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WATER RESOURCES ADAPTATION TO CLIMATE AND DEMAND CHANGE IN THE POTOMAC RIVER

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ABSTRACT

The effects of climate change are increasingly considered in conjunction with changes in water demand and reservoir sedimentation in forecasts of water supply vulnerability. Here, the relative effects of these factors are evaluated for the Washington, DC metropolitan area water supply for the near (2010 to 2039), intermediate (2040-2069), and distant future (2070 to 2099) by repeated water resources model simulations. This system poses water management challenges due to long water delivery travel times that increase uncertainty, multiple water jurisdictions that constrain potential decisions, and future scenarios that simultaneously increase demand and decrease water supply during the critical summer period. Adaptation strategies were developed for the system using a multi-objective evolutionary algorithm. Optimized reservoir management policies were compared using six distinct objectives, ranging from reservoir storage to environmental and recreational benefits. Simulations of future conditions show water stress increasing with time. Reservoir sedimentation is projected to more than double (114% increase) the severity of reservoir storage failures by 2040. Increases in water demand and climate change are projected to further stress the system, causing longer periods of low flow and a loss of recreational reservoir storage. The adoption of optimized rules mitigates some of these effects, most notably returning simulations of 2070-2099 climate to near historical levels. Modifying the balance between upstream and downstream

reservoirs improved storage penalties by 20.7% and flowby penalties by 50%. Changing triggers for shifting load to off-line reservoirs improved flowby (8.3%) and environmental (4.1%) penalties slightly, while changing demand restriction triggers provided only moderate improvements, but with little adverse effects.

Keywords: Water resources management; optimization; climate change adaptation; drought.

INTRODUCTION

Climate research indicates that the Earth's climate is changing in response to changes in the global atmospheric composition, brought about by human activities (IPCC 2014). As atmospheric research improves the reliability of climate projections, water resources planners and engineers must consider climatic changes as important factors for water supply planning, along with more traditional non-stationary factors, such as demand change and reservoir sedimentation. Once future vulnerabilities to any of these factors are identified, adaptation strategies can be developed to mitigate their effects. Like many major cities, the Washington, DC metropolitan area (WMA) is interested in identifying changes in water supply vulnerability due to (a) increased water demand, (b) losses of storage, and (c) changes in natural water availability due to the effects of climate change. This study explores these questions and demonstrates how water resources optimization can be combined with projections of future conditions to develop adaptation strategies, using the WMA as a case study.

The WMA is the 6th largest metropolitan area in the U.S. (U.S. Census Bureau 2016), housing an estimated 6.1 million residents across 15 counties in Maryland (MD), Virginia (VA), and the District of Columbia (DC). Each of these three regions operate under separate water suppliers, creating an interesting jurisdictional challenge that was largely addressed by a unique shared decision-making scheme designed to ensure equitable water access during water shortages (U.S. Army Corps of Engineers 1982). Water for the region (Fig. 1) is primarily provided by withdrawals from the Potomac River, whose flow can be augmented by the Jennings Randolph Reservoir, located a nine to ten day travel time (300 km) upstream of the Washington, DC water supply intakes, and the smaller Little Seneca Reservoir, located only one day travel time upstream, that can be used to fine-tune releases (Sheer and Flynn 1983). This design, completed in 1982, allows the 38,000 km^2 Potomac watershed to remain largely uncontrolled, but also increases the importance of effective water management policies. Maryland and Virginia maintain off-line water storage, the Patuxent and Occoquan reservoirs, respectively, which can supplement water extracted from the Potomac River. In 2008, 31% of suburban Maryland's water production came from the Patuxent reservoirs and 42% of suburban Virginia's water production came from the Occoquan Reservoir, with the remainder and all of Washington DC's water supply coming from the Potomac River. For more detail and history on the WMA water supply system, please refer to Stagge and Moglen (2014) or Sheer and Flynn (1983).

Optimization of the WMA water supply system has its origins in the initial water allocation studies (Palmer et al. 1979; Palmer et al. 1982) , which concluded that demand could be met through coordinated operation of the existing Patuxent and Occoquan reservoirs along with the Jennings Randolph and a then-proposed reservoir, which would eventually become the Little Seneca reservoir. The system has been stressed several times, with water supply releases made on three occasions, in 1999, 2002, and 2010. Following the 1999 drought event, specific triggers were added to the management plan that guaranteed all regions (MD, VA, and DC) would enact water use restrictions automatically and simultaneously to prevent jurisdictional disagreements. In an optimization study of the region, Stagge and Moglen (2014) concluded that these triggers were unnecessarily conservative, never engaging during simulations of the historical drought of record, but that accepting infrequent use restrictions would greatly decrease the system's vulnerability. Stagge and Moglen (2014) considered other water management rules, concluding that improvements to reservoir storage and environmental flowby could be achieved by modifying rules that shift demand from the Potomac River to the off-line reservoirs. Rules controlling the relative releases from the Jennings Randolph and Little Seneca reservoir were found to be relatively well optimized, though a slightly stronger reliance on releases from the Little Seneca improved overall storage and downstream flow targets.

Projections of climate change effects in the Potomac River watershed and the mid-Atlantic

United States predict moderate increases in mean annual temperature, precipitation, and streamflow over the next century (Najjar et al. 2009; Pyke et al. 2008; Hayhoe et al. 2008). An evaluation of the four best performing General Circulation Models (GCMs) in the Chesapeake Bay watershed suggests an increase in mean annual temperature of 3.9±1.1°C and an increase in precipitation of 9±12% by the end of the century under the A2 scenario (Najjar et al. 2009). This continues the historical trend of precipitation increases throughout the northeast U.S. during the 20th century (Groisman et al. 2001; Groisman et al. 2004). Despite projected increases in mean annual precipitation and flow for the mid-Atlantic, variation in the seasonality and distribution of precipitation and runoff is potentially more important for water resources management. Storm events are projected to become both more severe and intermittent, with precipitation intensity expected to increase by one standard deviation, concurrent with an increase in dry days and heat waves (Meehl and Tebaldi 2004; Tebaldi et al. 2006).

These projections suggest a moderate increase in mean flows, but with greater likelihood of both flooding, due to storm intensity, and drought, due to prolonged dry periods. Seasonality is also expected to shift, with the greatest increase in precipitation occurring during the winter and spring (Najjar et al. 2009). Similar seasonal trends were noted in Mccabe and Ayers (1989), Moore et al. (1997) and Hayhoe et al. (2007). This was further supported by detailed simulations of flow in the Potomac River that project a slight increase (1-7%) in mean annual flow by 2070-2099, with the increase occurring during the winter and early spring peak season (Stagge and Moglen 2013). At the same time, summer flows are projected to decrease, caused by a decrease in runoff from large, sustained storm events, the date of the minimum flow is expected to shift earlier by 2-5 days (Stagge and Moglen 2013).

In addition to climate change, demand increases and loss of storage due to sedimentation will further stress the system. The population of the WMA was predicted to increase by approximately 1 million people (25%) between 2010 and 2040, which corresponds to a projected water demand increase of 23% (MWCOG 2009). According to the most recent Census estimates (U.S. Census Bureau 2016), the region's population has already increased by 460,000 during the first 5 years of this period (2010-2015). Adding to this potential system stress, reservoirs in the WMA water supply system are projected to lose 7-15% of their usable storage volume due to sedimentation in the 30 years between 2010 and 2040 (Ahmed et al. 2010).

