-based parameters, namely a, b, c, and d, were used to simulate the time series of two important water storage variables: soil moisture and groundwater; and two additional parameters (T_b and e) were added to account for snow accumulation and melting. Parameters a, b, c, and d are related to surface runoff and recharge, soil moisture storage capacity, net groundwater inflow, and mean groundwater residence time, respectively (Thomas, 1981). Parameter T_b and e control the temperature-snowfall and temperature-snow melt relationships respectively. Temperature and precipitation inputs were obtained from the National Climate Data Center (NOAA, 2016). A detailed list of parameters and equations of the modified abcd model is provided in Table S-2 and Section S-1 of the SI.

2.1.1 River runoffs

The *a, b, c, d, e,* and T_b parameters for the Ware River and the Connecticut River were calibrated by minimizing the mean square error (MSE; Equation 1) between the modeled and observed runoffs. The MSE weighs large errors more heavily than the small ones, and it does not cancel out positive and negative errors.

$$MIN\left[\frac{1}{n}\sum(Q_{\mathrm{mod},t}-Q_{obs,t})^2\right] \quad \text{(Equation 1)}$$

Where n represents the total number of time-steps, and $Q_{mod,t}$ and $Q_{obs,t}$ represent the modeled and observed runoff in m^3/s at time t, respectively. $Q_{obs,t}$ data of each river were obtained from the US Geological Survey (USGS, 2016), and split into two segments for model calibration (two-third of the available data) and validation (one-third of the available data) based upon the literature (Chaibou Begou et al., 2016; Srinivas and Srinivasan, 2001) (Details of the model calibration and validation processes are provided in Section S-2 and Table S-3). The Ware River model was validated using a set of widely applied quantitative statistics, including Nash-Sutcliffe efficiency (*NSE*), percent bias (*PBIAS*), and the ratio of the root mean square error (*RMSE*) to the standard deviation of measured data (*RSR*) (Moriasi et al., 2007). The Connecticut River has a high degree of upstream flow regulation which was not captured by the runoff model. In this study, the Connecticut River runoff is only used to determine the Quabbin water release to the Swift River, which is a step function based upon three Connecticut River flow regimes (Table S-4). Therefore, the model performance is dependent on the model's capability in successfully predicting the occurrences of the three flow regimes and the magnitude of the error caused by a possible prediction failure. Accordingly, a success rate, defined as the ratio between the number of times that the modeled runoff is in the same flow regime as the observed one and the total number of times this particular regime occurs, was used to evaluate the model performance.

3.1.2 Quabbin and Wachussett watershed runoffs

Reservoir watershed runoffs were simulated based upon reservoir water mass balance. Since no historical observed runoff data exist for the two reservoirs, we use the historical observed reservoir water storages to calibrate the six parameters in the abcd hydrologic model. Storage in each reservoir at each time step of t can be calculated based on the inflows and outflows occurred at the current time step and the storage of the reservoir in the previous time step (Equation 2). It has to be noted that Tr_t is an inflow for the Wachusett reservoir but an outflow for the Quabbin reservoir. D_t is only applicable for the Quabbin reservoir.

$$S_t = S_{t-1} + R_t - See_t + SE_t + P_t \pm Tr_t + D_t - Re_t \quad \text{(Equation 2)}$$

Where,

- S_t = storage volume at the end of week t, m^3;
- R_t = runoff of the watershed in week t, m^3;
- See_t = seepage contribution to the reservoir storage in week t, m^3;
- SE_t = surface evaporation from the reservoir, m^3;
- P_t = precipitation received on the surface of the reservoir, m^3;
- Tr_t = transferred volume from Quabbin to Wachusett reservoir in week t, m^3;
- D_t = diversion volume from Ware River to Quabbin reservoir in week t, m^3; and,
- Re_t = released (including drinking water supply withdrawal) and spilled volume from the reservoir into the downstream in week t, m^3.

Reservoir storages and water levels can be converted between each other using Equations 3 and 4. The simulated reservoir storages were then compared against the observed storage obtained from plugging in observed water levels into Equations 3 and 4.

$$S_Q = 32324 \ \ - 487 \ \ El_Q + 78 \ \ El_Q^{\ 2} \quad \text{(Equation 3)}$$

$$S_W = 3367 \ \ - 70 \ \ El_W + 3 \ \ El_W^{\ 2} \quad \text{(Equation 4)}$$

Where S_Q and S_W are Quabbin and Wachusett reservoir storages respectively, m^3; and, El_Q and El_W are Quabbin and Wachusett reservoir elevations respectively, m. Historical Tr_t, D_t, Re_t, El_Q, and El_W values from October 2007 to June 2016 were obtained from the MWRA.

Through reservoir water mass balance, two additional parameters were calculated simultaneously in addition to the watershed runoff R_t: See_t and SE_t. Hence, the three parameters were calibrated and validated as a whole. Furthermore, SE_t is restricted by the existence of ice cover on the reservoirs. It is assumed that no surface evaporation will happen when the weekly average temperature is below the snow melting temperature of T_b (Equation 5) (Westphal, 2001).

$$SE_t = \begin{cases} 1000 a_i PE_t A & T_{av,t} > T_b \\ 0 & T_{av,t} \le T_b \end{cases} \quad \text{(Equation 5)}$$

Where,

SE_t = surface evaporation for week t, m^3/day;
a_i = calibrated surface evaporation multiplier of the reservoir in month i (Table S-5 in SI);
PE_t = potential evapotranspiration (Table S-2 in SI), mm/day; and,
A = reservoir surface area, m^2.

