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Reservoir operations under climate change: Storage capacity options to mitigate risk

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ABSTRACT

Observed changes in precipitation patterns, rising surface temperature, increases in frequency and intensity of floods and droughts, widespread melting of ice, and reduced snow cover are some of the documented hydrologic changes associated with global climate change. Climate change is therefore expected to affect the water supply-demand balance in the Northeast United States and challenge existing water management strategies. The hydrological implications of future climate will affect the design capacity and operating characteristics of dams. The vulnerability of water resources systems to floods and droughts will increase, and the trade-offs between reservoir releases to maintain flood control storage, drought resilience, ecological flow, human water demand, and energy production should be reconsidered. We used a Neural Networks based General Reservoir Operation Scheme to estimate the implications of climate change for dams on a regional scale. This dynamic daily reservoir module automatically adapts to changes in climate and re-adjusts the operation of dams based on water storage level, timing, and magnitude of incoming flows. Our findings suggest that the importance of dams in providing water security in the region will increase. We create an indicator of the Effective Degree of Regulation (EDR) by dams on water resources and show that it is expected to increase, particularly during drier months of year, simply as a consequence of projected climate change. The results also indicate that increasing the size and number of dams, in addition to modifying their operations, may become necessary to offset the vulnerabilities of water resources systems to future climate uncertainties. This is the case even without considering the likely increase in future water demand, especially in the most densely populated regions of the Northeast.

1. Introduction

Observed increases in global average surface temperature, frequency and intensity of heat waves and droughts, changes in precipitation frequency and intensity, reduced snow cover, widespread melting of ice, and changes in soil moisture and runoff are some of the key documented hydrologic changes often associated with global climate change (Huber and Knutti, 2011; IPCC, 2014, 2008; NCA, 2014a). Since 1950, average surface air temperatures in the U.S. have increased by 1 °C, and annual precipitation has increased by 50 mm (NCEI, 2015). If greenhouse gas emissions continue to rise, U.S. average temperatures may increase by 6 °C by 2100 (IPCC, 2014; NCA, 2014b). Further warming increases the likelihood of severe and irreversible changes in all components of the climate system and biosphere (IPCC, 2014). For summer and fall, more frequent and severe seasonal drought is projected (Horton et al., 2014; NCA, 2014b). Regions supplied by meltwater from snow cover are projected to experience an increase in the ratio of winter to annual flows, and reductions in low-flows (IPCC, 2013, 2008).

Anticipated increases in the frequency and intensity of extreme weather events will in turn alter streamflow patterns affecting the operations and downstream hydrologic impacts of existing water infrastructure (Asadieh et al., 2016; Asadieh and Krakauer, 2015; McDaniels et al., 2008; Pahl-Wostl, 2006) and may result in flooding events that will exceed the design limits of dams (Jothityangkoon et al., 2013; Madsen et al., 2014; Najibi et al., 2017). Traditional water management practices are based on stationarity and past hydrological experience that underpin infrastructure planning and operations (National Research Council, 2011). Yet, even under the current levels of climate variability, water managers are struggling, as increasingly large flood and

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drought damages proliferate across the globe (Bouwer, 2011; IPCC, 2008). Under the assumption that expansion of water infrastructure reduces the vulnerability of water resources to climate change (Watts et al., 2011), several bills were introduced in the U.S. Congress calling for feasibility studies relating to the construction of new dams (Christensen, 2014; Feinstein and Boxer, 2015; Huffman et al., 2015).

Dam construction is a long-standing strategy to reduce the spatiotemporal variability of natural water supply. By regulating the flow of water, dams alter the natural hydrograph to secure a reliable source of water for a wide variety of human and environmental needs. The suite of undesirable environmental impacts of dams and reservoirs (Baker et al., 2011; McCully, 1996; Mirchi et al., 2014; Poff et al., 2007; Poff and Schmidt, 2016) make the construction of new dams socially and politically controversial. Nevertheless, the role of dams and conveyance facilities is indisputable in achieving water security and providing the economic services required for development (Goldsmith and Hildyard, 1984; Khagram, 2004).