This study has two primary objectives: first, to estimate future water supply vulnerability in the Potomac River and WMA, and second, to optimize water system rules based on future conditions and thereby provide adaptation strategies. The WMA represents an interesting challenge for this approach, given its tranboundary jurisdictional constraints and uncertainty due to the lag between reservoir releases and water delivery. Future conditions are simulated using the best available projections of demand change and reservoir sedimentation, while climate change effects are based on stochastically generated flows (Stagge and Moglen 2013) driven by Coupled Model Intercomparison Project Phase 3 (CMIP3) projections (Meehl et al. 2007). Adaptation strategies are derived by considering several conflicting objectives using start-of-the-art multi-objective evolutionary algorithm optimization. The advantage of this approach is greater flexibility in objectives and system models, while allowing decision-makers to easily compare alternatives by metrics that are used in practice. The resulting strategies show how current levels of service in the WMA could be maintained in the future using only better management, avoiding the need for physical modification to the system. This demonstrates an approach merging climate projections and optimization that could be replicated in other water systems to develop adaptation strategies.

METHODS

This study extends prior research on optimal water management on the Potomac River under current conditions Stagge and Moglen (2014) to instead test the vulnerability of the WMA water supply system to projected future climate, demand, and storage change and then to address the critical topic of adaptation to these future conditions. Future vulnerability was tested by comparing system performance using current conditions to three future climate periods (2010-2039, 2040-2069, 2070-2099) and projections of demand and reservoir sedimentation at five year intervals from 2010 to 2040. Vulnerability was estimated for each of these scenarios separately and together, while performance was quantified using six objective functions considered in previous studies of the system. Adaptation strategies were determined by optimizing system rules using a multi-objective evolutionary algorithm approach and highlighting how optimal rules might mitigate vulnerabilities identified in the first part of the study.

Washington Metropolitan Area Water Supply Model

This study uses the water supply model developed and described in detail by Stagge and Moglen (2014). Hydraulic routing and reservoir operations were simulated using OASIS (Version 3.09.033), developed by Hydrologics, Inc (Hydrologics Inc. 2009). OASIS is a water management simulation and decision model, which uses a node-arc architecture to model reservoirs, reaches, inputs and withdrawals. Operating rules are expressed as goals or constraints and solved via linear programming using a daily time step, mimicking the imperfect foresight of daily operational decision-making.

The OASIS model was developed in conjunction with the Interstate Commission on the Potomac River Basin (ICPRB) and water suppliers to ensure that all data, operating rules, and assumptions were accurate. Reservoir details, including stage-storage curves, sedimentation rates, and existing operational rule curves, were provided by the ICPRB, as well as the current Potomac channel routing and travel time estimates. Daily demand among the three major WMA water suppliers was simulated using a set of multivariate regression equations, incorporating an autoregressive–moving-average (ARMA) error term, provided in Ahmed et al. (2010). Municipal water needs of the WMA are managed by three major suppliers:

Washington Suburban Sanitary Commission (WSSC), which serves the Maryland suburbs,

Fairfax Water, which serves Fairfax County and other northern Virginia suburbs, and

Washington Aqueduct, which provides water to the District of Columbia.

The current water supply system (Fig. 1) is the result of several design iterations and collaboration among the numerous levels of government, water suppliers and citizen groups. Details of the system are provided by Stagge and Moglen (2014) and Ahmed et al. (2010). This system relies predominantly (approximately 78% annually, Ahmed et al. 2010) on flow from the Potomac River to satisfy water demands, with the remainder of water provided by two off-line reservoirs: the Patuxent Reservoir system operated by WSSC and the Occoquan Reservoir operated by Fairfax Water (Table 1). Flow in the Potomac is augmented by two reservoirs. The Jennings Randolph Reservoir is the larger of the two (109×10^6 m^3), but is located approximately 9-10 days hydrologic travel time upstream of the WMA intakes (Table 1). The Little Seneca Reservoir is located only a day upstream of the MWA intakes, but has significantly smaller usable storage and a smaller watershed area. These two reservoirs are, therefore, operated in concert, with the Jennings Randolph providing primary releases and the Little Seneca used to "fine tune" flows immediately upstream of the intakes. The Savage Reservoir, located eight kilometers downstream from the Jennings Randolph Reservoir, is operated to to satisfy local North Branch low flow requirements and to supply water to the nearby town of Westernport, Maryland. It was not considered for optimization because it operates independently; however, the Savage Reservoir does make water supply releases during severe droughts according to a matching relationship with Jennings Randolph releases and therefore is also included in the model. While allowing the main stem of the Potomac River to remain relatively uncontrolled, this system layout possesses considerable uncertainty, as release decisions must be made in advance of accurate weather forecasts.

Climate Change Flow Simulation

The effect of climate change was simulated by stochastically generating daily climate-adjusted streamflow and precipitation time series using the method described in Stagge and Moglen (2013). Five GCM models (Table 2) from the CMIP3 experiment (Meehl et al. 2007) were used to generate flows for three emissions scenarios (SRES A2, A1b, and B1). Projections of GCM-scale climate variables were related to discrete monthly climate states identified from the historical record for the study region. The Markov chain transition probabilities between these climate states are then adjusted based on GCM climate projections. The parameters of a daily streamflow model, similar to Aksoy (2003) and Szilagyi et al. (2006), are defined by the monthly climate state and ultimately used to generate climate-adjusted daily streamflow. Daily flow is modeled using a two-state (increasing/decreasing) Markov chain, with rising limb increments randomly sampled from a Weibull distribution and the falling limb modeled as an exponential recession. This model was demonstrated to accurately reproduce historical streamflow statistics at the daily, monthly and annual time step in the Potomac River (Stagge and Moglen 2013) and to produce climate-adjusted streamflows that match the general findings of classical climate downscaling studies (Najjar et al. 2009; Milly et al. 2005; Hayhoe et al. 2007).

Daily streamflow was generated for USGS stream gauge 01646500, located on the Potomac River near the Little Falls pumping station in Washington, DC and spatially disaggregated to daily streamflow and precipitation values at the necessary upstream sites using the "Method of Fragments" (Srikanthan and McMahon 1982; Porter and Pink 1991), as in Stagge and Moglen (2014). Flows were bias-corrected using quantile-quantile mapping to remove residual model bias, particularly at the upstream sites.

Demand and Sedimentation Projections

Demand projections (Table 3) were based on the most recent population and demand projections for the WMA (Ahmed et al. 2010). This projection evaluates demand change through the year 2040, modeling beyond the 20 year forecast legally mandated to be performed once every five years. These predictions are based on recent water use information provided by the WMA water suppliers and demographic projections from the most recent Metropolitan Washington Council of Governments (MWCOG) Round 7.2 Cooperative Forecast (MWCOG 2009). Demand change beyond year 2040 is not considered in this study, as water demand forecasts tend to become unreliable beyond the 30 year horizon in this region (Ahmed et al. 2010), given the added uncertainty of population change and innovations in water efficiency.

Sedimentation rates (Table 4) were based on historical trend analysis (Ahmed et al. 2010) using the Kendall-Theil Robust Line (Sen 1968). This non-parametric method is a popular alternative to linear regression and is more robust to outliers. The rate of sedimentation was assumed to remain constant for all future time steps, but was only projected until 2040 to match demand changes. This limit on the time horizon was meant to account for uncertainty in sediment capture methods or land cover change.