Similar to the river runoff model, the $a, b, c, d, e,$ and T_b parameters for calculating R_t, See_t, and SE_t were calibrated by minimizing the MSE of the modeled and observed reservoir storage. Typical ranges of the six parameters were applied to reduce the computation time (Table S-6 in SI). The watershed runoffs were validated using the Root Mean Square Percentile Error (RMSPE) as suggested by (Sterman, 1984).

2.2 Water Systems Model

Once reservoir runoffs were calibrated and validated, Tr_t, D_t, and Re_t values were further simulated based upon current operation rules at the MWRA. Tr_t, D_t, and Re_t decisions are made based upon the water levels of the two reservoirs. Water supply is set as the primary objective of the MWRA, while hydropower generation is a secondary objective. To ensure sufficient quantity and quality of water in the Wachusett reservoir, its water level is maintained at a relatively fixed level. Energy is only generated when the required Wachusett water level is met.

2.2.1 Water diversion from the Ware River to the Quabbin reservoir

Both water diversion from the Ware River to the Quabbin reservoir ("diversion" below) and water transfer from Quabbin to Wachusett reservoir ("transfer" below) require the Quabbin aqueduct. Hence, only one of the two operational modes can take place at a given time. Diversion happens when the Quabbin water level is lower than its monthly baseline values (Table S-7 in SI). It has a higher priority than water transfer to ensure sufficient water availability in the Quabbin reservoir. The amount of diversion is calculated based upon the difference between the actual storage and the baseline storage. Diversion is also restricted by the aqueduct capacity and the water availability in the Ware River. The diversion model also determines the number of days that diversion would happen in a week ($N_{div,t}$) (Equations 6 and 7).

$$Q_{div,t}(m^3/s) = \begin{cases} if\ (Q_{WR,t} > Q_{WR,th}\ and\ \ S_{Q,t-1} < S_{Q,b,i}) & m \times Min\,(Q_{div,\max}, (Q_{WR,t} - Q_{WR,th})) \\ else & 0 \end{cases} \quad \text{(Equation 6)}$$

$$N_{div,t} = \begin{cases} if\ (Q_{div,t} \neq 0) & k \times integer(\dfrac{S_{Q,b} - S_{Q,t-1}}{Q_{div,t}} + 1) \\ else & 0 \end{cases} \quad \text{(Equation 7)}$$

Where,

$Q_{div,t}$ = diversion rate from Ware River to Quabbin reservoir in week t, m^3/s;
$Q_{WR,t}$ = Ware River streamflow estimation at the end of week t, m^3/s;
$Q_{div,max}$ = maximum capacity of diversion, 29 m^3/s;
$Q_{WR,th}$ = a flow rate threshold in Ware River at which diversion starts, 3.72 m^3/s;
$S_{Q,t-1}$ = Quabbin storage at the end of week $t-1$, m^3;
$S_{Q,b,i}$ = Quabbin baseline storage at month i, m^3;
m = calibration factor obtained from comparison with the observed diversions, 0.33;
$N_{div,t}$ = the number of days in a week t that Quabbin aqueduct will be used for diversion, day; and,
k = unit conversion factor, 1/86400.

2.2.2 Water transfer from the Quabbin reservoir to the Wachusett reservoir

Water transfer rate from Quabbin to Wachusett is determined by Wachusett water elevation. At each time step, water level in the Wachusett reservoir will be compared to its desired average monthly elevation (baseline, Table S-7 in SI). If the elevation is lower than the baseline, transfer will be carried out to replenish the Wachusett reservoir. The required transfer is hence equal to the difference between the baseline storage and the current reservoir storage. Given that diversion has a higher priority, the number of days that can be used for transfer in a week can be calculated as $7\text{-}N_{div}$. If the required transfer is within the turbine flow capacity of the remaining $7\text{-}N_{div}$ days, all water will be used for energy generation. The turbine flow rate is influenced by the available water head, which is determined by the elevation difference between the two reservoirs ($\Delta El_{Q\text{-}W}$). When $\Delta El_{Q\text{-}W}$ is ≥40.5 m, water can pass the turbine at a rate of 15.8 m^3/s (Westphal, 2001). When $\Delta El_{Q\text{-}W}$ is <40.5m, water can only pass the turbine at a rate of 14.7 m^3/s (Westphal, 2001). If the required transfer exceeds the turbine flow capacity of the remaining 7-N_{div} days, a certain number of days (N_{bypass}) will first be used for water to bypass the turbine at a higher flow rate and the remaining days will be used for energy generation ($N_{Tur}=7\text{-}N_{div}\text{-}N_{bypass}$). This is achieved by gradually increasing N_{bypass} until the required transfer amount is satisfied in the target week. The maximum flow rate through the bypass system is estimated assuming total head loss (due to friction, orifices, and bends) in the aqueduct is equal to the water elevation difference between the two reservoirs (Section S-3 in SI).