Dams are major capital-intensive investments that increasingly control regional and even continental-scale hydrology (Lehner et al., 2011) and will continue to be relied on well into the future, especially in developing nations (Zarfl et al., 2015). Yet their cumulative environmental, ecological and economic effects remain largely unexplored at these larger scales due to the lack of reliable methods for simulating their operations. Given their long lifespans, understanding the benefits and externalities of large water resources infrastructure are critical in planning and designing future climate change adaptation measures that are expected to be sustainable at regional and global scales (Bhaduri et al., 2016).

The hydrological implications of future climate change will likely require important changes to present-day water management policies (Graham, 2004; Medellín-Azuara et al., 2008), with alteration of dam operations figuring prominently (Watts et al., 2011). However, while much work has documented the potential impacts of climate change on operations at individual reservoir facilities (Fearnside, 2005; Kang et al., 2007; Kim et al., 2009) or even in the context of tributary basins (Christensen et al., 2004; Lauri et al., 2012; Payne et al., 2004), the impact of an entire population of reservoirs at a regional scale (i.e., across the entire regional network of rivers), has yet to be established.

At the macro-scale, reservoir operating rules of individual dams are not routinely recorded or made available (Ehsani et al., 2016; Nazemi and Wheater, 2015a, 2015b), thus making it virtually impossible to assign accurate operating rules for hydrologic simulations, particularly over regional or larger domains where thousands of dams can exist. To circumvent this issue, scientists have applied either implicit assumptions to assess the aggregate impact of dams (Dynesius and Nilsson, 1994; Graf, 1999; Nilsson et al., 2005; Vörösmarty et al., 2003, 1997), or used simple conceptual and empirical relationships to model reservoir operations (Coe, 2000; Döll et al., 2003; Haddeland et al., 2006; Hanasaki et al., 2006; Meigh et al., 1999; Wisser et al., 2010; Yoshikawa et al., 2013).

Climate change is expected to affect the future water supply and demand in the Northeast US (NCA, 2014b). It is not the primary goal of this study to provide a detailed analysis of climate change uncertainties or to make absolute predictions of available water resources in the future; rather, we seek to provide a broad overview of the effects of different levels of climate warming on water resources of the Northeast with a focus on the role of dams. In this context, this analysis is guided by three general questions: Will dams be as effective, in the future as they have been in the past, in providing the full suite of services that they were designed for? Will the degree of natural flow disturbance by dams change substantially in the future? What are the consequences of broad-scale dam removal or building on Northeast regional hydrology?

To estimate the potential impacts of different levels of climate warming on water resources of the Northeast we have used a single Global Circulation Model (GCM) and four respective Representative Concentration Pathways (RCP). A General Reservoir Operation Scheme (GROS) (Ehsani et al., 2016) is added to a coupled water balance and transport model (WBM_{plus}) (Vörösmarty et al., 2010, 2000, 1996, 1989) to simulate time-varying storage and releases from a population of dams geospatially distributed along simulated river networks. To investigate the implications of climate change for the function of dams in the regional scale we are analyzing a combination of four climate and four dam scenarios (16 model runs) at a resolution of 0.05° (lat × long; ca. 4.5 km) for the period of 1950 to 2099. The results presented in the main narrative are aggregated for the whole Northeast region. State level findings are presented in the Supplementary Material.

2. Data sets and methods

The study domain is the Northeastern United States (Fig. 1), comprising 8% of the nation's contiguous land area and extending from Virginia in the south to Maine in the north (BOC, 2016). According to U.S. Census Bureau records (2010), 72 million people or 23% of the U.S. population live in this region and produce 26% (4.1 trillion dollars) of U.S. gross domestic product (BEA, 2015).