Optimization of Operating Rules

Optimization of system operating rules was carried out in a manner similar to Stagge and Moglen (2014), using SMS-EMOA (Emmerich et al. 2005; Beume et al. 2007), a steady-state multi-objective evolutionary algorithm designed to maximize the multi-dimensional hypervolume (S-metric) dominated by a finite number of points. Hypervolume metrics, developed by Zitzler and Thiele (1998) and Fleischer (2003), are invariant to objective scaling, tend to converge on the Pareto set, and assign a greater weight to regions with unique points or high curvature in the objective space. Optimization was carried out using the EMOA R package (Mersmann 2011) with simulated binary crossover (SBX) and polynomial mutation. This optimization scheme has proven efficient and effective relative to other multi-objective evolutionary algorithms in benchmark studies (Beume et al. 2007).

Within the range of available water resources optimization techniques, evolutionary, or genetic, algorithm solvers have proven successful because of their robustness and flexibility (Chen 2003; Momtahen and Dariane 2007; Oliveira and Loucks 1997; Wardlaw and Sharif 1999). Evolutionary algorithms are capable of searching large and complex decision spaces and evaluating nonlinear and non-convex objective functions. Multi-objective evolutionary algorithm optimization solves for a set of compromise solutions, termed the Pareto optimal front, that represent optimal solutions which cannot be improved without affecting the other objectives.

Six objective functions were developed in conjunction with water suppliers and the ICPRB and designed to cover the range of potential benefits within the Potomac River system. Target volumes and flows were often based on legal agreements, such as the Low Flow Allocation Agreement (U.S. Army Corps of Engineers 1982). Because the functional limit of current multi-objective evolutionary algorithms has been shown to be approximately 10 objectives (Reed et al. 2013), this optimization model uses six objectives. Each objective is followed by the units of that objective in parentheses.

1. **Shortage**, which minimizes delivery shortages to the water suppliers (volume)
2. **Storage**, which minimizes low storage volumes in any of the reservoirs (volume)
3. **Flowby**, which minimizes days when flow in the Potomac does not exceed low flow requirements (days of violation)
4. **Rec Season**, which minimizes days during the recreation season that Jennings Randolph levels fall below recreation facilities (days of violation)
5. **Whitewater**, which minimizes days when whitewater releases cannot be made due to low storage volume (days of violation)
6. **Env Flows**, which minimizes days when flow in the Potomac falls below recommended environmental levels for three consecutive days (days of violation)

These objectives are presented as a constrained multiobjective optimization problem, identical to that posed in Stagge and Moglen (2014):

$$\text{Minimize} \quad Z = Z_{\text{Short}}, Z_{\text{Stor}}, Z_{\text{Flowby}}, Z_{\text{Rec Season}}, Z_{\text{WW}}, Z_{\text{Env Flows}} \tag{1a}$$

$$Z_{\text{Short}} = \sum_{i} \sum_{t=0}^{n} \begin{cases} \frac{\text{Dem}_i(t) - \text{Del}_i(t)}{\text{Dem}_i(t)} & \text{if } \text{Dem}_i(t) > \text{Del}_i(t) \\ 0 & \text{otherwise} \end{cases} \tag{1b}$$

$$Z_{\text{Stor}} = \sum_{j} \sum_{t=0}^{n} \begin{cases} 100 - 6 \times \text{Stor}_j(t) & \text{if } 0 \leq \text{Stor}_j(t) < 10\% \\ 60 - 2 \times \text{Stor}_j(t) & \text{if } 10 \leq \text{Stor}_j(t) < 20\% \\ 40 - \text{Stor}_j(t) & \text{if } 20 \leq \text{Stor}_j(t) < 40\% \\ 0 & \text{if } \text{Stor}_j(t) \geq 40\% \end{cases} \tag{1c}$$

$$Z_{\text{Flowby}} = \sum_{k} \sum_{t=0}^{n} \left(\frac{Q_k(t) < Q_{\text{Flowby}}}{n} \right) \tag{1d}$$

$$Z_{\text{Rec Season}} = \sum_{t=0}^{n_{\text{Rec Season}}} \left(\left(\frac{\text{Elev}_{\text{JR}}(t) > \text{Elev}_{\text{Beach}}}{n_{\text{Rec Season}}} \right) + 2 \times \left(\frac{\text{Elev}_{\text{JR}}(t) > \text{Elev}_{\text{WV}}}{n_{\text{Rec Season}}} \right) + 5 \times \left(\frac{\text{Elev}_{\text{JR}}(t) > \text{Elev}_{\text{MD}}}{n_{\text{Rec Season}}} \right) \right) \tag{1e}$$

$$Z_{\text{WW}} = \sum_{t=0}^{n_{\text{WW}}} \left(\frac{Q_{\text{WW}}(t) = 0}{n_{\text{WW}}} \right) \tag{1f}$$

$$Z_{\text{Env Flows}} = \sum_{t=0}^{n} \left(\frac{(Q_{\text{LF}}(t) \text{ and } Q_{\text{LF}}(t-1) \text{ and } Q_{\text{LF}}(t-2)) < 200 \text{ MGD}}{n} \right) \tag{1g}$$

where each of the Z terms represent individual objective functions. For all objective functions, n represents the total number of days in the time series, i represents the 5 individual water suppliers, and j represents the 6 reservoir storage accounts: (1) Jennings Randolph Water Quality, (2) Jennings Randolph Water Supply, (3) Savage, (4) Patuxent, (5) Occoquan, and (6) Little Seneca. Z_{Short} (Eq. 1b), sums the percent water delivery shortage at all supply points, including WSSC, Fairfax Water, the USACE, the city of Westernport, and the city of Rockville, where Dem_i refers to daily demand, Del_i refers to daily delivery. Z_{Stor} calculates a penalty when reservoir usable storage falls below 40% of the usable storage in the baseline year 2012. Penalties increase as storage approaches zero using a piecewise function which approximates the existing drought restriction setpoints (MWCOG 2000). Z_{Flowby}, which sums all days when the legally prescribed flowby, Q_{Flowby} is not satisfied by flow, Q_k, at each of the k locations. The pertinent flowbys are 227

$\times 10^3$ m^3/d at Luke, 1140 $\times 10^3$ m^3/d at Great Falls and 379 $\times 10^3$ m^3/d at Little Falls. $Z_{\text{Rec Season}}$ (Eq. 1e), refers to the summer Recreation Season, which occurs each year between May 1 and Aug 31, represented in the function by $T_{\text{Rec Season}}$. During this period, water managers strive to maintain water levels in the Jennings Randolph Reservoir, represented as Elev_{JR}, above three recreation access points. These points, termed E_{Beach}, E_{WV}, and E_{MD}, are 443 m, 440 m, and 433 m, respectively. Z_{WW} (Eq. 1f) calculates the ratio of days when whitewater releases, Q_{WW}, cannot be made due to low storage volume. Whitewater releases are set to occur on the 15$^{\text{th}}$ and 30$^{\text{th}}$ of April and May, whose set is represented as T_{WW}. $Z_{\text{Env Flows}}$ (Eq. 1g), uses a measure to summarize water supply activity's effect on the ecological health of the Potomac River. While the legal flowby requirement below Little Falls is set at 757 $\times 10^3$ m^3/d, the Potomac Basin Large River Environmental Flow Needs study stated that there "is strong concern that a continuous, multi-day period of flows at or very close to 379 $\times 10^3$ m^3/d MGD would be injurious to the biota" (Cummins et al. 2010). This function sums the number of occurrences when flow below Little Falls, Q_{LF}, remains below 757 $\times 10^3$ m^3/d for 3 or more consecutive days.