2.2.3 Water release from the two reservoirs

Water is withdrawn directly from the Wachusett reservoir for drinking water supply. Monthly averaged water supply rates were obtained directly from the MWRA (Table S-8 in SI). These values were then used to estimate weekly water supply rates, assuming all days of a particular month have the same supply rate. In addition, the Wachusett reservoir regularly releases 0.05 Mm^3 of water per week to the Nashua River to meet its downstream environmental demands. The Quabbin reservoir flows into the Swift River and eventually enters the Connecticut River lying on the west side of the reservoir. The ecological flow requirement of the Connecticut River governs the minimum daily downstream release of the Quabbin reservoir (Table S-4 in SI). High release rates usually happen during the dry season between June and November. In cases when the Wachusett or Quabbin storages still exceed the baseline after the regular releases, the excess water will also be released to their downstream rivers. However, the amount of the excess release is subject to the maximum capacity of the downstream rivers provided in Table S-9 in SI. These practices are carried out to minimize the flooding risk at the reservoirs and the downstream rivers.

2.3 Energy Generation Model

Weekly energy generation at the Oakdale station is calculated using Equation 8. Head loss is calculated using the Darcy-Weisbach equation for energy loss in an enclosed conduit (Section S-3 in SI). q_{Tur}, N_{tur}, and El_{Qavg} are fed by the water systems model dynamically.

$$P = N_{Tur} q_{Tur} (El_{Q_{avg}} - El_{tur} - h_L) \rho g \eta k \qquad \text{(Equation 8)}$$

Where,

P = power generation at the Oakdale hydropower station, W;
N_{Tur} = number of days that the turbine is used for energy generation;
q_{Tur} = turbine water flow rate, 15.8 or 14.7 m^3/s;
El_{Qavg} = Quabbin reservoir average elevation in a week, m;
El_{tur} = turbine elevation at Oakdale station, 121.31 m;
h_L = head loss, m;
ρ = density of water, 1000 kg/m^3;
g = acceleration of gravity, 9.8 m/s^2;
η = combined hydraulic and mechanical efficiency of the turbine, 90%; and,
k = unit conversion factor, 1/86400.

Electricity generation at the Cosgrove station only happens when it is safe for the downstream water treatment plant. Any large hydraulic surge may cause malfunctioning of the ozone disinfection units and plant shutdowns. Around 50% of the water supplied by the MWRA through the Cosgrove aqueduct is used to generate hydropower. Calculations of energy generation in the Cosgrove station are provided in Equation 9.

$$P = \begin{cases} if\ \ (77 < J < 319) & \rho (50\% \times q_{supply})\, g\ (El_{Wavg} - 99.67) \eta \\ otherwise & \rho\ q_{win} g\ \ (El_{Wavg} - 99.67) \eta \end{cases} \qquad \text{(Equation 9)}$$

Where,

J = Julian day;
EL_{Wavg} = Wachusett reservoir average elevation in a week, m;
q_{supply} = water supply rate to Boston area, m^3/s; and,
q_{win} = constant flow rate through Cosgrove turbine in winter, 2.63 m^3/s.

The simulated energy generation in both hydropower stations were compared to the observed values obtained from the MWRA for the period of October 2007 to October 2016, and their linear correlation were evaluated using R^2 values.

3 Scenarios

The water-energy tradeoffs of the MWRA were tested under different operation, climate change, and population growth scenarios.

3.1 System Operation Scenarios

Given the importance of water elevation for water supply and energy generation at the MWRA, five target elevation levels of the Wachusett reservoir were examined: 118.3m (1m below the baseline), 118.8m (0.5m below the baseline), 119.3m (baseline, current target elevation), 119.8m (0.5m above the baseline), 120.3m (1m above the baseline). Under each of the five scenarios, water transfer, diversion, and release operations were performed to maintain the Wachusett elevation at the target level, following a priority order of release, diversion, and transfer. Additionally, five target elevation scenarios of the Quabbin reservoir were also investigated. These scenarios, similar to Wachusett, apply a change of -1m, -0.5m, 0m (current), +0.5m, +1m to the monthly Quabbin water elevation baselines. For each of the ten scenarios, simulations were carried out for a 10-year run period (2007-2016) using the same temperature and precipitation input data and the same priority order of release, diversion, and transfer as the baseline model.

3.2 Climate Change Scenarios

Climate change is another factor that could potentially influence the water-energy tradeoffs at the MWRA. Two statistically downscaled emission scenarios generated by the Intergovernmental Panel on Climate Change (IPCC) were adopted in this study. A high emission scenario (A2) represents a future where global population increases continuously, economic development is primarily regionally oriented, and technological change is slow. A low emission scenario (B1) depicts a future where economic structures rapidly change towards a service and information economy, and clean and resource efficient technologies are introduced. These downscaled climate change predictions were estimated as multi-model means of 29 (14 for B1 scenarios and 15 for A2 scenarios) Climate Model Intercomparison Project phase 3 (CMIP3) global climate simulations (Kunkel, 2013; Mo et al., 2016). For each of the two emission scenarios, both the highest and lowest predicted temperature and precipitation changes were simulated. Under each simulation, the model runs for four 3-year discrete periods starting from 2015 (baseline), 2035, 2055, 2085. Within each run period, temperature and precipitation were assumed to have the uniformed changes in all time steps as indicated by Table 1 compared with the 2015 baseline. Table 1 provides the lowest and highest temperature and precipitation changes towards the end of this century under each scenario.

Table 1 Future temperature and precipitation changes in northeast US obtained from the National Climate assessment reports(Kunkel, 2013; Mo et al., 2016)

Climate scenarios		Δ Temperature (°C)			Δ Precipitation (%)		
		2035	2055	2085	2035	2055	2085
A2	Lowest	0.9	1.6	2.7	−5	−6	−8
	Highest	2.5	3.6	6.3	7	10	16
B1	Lowest	0.9	1.2	1.9	−5	−4	−2
	Highest	1.9	2.6	3.5	9	8	10

∗A2 is a high emission scenario with a global CO^2 concentration of 800 ppm by 2100. B1 is a low emission scenario with a global CO^2 concentration of 500 ppm by 2100. Both scenarios are developed by the Intergovernmental Panel on Climate Change (IPCC).