Spatially distributed data sets depicting contemporary land cover and vegetation, soil properties, a Simulated Topological river Network (STN), dams and reservoirs and climate forcing time series were assembled for the period of 1950 to 2099. Water supply is computed as the Total Available Water resources (TAW) over administrative units, while the underlying hydrological calculations are carried out at the higher spatial resolution (0.05° grid), aggregated over the STN and with water supply inputs and exports reconciled over the administrative units (Fekete et al., 2002). TAW of a region is calculated as the sum of (I) internal surface water runoff generated in the region, and (II) external water resources entering the region. TAW has the same dimensional units as stream flow (i.e., m^3/s).

2.1. Dams and reservoir storage

The study region has 11037 georeferenced dams listed in the U.S. National Inventory of Dams (NID) with total storage capacity of 7.15×10^{10} m^3 (Table 1), which can store up to 20% of the annual TAW in the Northeast. Over three-quarters (77%) of these dams have a capacity smaller than 10^6 m^3 and are essentially considered as 'run of the river' dams that have little effective storage capacity and impact on downstream flows. There are only eight dams in the region with a capacity larger than 10^9 m^3 (1.0 km^3) (Fig. 1). The hydrologically-relevant criteria by which a dam is included within the NID requires the following (USACE, 2013): dam height exceeds 25 feet (7.6 m) and storage exceeds 15 acre-feet (18502 m^3), or reservoir storage exceeds 50 acre-feet (61674 m^3), and its height exceeds 6 feet (1.8 m).

Each entry in NID represents a structure, and each dam may have multiple structures (i.e., dikes, spillways) such that the number of entries in NID does not unequivocally indicate the precise number of dams. Many of the reports and statistics that are based on NID (including the NID official website: http://nid.usace.army.mil/) do not take this into account and (in our view) report erroneous count and storage estimates. To the highest degree practical, this study has corrected the dataset to prevent double-counting. A total of 107 dams with multiple entries in NID were identified to avoid double counting, which would have resulted in an 18%