Five operating rule modifications were considered based on recommendations by water suppliers and stakeholders. These rule modifications span a range of typical water management and conservation approaches and are identical to those considered by Stagge and Moglen (2014): (1) the "buffer equation" which shifts load between the upstream (Jennings Randolph) and downstream (Little Seneca) mainstem Potomac reservoirs, (2) "load shifting" which shifts load from the Potomac to the off-line reservoirs, (3) metropolitan demand restrictions, and seasonal reservoir release rule curves for the (4) Jennings Randolph and (5) Patuxent reservoirs. Each candidate rule was optimized separately to determine their potential adaptation effect. Adaptation rules were generated using both the historical record and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Gordon et al. 2002) A2 scenario (2070 to 2099), both subject to year 2040 levels of demand and sedimentation. The CSIRO output was chosen as representative of SRES A2 conditions at the end of the next century, while the A2 scenario was chosen as the most extreme case. In verification tests, the CSIRO model consistently produced good statistical agreement with the historical record across daily, monthly and annual time steps.

RESULTS

Projected Changes to WMA Reliability

Three major processes are projected to affect the reliability of the WMA water supply system over the next century. These are demand change, reservoir sedimentation, and climate change. To identify the relative impact of these processes on the system, the system was simulated while adjusting to each parameter in isolation.

Vulnerability due to Demand Change

Demand forecasts predict a population increase of approximately 1 million (25%) between 2010 and 2040, which corresponds to a projected water demand increase of 430 m^3/d (23%) (Table 3, MWCOG 2009). The greatest increase in population, and therefore water demand, is projected to occur within the Fairfax Water service area of Northern Virginia. Demand increase for Fairfax Water is projected to increase by 31% between 2010 and 2040, while the WSSC and Washington Aqueduct service areas are expected to increase demand by 19% and 18%, respectively. The City of Rockville, MD which maintains a separate water supply, is projected to have a relatively large increase in demand by percent (31%), but this remains a small portion of the total WMA water supply because of Rockville's small service area.

This projected increase in demand will produce a consistent increase in Storage penalty failures, Z_{Stor}, and Recreation Season failures, $Z_{\text{Rec Season}}$ (Fig. 2). However, it is important to note that impacts are different, with sedimentation strongly affecting available storage (Fig. 2a) and increased demand strongly affecting recreation season storage (Fig. 2b). By the year 2040, this increase in demand alone will result in an additional loss of approximately 0.5 days/year with access to the Beach (2.0% increase) and 0.9 days/year with access to the West Virginia boat ramp (58.3% increase). While this loss of recreation time may not appear large, a 58.3% increase in the more severe WV boat ramp failures suggests that demand will drive a loss of recreation revenue. Additionally, recreation failures tend to occur in extended groups, rather than a single instance. In this way, the additional failures may have a considerable effect on individual recreation seasons. While increased demand does not dramatically affect WMA storage across all reservoirs (Fig. 2a), by year 2030 it begins to adversely affect storage in the Little Seneca Reservoir, shown as an increased deviation between sedimentation only scenarios and combined sedimentation and demand.

Vulnerability due to Sedimentation

Usable reservoir storage volume is expected to decrease due to the deposition of sediment carried by reservoir inflows over time. Reservoirs in the WMA water supply system are projected to lose 7 to 15% of their usable storage volume due to sedimentation in the 30 years between 2010 and 2040. Based on the most recent survey, the sedimentation rate in the Jennings Randolph Reservoir is particularly high relative to the other reservoirs (Table 4), and much greater than the original "design" sedimentation rate of 25 m^3/yr (Burns and MacArthur 1996). By year 2040, the storage capacity loss in the Jennings Randolph Reservoir is projected to be 25% of the original storage volume (14.1% between 2010 and 2040). Despite these predictions of storage loss, sedimentation rates tend to change with time, as the sediment contribution of upstream watersheds change. Increased development tends to increase sediment load per area (Allmendinger et al. 2007), though this effect may be mitigated by improvements in non-point source runoff treatment. It is important to note that the Jennings Randolph watershed, historically home to coal mining, has seen a decrease in this industry and has been subject to increased oversight with respect to non-point source runoff.

As expected, reservoir sedimentation is expected to increase the frequency and severity of reservoir storage failures, defined as usable storage less than 40% by Z_{Stor} (Fig. 2). This noted increase is due primarily to storage failures in the Patuxent and Savage reservoirs. Interestingly, the Jennings Randolph and Little Seneca water supply reservoirs do not develop storage failures until the year 2040 sedimentation level. This suggests that there may be opportunities for improving Z_{Stor} as storage is lost to sedimentation through changes in how load is allocated among the reservoirs. Because $Z_{\text{RecSeason}}$ is strongly tied to storage in the Jennings Randolph, it is not surprising that $Z_{\text{RecSeason}}$ is relatively unaffected by sedimentation losses (Fig. 2). Further, sedimentation has little impact on the flow measures, Z_{Flowby} and Z_{EnvFlows}.

Vulnerability due to Climate Change

Output from five GCM simulations (Table 2) was used to generate streamflow and precipitation throughout the Potomac watershed at 30 year intervals (2010 to 2039, 2040-2069, 2070 to 2099). These simulations predict a slight increase (1-7%) in mean annual flow over the next century, with increases during the winter and early spring, followed by decreased flow during summer (Stagge and Moglen 2013; Najjar et al. 2009; Hayhoe et al. 2007). Projections also show that summer flows will be characterized by longer periods of low flow (Tebaldi et al. 2006), with shorter but more intense storm events and an earlier occurrence of the annual minimum flow. As expected, the highest emission scenario, SRES A2, produced the most severe shifts in streamflow, while the low emission scenario, SRES B1, produces a more modest change.

The effect of climate change alone on water supply reliability in the WMA region is shown graphically in Fig. 3. Climate change simulations project an increase (worsening) for nearly all objective functions over the next century. Results presented in Fig. 3 account for model bias by using quantile-quantile bias correction and always comparing projections against current conditions simulated using the same GCM. Interestingly, the greatest change for most objective functions occurs during the first part of the upcoming century (2010 to 2039), despite streamflow trends continuing consistently until 2099 (Stagge and Moglen 2013).

When examined in greater detail, the climate change scenarios result in an increase in the frequency of Patuxent and Savage storage failures, though the severity of these failures actually tends to decrease throughout the century. This is partially because load is shifted to other reservoirs such as the Little Seneca and the Occoquan, which previously did not produce storage failures, but begin to once subjected to climate change streamflows. Though storage in the Jennings Randolph Reservoir is never low enough to be considered a storage failure, climate change conditions greatly decrease the number of days with access to the Jennings Randolph beach by 3.9-5.2 days/year. Access to the WV boat dock is decreased by an average of 0.4 to 1.3 days/year. Whitewater releases are predicted to be curtailed an additional 4-14 days over the simulation period, an increase of 18%

to -41%.