3.3 Population Growth Scenarios

Per the US Census Bureau, the current annual population growth rate of MA is around 0.06% (Strate et al., 2016). Three growth rates were investigated in this study, representing 50%, 100%, and 200% of the current rate respectively. We assume water demand increases proportionally to the population growth, and hence the same three percentage increases in water demand relative to the 2015 baseline were investigated. Under each scenario, the model runs for four 3-year discrete periods starting from 2015 (baseline), 2035, 2055, 2085.

4 Results and Discussion

4.1 Hydrologic Model

Table 2 shows the calibrated *a, b, c, d, e,* and T_b values obtained for four hydrologic components of the MWRA. Calibration and validation outcomes of the hydrologic models are described in detail in Section S-4 of the SI.

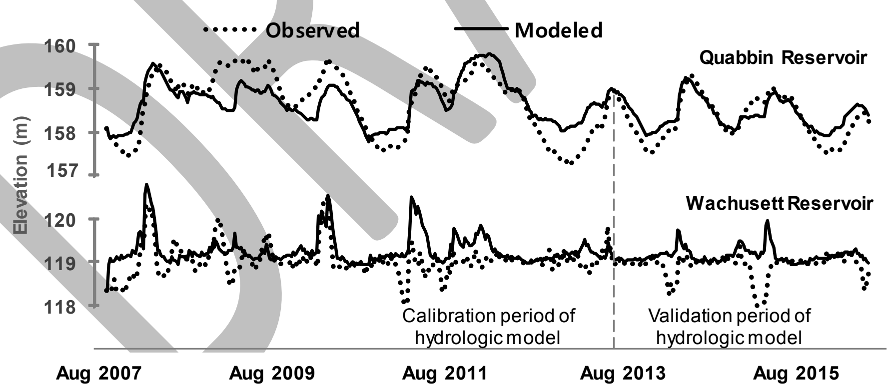
Table 2 Calibrated *a, b, c, d, e,* and T_b values of the river and watershed runoff models

Parameters	*a*	*b*	*c*	*d*	*e*	T_b (℃)
Ware River	0.997	15.54	0.720	0.443	0.398	-2.42
Connecticut River	0.950	16.42	0	0.188	0.481	-1.93
Wachusett watershed	1.000	83.420	0	0.164	2.080	-1.55
Quabbin watershed	0.979	8.010	0.590	0.205	2.080	-2.98

The developed hydrologic model for the four independent watersheds of this study were evaluated for the validation period. The Ware River runoff model has a NSE value of 0.84, PBIAS value of 3.58%, and RSR value of 0.41, all of which are within the acceptable ranges as suggested by Morisi et al. (Moriasi et al., 2007). The Connecticut River model has a success rate of 99% at the flow regime with the highest frequency. The Wachusett and Quabbin watershed runoff models have RMSPE values of 0.46 and 0.12 respectively, which are both within the acceptable range of 5% as suggested by Sterman (Sterman, 1984). These evaluation outcomes indicate the suitability of the calibrated hydrologic models for the following modeling steps.

4.2 Water Systems Model

A comparison of the simulated and observed historical diversion, transfer, and release was performed, and the outcomes are provided in Figure S-4 in the SI. These simulated diversion, transfer, and release values were then integrated with the watershed runoff models to simulate the elevation changes of the two reservoirs (Figure 3). General operation rules were incorporated into the model to capture the real constraints and decision-making at the MWRA to a maximum possible extent, while the stochasticity of the actual decision-making is not included. Furthermore, the current model determines the amount of diversion, transfer, and release at each time step based entirely upon the reservoir conditions of the previous time step. This is not necessarily the norm of actual operation, as utility managers sometimes make decisions based on both current and forecasted weather conditions to take precautionary measures. For instance, extra water might be released from the Wachusett reservoir to reduce the flooding risk associated with a future storm event. Such precautionary decision-making is not captured by the current model due to the lack of established rules in responding to uncertain future events. As a result, a couple water level drops resulted from precautionary water releases (e.g., drops in February 2014 and March 2015) in the Wachusett reservoir are not captured by the water systems model. Collectively, the water systems model has a higher uncertainty (relative to the observed values) compared to the water runoff models when historical operation data were applied. Nevertheless, the water systems model still generates satisfactory RMSPE values for both calibration and validation periods for both reservoirs.



	Root Mean Square Percent Error RMSPE (%)	
	Calibration period of hydrologic model	Validation period of hydrologic model
Wachusett	0.35	0.34
Quabbin	0.28	0.17

Figure 3 Comparison of the modeled reservoir water elevations using the simulated water diversion, transfer, and release values (solid line) and the observed (dotted line) reservoir water elevations, and model performance evaluations