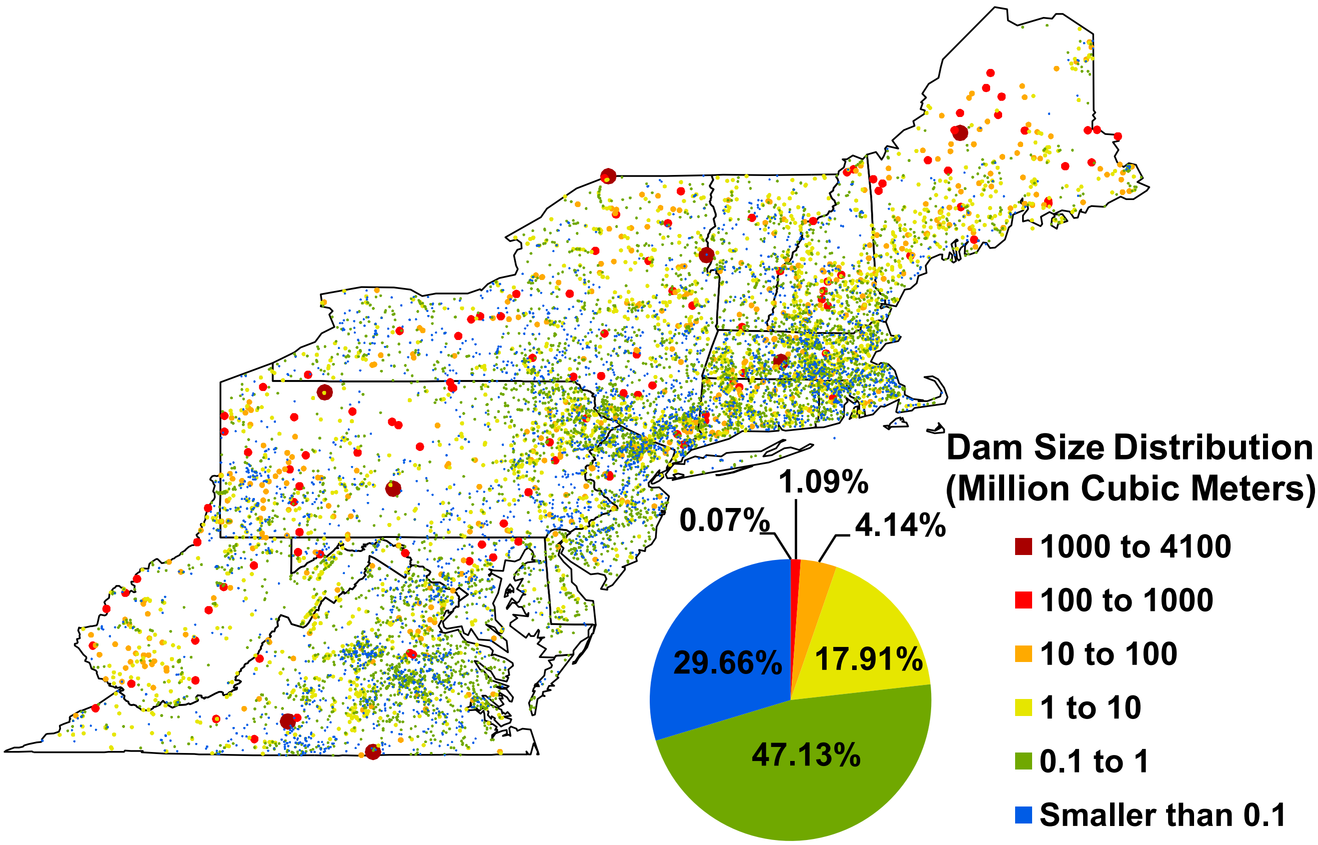

Fig. 1. Dam size distribution in the region. Percentages refer to the number of dams in each size class.

Table 1
Total count and storage capacity of dams in the Northeast US.

State	Connecticut (CT)	Delaware (DE)	Massachusetts (MA)	Maryland (MD)	Maine (ME)	New Hampshire (NH)	New Jersey (NJ)	New York (NY)	Pennsylvania (PA)	Rhode Island (RI)	Virginia (VA)	Vermont (VT)	West Virginia (WV)	Northeast (NE)
Number of Dams	703	83	1426	321	562	634	798	1896	1519	214	2008	356	517	11037
% of Total Number of Dams	6%	1%	13%	3%	5%	6%	7%	17%	14%	2%	18%	3%	5%	100%
Total Storage (10^9 m^3)	2.3	0.1	5	1.8	9.7	3.2	2.4	18.5	11.3	0.4	10.2	1.2	5.4	71.5
% of Total Regional Storage	3%	0%	7%	3%	14%	4%	3%	26%	16%	1%	14%	2%	8%	100%

overestimate of the total regional water storage capacity. Thus, numbers reported in Table 1 may be different from other sources.

On a practical level, matching individual reservoirs in NID with the correct position on digital flow paths is not possible due to inaccurate geo-referencing in the original data sets, and limitations in using an STN at 0.05° to represent rivers. For macro-scale hydrological applications, we have found it reasonable to aggregate the capacity of multiple smaller dams into a hypothetical larger dam bearing the same total storage capacity (Ehsani et al., 2016; Vörösmarty et al., 2003). Our STN (Fekete et al., 2002) reliably represents the characteristics of Hydrologic Unit Code 12 (HUC12) watersheds. HUC12 is the smallest level of the hierarchical classification of hydrologic drainage basins in the United States (USGS, 2017). Therefore, in our modeling, we have aggregated the capacity of all reservoirs located in HUC12 watersheds in the region and assumed explicitly that a dam with the same total storage is positioned at the mouth of HUC 12 watersheds. This technique considerably improved the representation of NID on our digital gridded river network.