Adaptation Strategies

As expected based on the vulnerability portion of the study, runs combining the climate projections of the 2070-2099 A2 emissions scenario with 2040 demand change and sedimentation was the most challenging scenario for the WMA system. The value of implementing adaptation strategies to this extreme case was determined by comparing system penalties (objective function values) using optimized rules to curent rules (Table. 5). These results show that adjustments to the Buffer Equation can produce the greatest improvement under future conditions for most objectives. Load shifting to reservoirs off the mainstem offers modest improvements, primarily to the flowby penalty, while modifying demand restricts produces the smallest impact. Modification of the Jennings Randolph rule curve is effective for addressing objectives related to recreation storage and Potomac low flows, while Patuxent rule curve modifications decrease reservoir storage penalties. No system shortage failures were noted and were, therefore, not included in the discussion. This is because the existing operating rules prioritize satisfying daily demand at the expense of violating the other objectives.

Buffer Equation

Within the WMA water supply operating rules, the Buffer Equation is designed to balance storage levels between the reservoirs on the main-stem of the Potomac River, the upstream Jennings Randolph Reservoir and downstream Little Seneca Reservoir. Reservoir releases are calculated based on estimated demand; however, the buffer equation adds a so-called "buffer flow" to Jennings Randolph releases to account for imbalance in percent usable storage between the Jennings Randolph Water Supply volume and downstream Little Seneca storage. The existing Buffer Equation is represented by a black diagonal line in Fig. 4), in which a negative storage imbalance recommends a larger than necesary release from the Jennings Ranolph to reduce load on the Little Seneca. The right side of these plots (positive imbalance) reduces Jennings Ranolph releases under the assumption that the deficit will be satisfied through releases from the downstream Little Seneca Reservoir. Under the current policy, the slope of the Buffer Equation (Fig. 4) is linear for both of these situations, with a maximum buffer flow of 568 m^3/d.

Modification of the Buffer Equation produced the largest improvement of the considered modifications for future conditions, reducing the frequency of missed flowby targets (Z_{Flowby}) and the number of consecutive days with extreme low flows (Z_{EnvFlows}) (Table. 5). Buffer equation adjustments were partially capable of mitigating the impact of climate change, reducing most penalties for the 2070 to 2099 scenario to levels simulated with only demand and sedimentation. However, no version of the Buffer Equation is capable of reducing system-wide penalties under climate change, demand increase and sedimentation to current levels.

The Buffer Equation reduces Z_{Flowby} and Z_{EnvFlow} failures by increasing the buffer flow when usable Little Seneca storage (%) is lower than Jennings Randolph (Fig. 4a). Under these optimized rules, a much greater release is made from the Jennings Randolph Reservoir in this situation, which in turn reduces load on the Little Seneca Reservoir and acts as a pulse in the Potomac River to prevent extreme low flows downstream of Little Falls. Similar recommendations were made for current climate conditions (Stagge and Moglen 2014) and the shape of the optimal Buffer Equation does not change substantially with time between current conditions and the 2070 to 2099 projection.

Although the right side of the equation has little effect on Z_{Flowby}, it is important for improving $Z_{\text{RecSeason}}$ (Fig. 4b), particularly for the 2070-2099 projection. This extreme scenario produced the most stress on the Jennings Randolph storage, where Recreation Storage is measured. Therefore, it follows that a lower Buffer Equation on the right side would reduce Jennings Randolph releases when storage is low relative to other reservoirs, thereby protecting recreation storage.

Load Shifting

While the Buffer Equation deals with balancing releases along the Potomac River, Load Shifting controls how demand is allocated to the offline reservoirs, the Patuxent and Occoquan. When predicted flow in the Potomac River is not sufficient to satisfy predicted demand, production at the Patuxent and Occoquant water treatment plants is temporarily increased above typical production levels. Following this load shifting event, production at the offline reservoirs is curtailed an equivalent amount, to replenish storage. Load shifting occurs only when storage in the Jennings

Randolph, Little Seneca, Occoquan and Patuxent remains above trigger points, called Load Shift Storage Indices.

Modification of the Storage Indices and Load Shift equation has relatively little impact on the WMA system in simulations of future demand/sedimentation conditions and climate change (Table 5). While changes to load shifting generally results in better performance than the current policy, this improvement cannot completely mitigate the effects of either climate change or of demand and sedimentation change. No trends exist over time among the optimized load shifting parameters, suggesting that the effectiveness of load shifting has been maximized and that no further improvements will be realized with time.

Adjustments to the load shift equation were shown to be effective under current conditions because the Occoquan Reservoir had unused storage which could be used to reduce load on the already stressed Patuxent Reservoir (Stagge and Moglen 2014). However, as future conditions further constrain and stress the WMA system, the additional Occoquan storage is not as readily available, as shown by increases in Occoquan storage penalties (storage < 40 %). Increasing the Load Shift Storage Indices was another method of decreasing load on the stressed Patuxent Reservoir under current climate conditions (Stagge and Moglen 2014). However, under future conditions, it puts undue strain on the Little Seneca Reservoir, suggesting that the benefits of this approach are already maximized.

Monthly Rule Curves

All reservoirs in the WMA water supply system operate, at least during a portion of the year, according to zone-based rule curves, except for Little Seneca which maintains a full storage volume throughout the year. To determine adaptation potential, operating rule curves for the Jennings Randolph and Patuxent Reservoirs were evaluated using multiobjective optimization. The Jennings Randolph Reservoir was chosen for evaluation because it is the primary water supply reservoir on the Potomac River, while the Patuxent Reservoir was most vulnerable to storage failures. Jennings Randolph water quality storage is managed by the Baltimore District of the U.S. Army Corps of Engineers and uses 3 zone-based rule curves (high, medium, and low) to guide water quality releases during the non-Recreation Season months (September through April). These releases are designed to approximate the natural contribution of the Potomac River's impounded North Branch, while refilling the reservoir prior to the summer recreation season.

Modifications of the Jennings Randolph rule curves primarily improved objectives related to Jennings Randolph storage (Table 5), reducing $Z_{\text{Rec Season}}$ by 0.1-9.2% and Z_{WW} by 83.3-98%. It had little effect on storage failures, as these primarily occured in other reservoirs or during the summer season when the seasonal rule curves are not in effect. The projected climate change shift towards higher flows during the winter and spring, followed by lower flows in the summer and early fall was mirrored by the optimized Jennings Randolph Reservoir rule curves. The optimized curves increased trigger points between March and May, immediately prior to the recreation season, forcing the Jennings Randolph Reservoir to operate more conservatively, making smaller releases during this time. In this way, the increase in spring flows is used to increase the storage buffer prior to a summer flow regime characterized by more severe low flows.

Modification of the Patuxent rule curve is designed to maintain adequate storage in the highly stressed Patuxent Reservoir while providing additional water supply for the WSSC. Simulations suggest that the Patuxent Reservoir is vulnerable during future droughts, typically entering low storage ($< 40\%$) conditions before the remaining WMA reservoirs and thereby contributing to the Z_{Stor} penalty. For future conditions, adjusting the Patuxent rule curves improves Z_{Stor} by 6.1-6.4 % (Table 5). The Patuxent Reservoir operates using 2 rule curves which control daily water treatment withdrawals based on storage zone. The adaptation improvement is attributed to an increase of approximately $1{,}000\text{-}1{,}500\times10^3$ m^3 in both the upper and lower rule curves between the months of September and February. This modification allows the Patuxent Reservoir to refill more effectively if storage is low during the fall and winter by decreasing water treatment rates and shifting load back to the Potomac River. While this shift is similar in both the climate change simulation and the sediment and demand change simulation, the optimal rule curves deviate in mid-summer. Likely because of increased summer drought severity due to climate change, the optimized upper and lower Patuxent rule curves for this scenario tend to be approximately 300×10^3 m^3 higher through the months of July and August. This allows the Patuxent Reservoir to operate even more conservatively for the most extreme scenario.