4.3 Energy Generation Model

Evaluation of the energy generation model was carried out in two steps: 1) evaluating the energy generation model alone using historic reservoir elevation and operation data, and 2) evaluating the entire model framework using simulated reservoir elevation and operation data. Results from both steps are provided in Figure 4. For the energy generation model alone, the R^2 values of the Oakdale and Cosgrove stations are 0.84 and 0.73 respectively when compared with the observed generations. Furthermore, total energy generation at Oakdale and Cosgrove stations during the modeled time period are about 1% and 5% less than the observed energy generation, respectively. The Cosgrove model performs better than the Oakdale model because energy generation at the Cosgrove station is primarily restricted by the known limitations of the turbine operation rather than the actual amount of water available for power generation. For the entire model framework evaluation, the simulated outcomes reflect the accumulated error in the entire model. The R^2 values of the Oakdale and Cosgrove stations are 0.40 and 0.73 respectively. Total energy generation at Oakdale and Cosgrove stations are about 26% and 4% less than the observed energy generation, respectively. The model framework was considered acceptable with reasonable accuracy in predicting water availability and hydropower generation. The amount of electricity generated annually is around 1.23 times of the amount of electricity consumed onsite of the MWRA (Mo et al., 2016). This could potentially lead to a greenhouse gas (GHG) emission reduction of 7.7 Gg CO_2e, assuming all hydropower is used to replace electricity obtained from the New England regional grid (EPA, 2012).

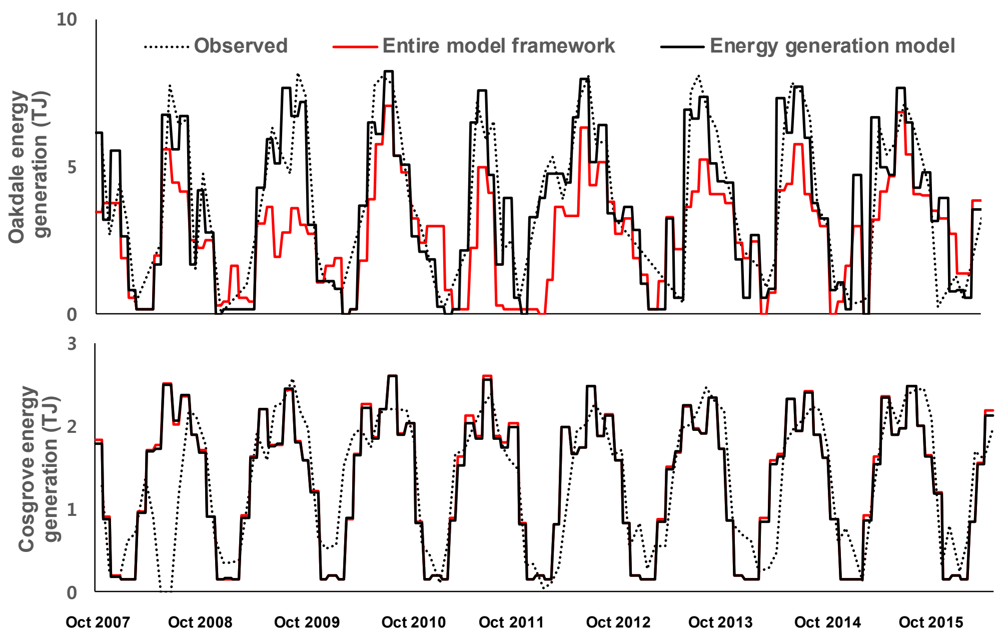


Figure 4 Comparison of the outcomes from energy generation model alone (solid black line), the entire model framework (solid red line), and the observed generations (dotted line) for both Oakdale (top) and Cosgrove (bottom) hydropower stations

4.4 Scenario Analysis

4.4.1 Operation scenario

The different operation scenarios were simulated and compared for a period of about 10 years, similar in length to the period of observed water elevation and energy generation records (2007-2016). The changes in energy generation under the different operation scenarios are presented in Figure 5. Energy generation at the Cosgrove station will increase linearly with the increase of Wachusett's maintained elevation. This is because the available water head increases linearly with the increasing Wachusett reservoir elevation. One-meter increase in Wachusett's maintained elevation could result in 5% (7.06 TJ) increase in Cosgrove's total energy generation. Energy generation at the Oakdale station, on the other hand, is non-linearly correlated with Wachusett's maintained elevation. When the Wachusett's maintained elevation increases from 1 m below the baseline to the baseline, no significant changes in Oakdale's energy generation is observed. However, when the elevation further increases from the baseline to 1 m above, a 3.7% increase (10.21 TJ) in total Oakdale energy generation is observed. This non-linearity can be explained by the combined effect of changes in the elevation difference between the Wachusett and Quabbin reservoirs ($\Delta El_{Q\text{-}W}$), the water flow rate passing turbine (q_{Tur}), and the head loss between the

Quabbin reservoir and the Oakdale turbine (h_L). It has to be noted that changing maintained Wachusett elevation does not significantly influence the major inflows (e.g., runoff) and outflows (e.g., public water supply) of the reservoir, and hence, the total amount of water that needs to be transferred remains relatively constant. Accordingly, the number of days that power is generated, N_{Tur} also remains constant (the red numbers in Figure 5). Nevertheless, depending on $\Delta El_{Q\text{-}W}$, the value of q_{Tur} could differ resulting in changes in power generation. When Wachusett elevation changes from 1 m below the baseline to the baseline, $\Delta El_{Q\text{-}W}$ is always higher than 40.5 m boundary condition, and hence, q_{Tur} is fixed at a higher rate of 15.8 m^3/s and the Oakdale generation remains relatively constant. When Wachusett elevation changes from the baseline to 1 m above, it gradually becomes less likely to maintain the 40.5m elevation difference. Therefore, the number of days that water has to pass the turbine at a lower rate of 14.7 m^3/s increases. The reduced q_{Tur} has two contrasting effects on energy generation. On one hand, reduced q_{Tur} decreases power generation as less water passes through the turbine. On the other hand, a lower flow rate also reduces h_L which could potentially increase power generation. In Oakdale's case, the latter effect outweighs the prior, and a gradual increase in energy generation is resulted from the reduced q_{Tur}.