2.2. Climate Scenarios: Historical and future trends in the Northeast

In this study, we considered the minimal setting scenarios of the Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP) (Davie et al., 2013; Warszawski et al., 2014), which comprise all four RCPs for one GCM (HadGEM2-ES). These four climate scenarios include one mitigation (RCP3PD; also known as RCP2.6), two medium stabilization (RCP4.5/RCP6.0), and one very high emission scenarios (RCP8.5) (van Vuuren et al., 2011), enable the comparison of impacts of different levels of climate warming on water resources and reservoirs. RCP2.6 is the scenario that aims to keep global warming below 2 °C above pre-industrial temperatures while under RCP8.5 the global mean surface temperature change may exceed 4 °C (IPCC, 2014). Although many climate change impacts studies have used only a single GCM as a basis for future projections for exploratory evaluations of adaptation possibilities and consequences, we recognize that multi-model ensemble simulations will be necessary to facilitate specific regional water management strategies and representation of uncertainty in projections and assessing hydrologic impacts due to climate change. However, such analysis is not our goal and is well beyond the scope of this work. We believe this middle ground preserves the salient character of regional-scale synoptic results and retains a sufficient analytical detail to address the core questions posed earlier.

All monthly and annual data presented here are aggregated from original daily inputs and simulation results. Here the contemporary conditions are constructed from the GCM historical temperature, precipitation, and simulated water resources from 1950 to 1999. To demonstrate the effects of climate change under each RCP, we compared means from 2080 to 2099 to those of the contemporary. Coarser resolution climate data were re-gridded from $0.5^\circ \times 0.5^\circ$ grids to $0.05^\circ \times 0.05^\circ$ grids using the inverse distance weighted 4-6-9 point (IDW469 p) interpolation (Fig. S 1) method (Fekete, 2001).

Since 1950, the mean temperature in the Northeast has increased by 1.1 °C (NCEI, 2015). A trend towards later freeze dates in autumn and earlier thaw in spring had led to a lengthening of the growing season (Kunkel et al., 2013; Lemke et al., 2007) and also later freeze-up and earlier break-up of ice on lakes and rivers (Magnuson et al., 2000). Annual precipitation in the region has increased by 140 mm, and the amount of precipitation falling as very heavy events has increased by 70% (Horton et al., 2014; NCA, 2014b). Despite the increase in annual precipitation, there has been a decrease in the proportion of winter snow-to-precipitation (Kunkel et al., 2009; USEPA, 2016) and the drought danger has increased over the region (Groisman et al., 2004). Soil wetness, as well as seven-day low flows (minimum streamflows), has generally increased in the Northeast (Groisman et al., 2004; Kunkel et al., 2009; USEPA, 2016). High streamflow and floods have generally become larger over the past half-century (Mallakpour and Villarini, 2015; Najibi and Devineni, 2017), and large floods have become more frequent across the Northeast (Groisman et al., 2004; USEPA, 2016).

Future mean temperature increases for the region are expected to exceed those across the contiguous U.S. (NCA, 2014a). Higher latitudes are projected to experience larger increases in temperature (IPCC, 2014; NCA, 2014a, Fig. S 2). More northern and eastern sub-regions may experience a greater than 20% increase in annual precipitation while to the south and west, annual precipitation may decline, on average, by 5% (IPCC, 2014; NCA, 2014a, Fig. S 2). Mean annual changes in temperature and precipitation mask the spatiotemporal variability of future climate impacts. Fig. S 3 shows the mean monthly precipitation and temperature anomalies from 2080 to 2099 under RCP4.5 and RCP8.5 compared to long-term 1950–1999 averages. Although annual precipitation is expected to increase over most of the region, monthly precipitation changes can fluctuate between −60% and +70% in some locations. Precipitation may decrease considerably in many parts of the Northeast between mid-spring and mid-fall (Fig. S 3). During these same seasons, temperature increases may be up to 4 °C higher than the mean annual temperature.

Freeze and thaw processes have a significant influence on the hydrologic regime. Freezing of ground reduces the hydraulic conductivity and water infiltration into soil and leads to increases in runoff from rain and snowmelt. The thickness of seasonally frozen ground is primarily controlled by the increase in air temperature (Frauenfeld et al., 2004; Lemke et al., 2007). Temperature is also a chief factor that determines if precipitation in winters will be in the form of snow or rain.