Demand Restrictions

The Metropolitan Washington Council of Governments standardized the implementation of water use restrictions by setting three demand restriction levels: voluntary, mandatory and emergency, each with a unique storage trigger (MWCOG 2000). As part of the MWCOG agreement, all regional governments have agreed to abide by these triggers, declaring restrictions simultaneously. Voluntary restrictions are triggered when combined storage in the Jennings Randolph and Little Seneca reservoirs falls below 60%. Trigger points for mandatory and emergency restrictions are set at 25 and 5% for Jennings Randolph or Little Seneca storage, respectively (Table 6). This is a simplification of the actual MWCOG demand restriction rules, but matches actual operation very well.

In a review of the WMA under current conditions, Stagge and Moglen (2014) found that the existing MWCOG demand restriction triggers would never be implemented during a repeat of the historical streamflow record with current demand levels. As stress on the WMA water supply increases with time, the likelihood of demand restrictions increases, highlighting the importance of an effective demand restriction policy. Under the existing MWCOG policy and 2040 demand and sedimentation levels but no climate change, the WMA service area would experience Voluntary restrictions once every 26 years, on average. Simulations based on the CSIRO 2070-2099 A2 climate scenario with demand change and sedimentation increase this frequency to once every 20 years, with 75% of Voluntary restriction years ultimately requiring Mandatory demand restrictions.

Improvements due to demand restrictions are limited and primarily focus on Z_{Flowby} and Z_{EnvFlows}. With regard to storage, these changes particularly improve storage in the Patuxent and Occoquan Reservoirs. System performance is improved by increasing the Voluntary trigger from 60% of Jennings Randolph and Little Seneca storage to 74-85% (Table 6). Operations also improved when the Mandatory restriction trigger point was decreased from 25% to 17-25% for Jennings Randolph storage but increased from 25% to 24-59% for Little Seneca storage (Table 6).

The trigger point is higher for the Little Seneca because it is more vulnerable due to its small size and slow refill rate. Trigger points for Emergency restrictions were also increased, although these were so infrequently used that there is significant uncertainty in the results. The benefits of these adaptation strategies are tempered by an increase in the frequency of demand restrictions, for example doubling the frequency of Voluntary restrictions from once every 20 years to once every 10 years.

Modifying the percent demand restrictions during the summer season (June-Sep) did not produce significant improvement in the objective functions. However, some improvements for Z_{Flowby} and $Z_{\text{Env Flows}}$ were realized by increasing the percent demand restrictions outside of the summer period to resemble summer restrictions. Continuing the more severe restrictions outside the summer drought period allowed reservoirs to refill prior to the next summer, better handling multi-year droughts.

DISCUSSION

This study utilizes evolutionary algorithms to optimize water management strategies. However, other alternatives exist and could be substituted into this framework to identify adaptation strategies. More traditional optimization techniques such as linear or nonlinear programming have the benefit of quick convergence to the global optima, but would require several simplifying assumptions with regard to constraints, objectives, and adaptation strategies (Labadie 2004). More recent heuristic optimization techniques could also be considered, such as particle swarm optimization (Reddy and Nagesh Kumar 2007; Taormina and Chau 2015), fuzzy programming (Chen and Chang 2010), or simulated annealing (Li and Wei 2008). Similar to the evolutionary algorithm approach used here, these alternative optimization approaches add a great deal of flexibilty, sacrificing the guarantee of finding global optima and requiring more processing time. More detailed comparisons of modern optimization techniques are available in several methodology overviews (Ahmad et al. 2014; Sahinidis 2004; Labadie 2004).

From among these alternatives, we chose to use evolutionary algorithms because they are one of the most common heuristic optimization techniques and are proven to be robust, flexible, and capable of searching large and complex decision spaces (Reed et al. 2013). Flexible optimization schemes are important in complex systems like the WMA because they can be directly linked to hydrologic models and can handle uncertainty due to time lags in water delivery and complex objective functions.

The objectives in this study were selected in close collaboration with the water suppliers and were designed to closely match the goals of the system as codified in legal agreements. However, there would be a benefit to considering new and more complex objective functions to determine how the set of optimal solutions would change. For example, the environmental and low flow objectives are based on quite simple legal requirements, but the objectives could be better targeted to ecological health by collaborating with ecologists and fisheries experts. Similarly, there may be some benefit to considering more complex economic drivers and objectives, using a framework similar to Harou et al. (2009).

This study utilized CMIP3 projections downscaled to daily streamflow using the method of Stagge and Moglen (2013) rather than more traditional approaches, such as statistical or dynamical downscaling. The benefit of the Stagge and Moglen (2013) approach is that it generates a suite of ensemble members to better test vulnerability over a wider range of feasible flows and does not require a full hydrologic model. As described by Stagge and Moglen (2013), the existing Potomac River model performed poorly for low flows, whereas the alternative approach better captured these. The CMIP3 set of GCM runs has been updated with CMIP5 output (Wuebbles et al. 2013). It would be helpful to consider CMIP5 output in the future, although the two experiments agree well with regard to precipitation and drought near the Potomac River (Wuebbles et al. 2013). The largest improvements have been for simulation of moonsoon precipitation, which mainly affects more southern and western parts of the United States (Cook and Seager 2013).

CONCLUSIONS

The effects of climate change are increasingly considered in conjunction with demand change and reservoir sedimentation in forecasts of water supply vulnerability. This study provides an example of how this can be accomplished, using the Washington, DC metropolitan area water supply as a case study. First, system vulnerability due to projected changes was evaluated using repeated simulation and then these vulnerabilities were addressed using multi-objective optimization to develop a set of optimized rules under future conditions. These rules form the basis for an adaptation strategy, using efficient management without the need for physical improvements.

A system-wide increase in demand of 23% by the year 2040 is projected to decrease available storage in the Jennings Randolph Reservoir, decreasing the number of Recreation days, measured above lake access points. Increased demand is also projected to increase the load on downstream reservoirs, resulting in an increase in consecutive low flow days. WMA reservoirs are projected to lose 7 to 15% of their usable storage volume due to sedimentation between 2010 and 2040, causing an increase in storage failures, particularly in the Patuxent Reservoir. By year 2040, the effects of sedimentation alone will begin to cause occasional storage failures in the Jennings Randolph and Little Seneca Reservoirs as well.

Climate change is also projected to increase water supply vulnerability in the WMA. Climatic trends in the region are towards higher flows in the winter and early spring, followed by more extreme low flows in the summer. Simulations of five GCMs predict an increase in storage failures within the system, with storage failures beginning to occur in the Little Seneca and Occoquan reservoirs, where historically they did not occur. An increase in storage penalties is accompanied by a decrease in whitewater releases and a doubling of Recreation Season failures.