Changes in Quabbin maintained elevation has no significant effect on Cosgrove energy generation, but it could result in a non-linear increase in Oakdale's energy generation. When Quabbin's maintained elevation increases from the baseline to 1 m above, q_{Tur} remains fixed at a higher rate but a 3.2% increase (8.93 TJ) in Oakdale's total energy generation is observed. This is because the water head available for Oakdale power generation increases with a higher Quabbin elevation. When Quabbin's maintained elevation decreases from the baseline to 1 m below, q_{Tur} decreases as it is less likely to maintain a $\Delta El_{Q\text{-}W}$ of 40.5m. The gradual decrease in energy generation (0.66% decrease from the baseline) in this range is resulted from the combined effect of reduced water head $\Delta El_{Q\text{-}tur}$, which decreases energy generation and the reduced h_L, which increases energy generation.

Overall, increasing Wachusett's maintained elevation is more effective in increasing the overall generation from the two hydropower stations than increasing Quabbin's maintained elevation, while maintaining similar water availability within the MWRA system. The results show that changing the current management practice to increase maintained reservoir elevations could lead to synergistic benefits of increased water storage and hydropower generation.

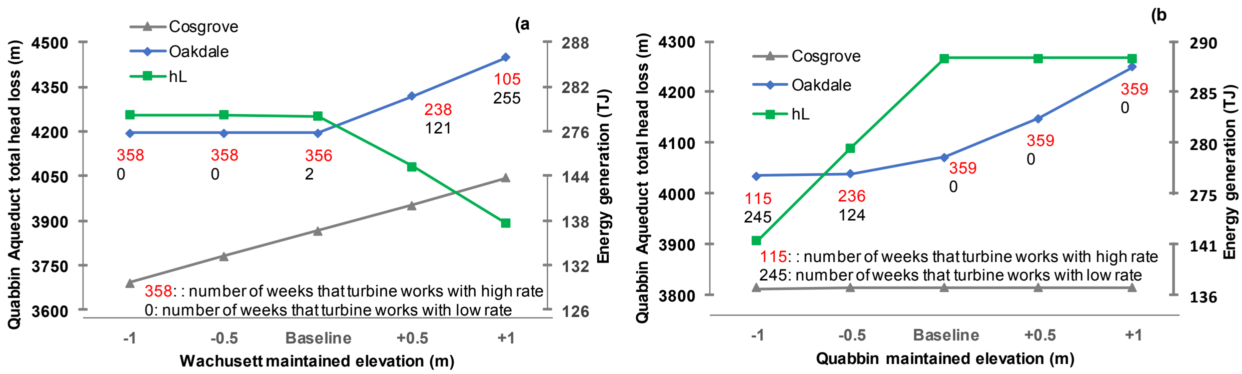


Figure 5 Energy generations at the Oakdale and Cosgrove stations and the total Quabbin aqueduct head losses under different **(a** Wachusett and **(b** Quabbin maintained elevations over a 10-year period (the assigned numbers indicate the number of weeks that turbines work under the high (red) and low (black) flow rates)

4.4.2 Climate change scenario

For each climate change scenario, four 3-year periods beginning from years 2015, 2035, 2055, and 2085 were simulated and the resulted changes in the energy generations of Oakdale and Cosgrove stations, the total water transfers, and the Quabbin averaged water elevations are presented in Figure 6. As Figure 6 shows, the climate change scenarios have little effect on Cosgrove's energy generation. This is because the key factors influencing Cosgrove's energy generation, the Wachusett's maintained elevation and the water supply rate, were assumed to be the same as the baseline period under the climate change scenarios. On the other hand, climate change could have a more significant influence on Oakdale's energy generation as shown in Figure 6. Energy generation at the Oakdale station is related to the total water transfer from Quabbin to Wachusett and the averaged elevation of Quabbin reservoir, El_{Qavg}. According to Figure 6, the total transfer plots mimic the trends of the Oakdale energy generation plots under the four climate scenarios, while the El_{Qavg} plots are inversely proportional to the energy generation and water transfer plots. The effect of small changes in El_{Qavg} on energy generation is in a much smaller magnitude compared to the changes in total transfer, therefore it is expected that the total water transfer will be the controlling element of Oakdale's energy generation.

Changes in the total water transfer requirement can be explained by the combined effect of temperature and precipitation changes under the four climate scenarios. Increased ambient temperature could raise reservoir surface evaporation and potentially reduce watershed runoffs, leading to reduced water availability in the Wachusett reservoir. As a result, a larger amount of water will need to be transferred from the Quabbin reservoir so more energy can be generated. On the other hand, precipitation is one of the direct inflows of reservoir water storage, as well as a major contributor of watershed runoffs. When precipitation increases, the abundancy of water in the Wachusett reservoir increases, which will result in reduced water transfer from the Quabbin reservoir to the Wachusett reservoir, and a decrease in energy generation. Under the A2Highest and B1Highest scenarios, energy generations at the Oakdale station present a similar trend of an initial drop from the baseline year of 2015 and then a slight increase towards the end of the century. The initial drop can be explained by the dominating effect of precipitation increase, while the slight increase later on indicates the effect of temperature increase gradually cancelling out and taking over the effect of precipitation increase. The A2Lowest scenario involves a gradual precipitation decrease and temperature increase, both of which lead to an increased water transfer requirement. This synergistic effect explains the gradual energy generation increase at the Oakdale station. The B1Lowest scenario, on the other hand, presents a precipitation decrease in the beginning, followed by a slight precipitation increase afterwards, in addition to the constant gradual temperature increase. Accordingly, energy generation at the Oakdale station shows an inversed trend of increasing followed by slight decreasing, indicating the precipitation's dominance effect under this scenario.