We defined the frozen period as the time when the mean daily temperature is strictly below 0 °C. Fig. 2 shows the trends in the timing of the beginning of the frozen period in fall and its end in spring. The frozen season is projected to be shortened between 26 days for RCP2.6, and 63 days for RCP8.5 (average for 2080–2099). The first day of the frozen period may occur in late December instead of late November, and the last day of the frozen period in winter may be in late February instead of during the end of March.

2.3. A General Reservoir Operation Scheme (GROS)

The latest version of WBM_{plus} (Vörösmarty et al., 2010, 2000, 1996, 1989) was applied to spatially simulate contemporary and future runoff, and to route river flows. WBM_{plus} is a daily, grid-based macroscale hydrology model, which simulates soil moisture, evapotranspiration, snow storage, and runoff on single grid cells. The runoff is propagated along the 0.05° resolution STN using a simple routing scheme employing the Muskingum-Cunge method to solve the St. Venant equations (Fekete et al., 2006).

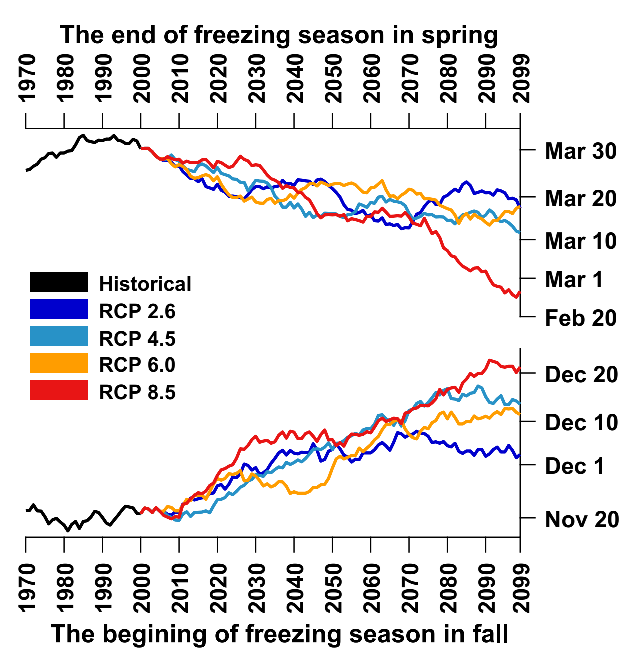

Fig. 2. Change in the length of freezing season. The last day of freezing season in spring (top), and the first day of freezing season in fall (bottom) based on 20-year moving average of daily temperatures.

To represent the daily operation of dams, a Neural Networks based General Reservoir Operation Scheme (GROS) was added to WBM_{plus} (Ehsani et al., 2016). GROS simulates the daily release from reservoirs based on changes in the daily water storage and is capable of capturing the aggregate hydrological effects of large dams as well as small reservoirs. Following an analysis of significance of variables (Improved Stepwise method (Gevrey et al., 2003)), three sets of inputs were selected to calculate the daily release $[R_t]$ (output at time t) from reservoir: Inflow = $[I_t, I_{t-1}, I_{t-2}]$, Release = $[R_{t-1}, R_{t-2}]$ and Storage = $[S_{t-1}]$. In the context of reservoir operational data being extremely limited, GROS was calibrated and then validated against detailed operational data from a set of existing dams (n=12), representing a wide range of reservoir size, flow rates, residence time and purpose (i.e. irrigation, flood control, hydropower, recreation and water supply) (Ehsani et al., 2016). Data from 10 dams (out of 12) were randomly divided into three subsets of training (60%), cross training (20%) and validation (20%). To ensure that the final Neural Network has not overfitted to the training sites, data from the other two dams were completely excluded from the training process to be used as independent validation datasets (Ehsani et al., 2016).