Five potential modifications to existing operating rules were evaluated using the multi-objective evolutionary algorithm optimization scheme. None of the optimized operating rules were able to completely mitigate the combined effects of demand change, sedimentation and climate changes. However, some, such as the Buffer Equation, were able to mitigate the effect of climate, with respect to the objectives. Flowby and environmental flow penalties were decreased by modifying the Buffer Equation to allow separate equations controlling upstream and and downstream imbalances. Results for the load shift equation remain very similar to the optimized load shift equation found for current conditions (Stagge and Moglen 2014). This suggests that the effectiveness of this rule is maximized. Optimization of the zone-based rule curves suggests that Jennings Randolph storage should be managed more conservatively during March, April and May in the future, while storage in the Patuxent could be improved by managing the reservoir more conservatively during the refill period (September to February). Evaluation of demand restriction triggers suggests that system-wide operation could be slightly improved by increasing the reservoir storage triggers for the minor, voluntary restriction. For the more severe, mandatory restriction, the optimized rules suggest a decrease in the Jennings Randolph trigger and an increase in the Little Seneca trigger. In this latter case, the increase in the Little Seneca trigger is due to its relatively small size and long refill rate.

Using a combination of synthetic streamflow generation, water resources decision modeling and multi-objective optimization, the potential vulnerabilities of the WMA water supply system were evaluated. The adaptation strategies outlined here could be implemented in the WMA, though several would require greater coordination and flexibility. This is a common challenge for trans-boundary and shared waterheds. Further, this work provides a framework for developing and comparing strategies to mitigate the effects of projected demand and climate change with an appropriate adaptation strategy.

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List of Tables

TABLE 1. WMA operational characteristics.

Reservoir	Manager	Total Storage 10^6 m^3	Available Storage 10^6 m^3	Watershed Area km^2	Upstream Distance km	Travel Time days
Jennings Randolph	CO-OP,USACE	109	51	681	320	9
Little Seneca	CO-OP	16	14	54	25	1
Savage	UPRC	24	23	272	320	9
Patuxent	WSSC	51	39	342	-	-
Occoquan	Fairfax	31	30	1,533	-	-

TABLE 2. Global Climate Models (GCMs) considered.

Model	Institution	Location	Reference
CCSM3	National Center for Atmospheric Research (NCAR)	USA	Collins et al. (2006)
CGM_3.1	Canadian Centre for Climate Modeling and Analysis	Canada	Flato (2005)
CSIRO_MK3	CSIRO Atmospheric Research	Australia	Gordon et al. (2002)
MIROC_3.2	Center for Climate System Research	Japan	Watanabe et al. (2011)
PCM1	National Center for Atmospheric Research (NCAR)	USA	Washington et al. (2000)

TABLE 3. Projected WMA population and demand change (2010-2040). Percent change from 2010 is presented in parentheses.

	Population (in Millions)		Water Demand (10^3 m^3/d)			
	2010	2040	2010	2020	2030	2040
Fairfax	1.54	2.03 (32.0%)	663	755 (13.8%)	826 (24.5%)	866 (30.7%)
WSSC	1.72	2.01 (16.6%)	651	707 (8.6%)	746 (14.7%)	771 (18.6%)
Aqueduct	0.98	1.23 (26.0%)	571	624 (9.2%)	652 (14.1%)	673 (17.8%)
Rockville	0.05	0.06 (37%)	18	20 (10.4%)	22 (20.8%)	24 (31.3%)
Total WMA	4.28	5.33 (24.5%)	1,903	2,106 (10.7%)	2,246 (18.0%)	2,335 (22.7%)

TABLE 4. Projected sedimentation and storage loss (2010-2040). Percent change from 2010 is presented in parentheses.

Reservoir	Usable Storage (10^6 m^3)		Sed Rate	Source
	2010	2040	(10^3 m^3/yr)	
Jennings Randolph	102.5	88.1 (-14.1%)	481	U.S. Army Corps of Engineers (1963)
Little Seneca	13.8	12.1 (-12.3%)	57	Hagen et al. (1998)
Occoquan	29.5	25.0 (-15.4%)	151	CDM (2002)
Patuxent	38.1	35.4 (-7.2%)	91	Ortt et al. (2007)
Savage	23.3	21.2 (-8.8%)	68	Ahmed et al. (2010)

TABLE 5. Optimization results for future conditions (CSIRO A2, 2070-2099 climate). All values represent the maximum % improvement relative to simulations using existing operating rules.

	Z_{Stor}	Z_{Flowby}	$Z_{\text{Rec Season}}$	Z_{WW}	$Z_{\text{Env Flows}}$
Buffer Eq	20.71	50	37.79	88	15.20
Load Shifting	1.29	8.33	0	0	4.09
JR Rule Curve	1.27	16.67	9.24	98	15.20
Patux Rule Curve	6.39	4.17	0	0	2.34
Demand Res	1.46	4.17	0.52	0	5.26

TABLE 6. Optimized demand restriction triggers, in % usable storage. Current demand restriction triggers are presented as a single value, termed "MWCOG", while optimized results for the 2040 Demand and Sedimentation case "2040" and the CSIRO A2 2070-2099 case, "2070", are presented as a range across all non-dominated solutions.

	Jennings Randolph			Little Seneca		
	MWCOG	2040	2070 A2	MWCOG	2040	2070 A2
Voluntary	60	74-85	74-83	60	73-82	72-83
Mandatory	25	17-25	18-25	25	24-53	26-59
Emergency	5	11-17	11-15	5	4-15	3-14

List of Figures

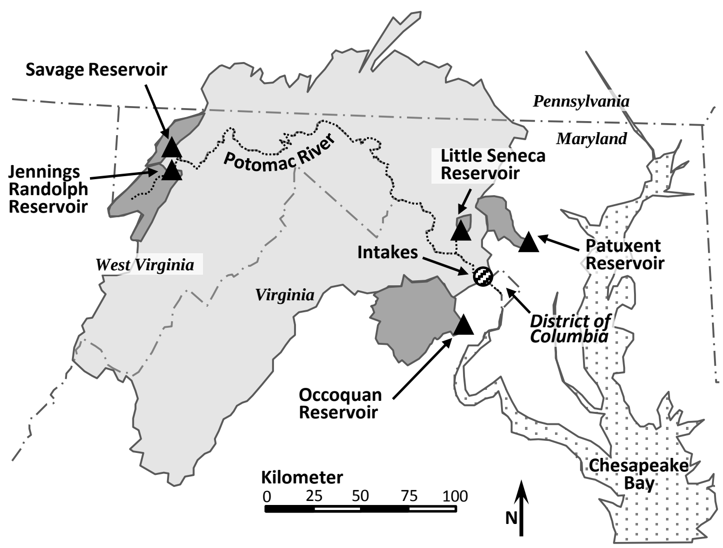
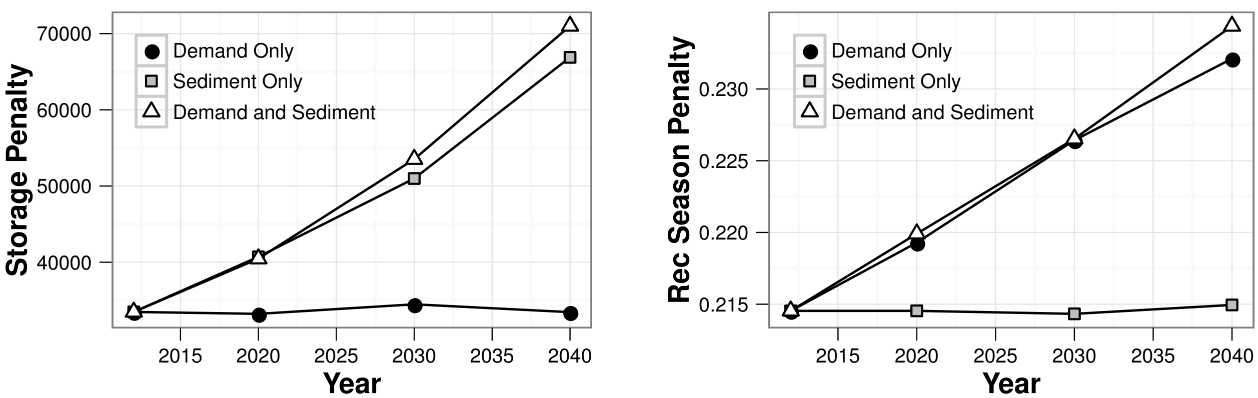