When comparing the trends of water storage (indicated by Quabbin elevation in Figure 6) and hydropower generation, a tradeoff is observed. An increase in water storage is always associated with a decrease in electricity generation, and vice versa. While the trends of these changes do not agree under different climate scenarios, Figure 6 indicates a relatively higher possibility of increased hydropower generation and decreased water availability in the coming century. This could be a "desirable" result as the MWRA is water abundant but relatively energy stressed. A reversed trend, however, could add to the energy stress and potentially flooding risks in the system. Electricity consumption in the MWRA, on the other hand, has been projected to decrease slightly when only consider the effect of temperature and precipitation changes (Mo et al., 2016). Thus, climate change could potentially enlarge the surplus of electricity by 1.1-6.8 TJ compared with the baseline scenario. This could further reduce 0.2-1.0 Gg of CO_2e.

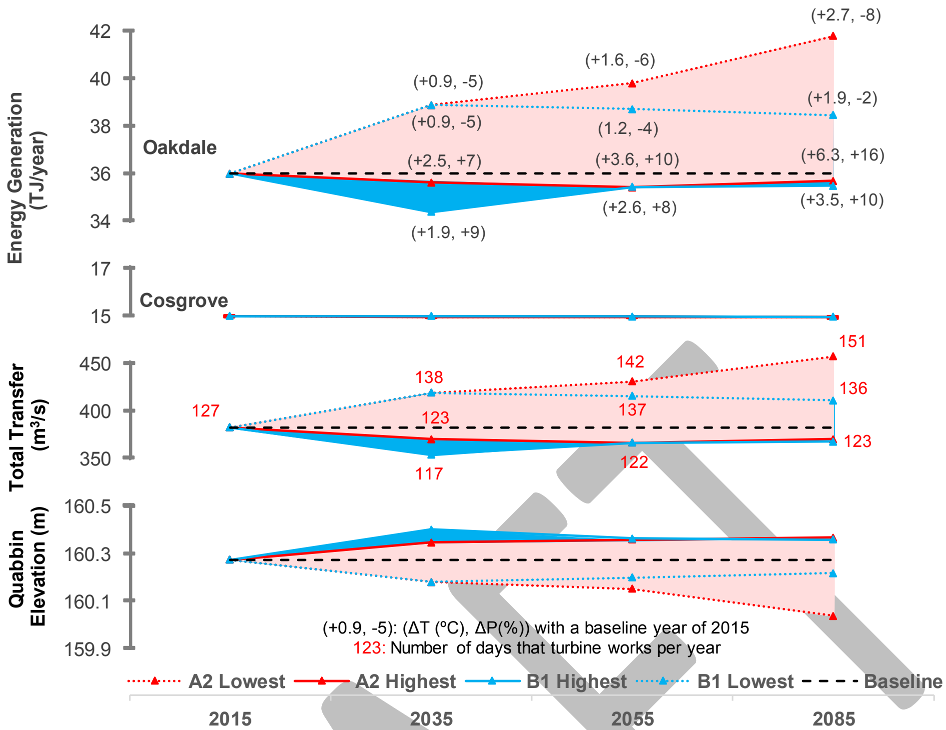


Figure 6 The Quabbin elevations, total Quabbin to Wachusett water transfers, and energy generations at the Oakdale and Cosgrove stations under four climate change scenarios over 3-year periods starting from years 2015, 2035, 2055, and 2085

4.4.3 Population scenario

For each population scenario, four 3-year periods beginning from the year 2015, 2035, 2055, and 2085 were simulated. The resulted changes in energy generations at the Cosgrove and Oakdale stations, the total water transfers between Quabbin and Wachusett reservoirs, and the Wachusett reservoir elevations are presented in Figure 7. Energy generation at the Cosgrove station is linearly correlated with population growth as more water will be transferred through the station and more energy will be generated under a higher water demand. Oakdale's energy generation also presents a general increasing trend under the growing population (as more water needs to be transferred from Quabbin to Wachusett under a higher water demand), except for the year 2085 under the high population growth scenario where Oakdale's energy generation decreases sharply. It has to be noted that water transfer at the same time period increases under this scenario. The drop of the energy generation is mainly resulted from the elevated amount of days that water has to bypass the turbine (from 13 days in 2055to 171 days in 2085) in the Oakdale station. In addition, there is an expected minor decrease of Quabbin averaged elevation (-0.02% from the baseline) under a higher water transfer rate, which further contributes to a drop in $\Delta El_{Q\text{-}tur}$. Therefore, less head will be available for energy generation at the Oakdale station. Decrease in Quabbin's averaged elevation will also affect $\Delta El_{Q\text{-}W}$, and hence, a gradual increase of days with low flow rate through Oakdale turbine is observed. This counterintuitive trend of energy generation at the Oakdale station demonstrates the importance of technology selection in reducing the negative effects of water and energy tradeoffs. In the case of the MWRA, replacing the non-regulating valves with regulating valves could substantially increase energy generation under a high water demand condition. Population growth also creates a tradeoff between water storage (indicated by Quabbin elevation in Figure 7) and hydropower generation. While an increase of hydropower generation is somewhat desirable given the abundancy of water at the MWRA, the growth of hydropower generation is not sustainable. Electricity generation collapses once the technology limitation is reached, which might require a subsequent system upgrade or utilization of new sources of electricity. Assuming electricity consumption increases linearly with the increase of water demand, population growth under 50% and 100% of the current rate will both lead to an increase of surplus electricity generation ranging from 4.7 to 6 TJ by 2085. This indicates a further reduction of 0.7-0.9 Gg of GHG emissions compared with the baseline scenario. Under a population growth rate of 200% the current rate, however, the initial surplus will decrease towards the end of the century and eventually collapse as more water has to bypass the Oakdale station.