FIG. 1. Potomac watershed and Washington, DC, water supply; Potomac watershed shown in lighter shade, with reservoir watershed shown in a darker shade; reservoirs shown as triangles and intakes for the Washington, DC, metropolitan area shown as a hashed circle.



(a) Storage

(b) Recreation Season

FIG. 2. Effect of demand increase and reservoir sedimentation on Storage (a) and Recreation Season (b) objectives.

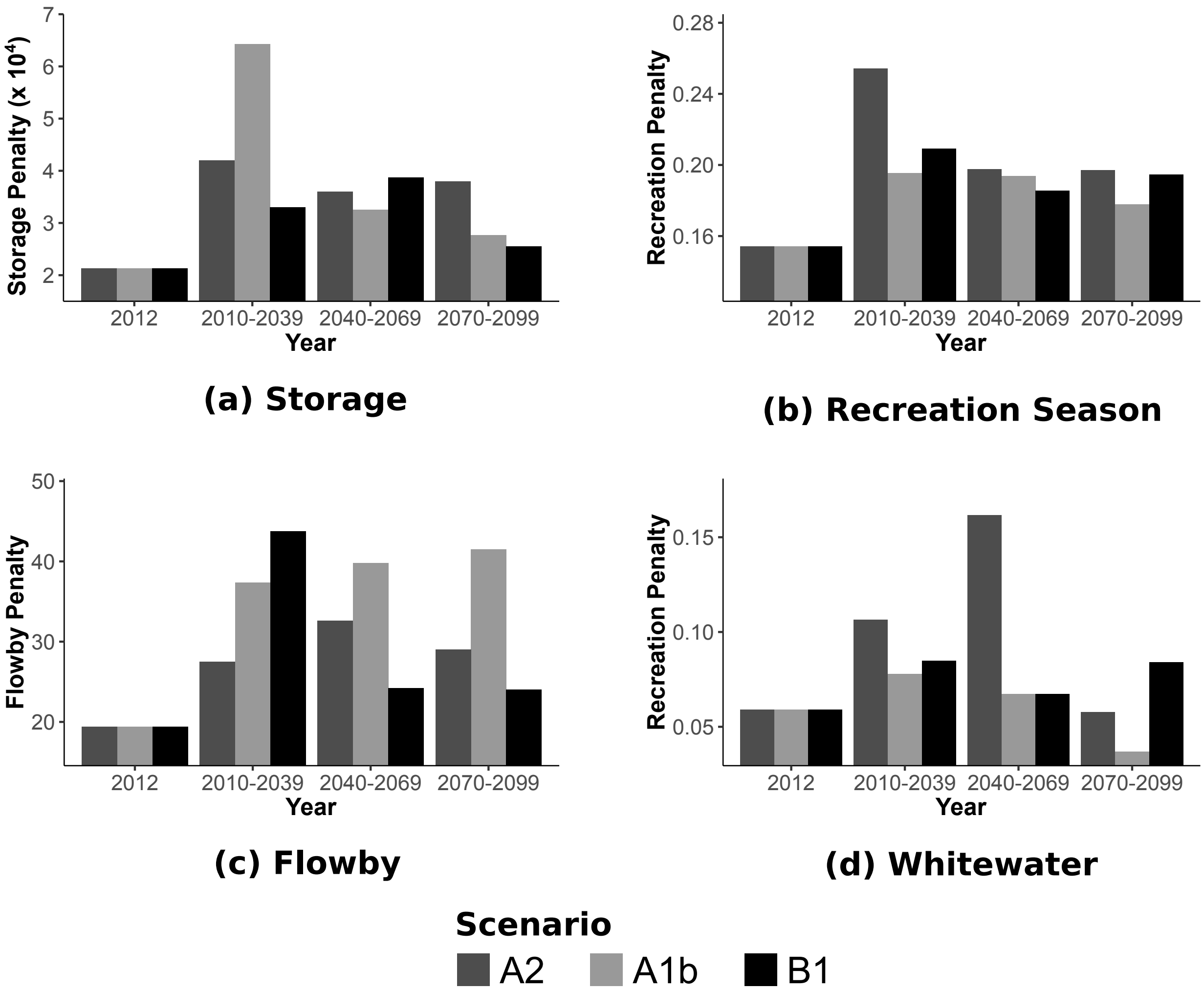
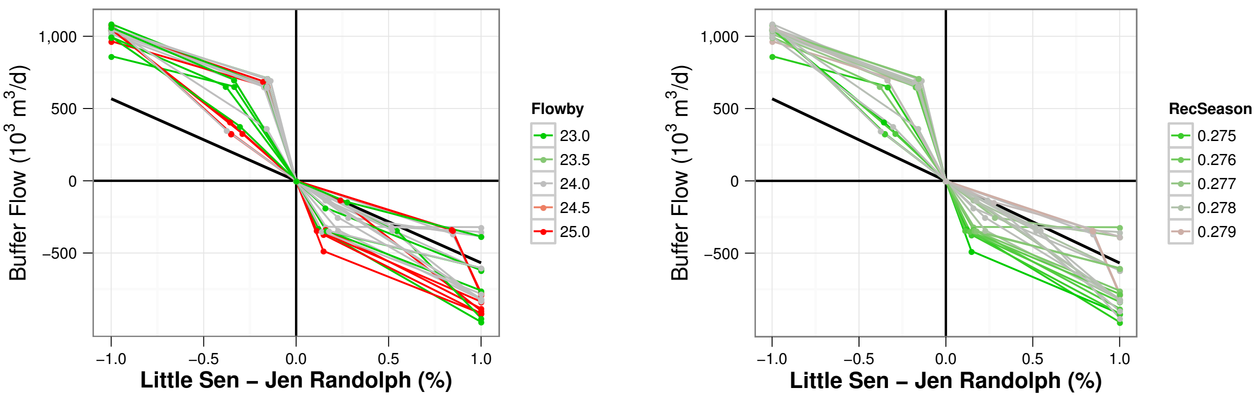


FIG. 3. Effect of climate change on system objectives. Lines represent the mean of all five considered GCMs for the SRES A2, A1b, and B1 emission scenarios.



(a) Flowby **(b) Recreation Season**

FIG. 4. Optimized buffer equation under 2070-2099 climate change conditions with respect to Flowby (a) and Recreation Season (b). Current operating rules are shown by the diagonal, black line. Each non-dominated solution is presented with the color scale corresponding to improvement (green) or worsening (red) of the objective function relative to current policy.