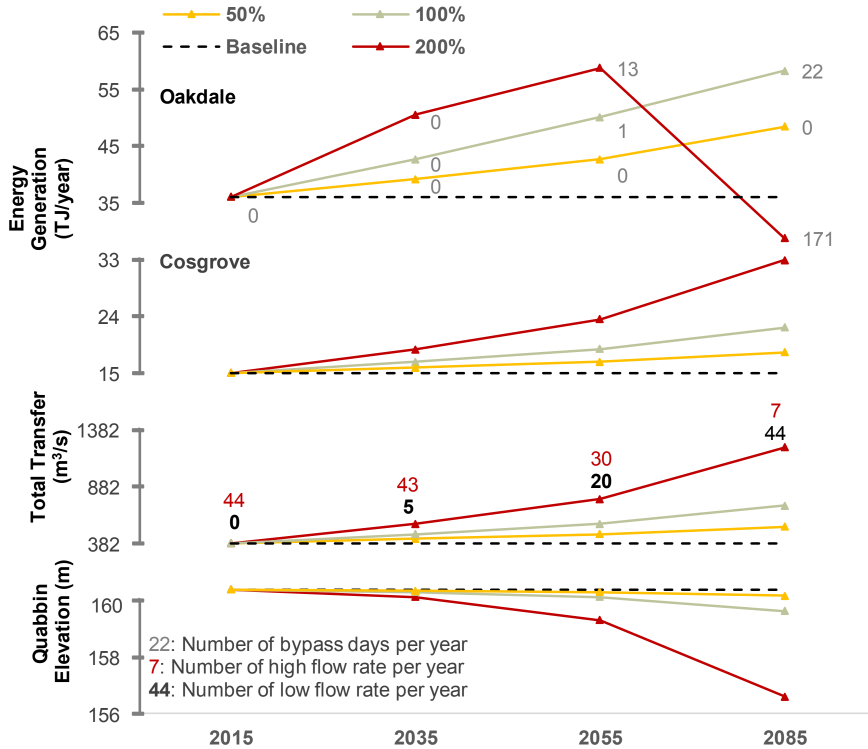


Figure 7 Energy generations at the Oakdale and Cosgrove stations, the total Quabbin to Wachusett water transfer, and the Quabbin averaged elevations under three population growth scenarios over 3-year periods starting from years 2015, 2035, 2055, and 2085

5 Implications

This study presents a modeling framework for investigating water supply and hydropower generation tradeoffs, which could be generalized to other water systems with hydropower generation capacities. The current study demonstrates that critical water-energy synergies and tradeoffs exist at the MWRA, and there is a possibility for integrated water and energy management to achieve better outcomes. For instance, raising Wachusett reservoir's maintained elevation is likely to increase the overall hydropower generation at the MWRA, which could also result in water quality improvement and reduction of water treatment energy requirement simultaneously. Raising Quabbin reservoir's maintained elevation could also result in increased hydropower generation (to a lesser extent), but it does not provide similar water quality benefits as the Wachusett elevation remains the same. Climate change, on the other hand, is likely to result in a tradeoff between water availability and hydropower generation. Under the four climate change scenarios, hydropower generation is always inversely correlated with the Quabbin and Wachusett water availability towards the end of the century. This implies that an increased hydropower generation is potentially at a cost of degradation of water quality, more restricted use of water by the communities they serve, and reduced capability to support ecosystem functions. These environmental and socioeconomic influences will eventually be converted into actual costs in certain ways, as water quality degradations consequently influence the water treatment energy. Restricted use of water might lead to exploration of new water sources. Reduced ecosystem service functions could manifest as environmental protection and remediation costs. A holistic understanding of the system would allow utility managers to make proactive long-term management decisions. Analysis of different population growth scenarios shows similar water and energy tradeoffs. In addition, it presents the importance of technology selection, especially under a high population growth scenario. The current turbine hydraulic capacity at the Oakdale station is not able to meet the large amount of water transfer under the high population growth scenario, and hence, water has to bypass the system without energy generation. Converting the non-regulating valve to a regulating valve is likely to improve energy generation in this case, yet the tradeoffs between the capital investment and the benefits of hydropower generation have to be carefully evaluated under future conditions. The modeling framework developed in this study can help identify solutions to increase energy generation while ensuring sufficient water storage and availability in water supply systems, as well as the water and energy constraints under future conditions. This modeling framework can be integrated with drinking water and wastewater treatment models to investigate the influence of water supply decisions on the urban water supply cycle and the broader water-energy nexus. Future studies should also investigate the combination of multiple scenarios to explore the potential strategies to optimize water and energy outcomes.

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