The goal of this model is to help better understand the broad impacts of a large number of dams in regional or larger scales. The last such comprehensive analysis was conducted for the region was by the U.S. Army Corps of Engineers in 1972, as part of the North Atlantic Regional (NAR) Water Resources Study (Major and Schwarz, 1990), on behalf of the U.S. Water Resources Council. As part of that study, a multi-objective water demand and supply systems planning model was developed to test a range of supply and demand scenarios and projections to 2020, under assumptions of a stationary climate. The NAR study concluded that just to meet future increased water demands (from 1970 baseline to 2020), an additional 5 km^3 of storage would be required.

The future water demands and thus future reservoir operations may be different from current trends and practices. We have not considered those changes in our modeling. Increased access to real-world reservoir operation rules and data is also essential to improving the representation of dams in hydrological models. A model that is able to accurately present thousands of reservoirs has yet to be developed.

The GROS module is completely integrated with our hydrologic model and represents the cumulative regional hydrological effect of dams on the regulation of downstream flows and was shown to be significantly more accurate than some other models in simulating releases from dams (Ehsani et al., 2016). GROS has been designed to capture the regional dynamics of engineered flows, where large numbers of dams with varying capacities produce collective macro-scale behaviors. It is a dynamic daily reservoir operation module that adapts to changes in climate and automatically adjusts the operation of dams based on the reservoir water storage level, timing, and magnitude of incoming river flow. The model readjusts the timing and magnitude of releases from the reservoirs based on changes in the timing and magnitude of inflows. This dynamic capacity of GROS to re-adjust operating rules based on changes in hydrologic inputs makes it particularly well-suited for climate change impact studies.

2.4. Estimating the magnitude of flow Regulation by dams

As an approximation of the potential impact of dams on downstream flows, Grill et al. (2014) introduced the "Degree of Regulation" (DR) as the ratio of the storage capacity of a reservoir (or a cluster of reservoirs) to a river's annual flow (residence time).

We have included the daily operation of reservoirs in this study, which allows us to define a more realistic and elaborate index to assess the effect of dams on the regulation of downstream flows (as the volume of water released and stored). Instead of using the storage capacity of dams (which is a constant value), we can use the volume of water that is displaced by the operation of dams (to reduce or increase natural flow).

In contrast with DR as an index that estimates the potential impacts of dams on downstream flows, we defined and calculated the Effective Degree of Regulation (EDR) as the ratio of the volume of water that is displaced (stored or released) by the operation of a dam or a cluster of dams, to the river's naturalized flow (without dams) (Eqs. (1) and (2)).

$$EDR_m = \frac{|\mathrm{TAW}_{d,m} - \mathrm{TAW}_{n,m}|}{\mathrm{TAW}_{n,m}} \tag{1}$$

$$EDR_a = \frac{\sum_{m=1}^{12} |\mathrm{TAW}_{d,m} - \mathrm{TAW}_{n,m}|}{\sum_{m=1}^{12} \mathrm{TAW}_{n,m}} \tag{2}$$

Subscripts m, a, n, and d respectively refer to monthly, annual, naturalized (no dams), and dammed. EDR_m is the monthly Effective Degree of Regulation and EDR_a is the annual Effective Degree of Regulation. The numerator in Eqs. (1) and (2) represents the volume of water that is displaced by the operation of dams, and the denominator is the river's naturalized flow in the same period (Fig. 3). The major advantage of EDR over DR is its sensitivity to changes in reservoir operation and seasonal variations in water availability caused by climate change.

To assess the effect of climate change on the operation of dams, we calculated the relative change in the EDR, ΔEDR, as follows:

$$\Delta EDR_t = \frac{EDR_t - EDR_{avg}}{EDR_{avg}} \times 100 \tag{3}$$

where ΔEDR_t is the percent change in the EDR of a dam or a cluster of dams at time t (EDR_t) compared to the mean contemporary (1950–1999) EDR (EDR_{avg}). ΔEDR may be calculated at monthly and annual time scales.

To evaluate the effect of dams on the regulation of the natural water availability, WBM_{plus} was applied to each climate scenario (historical and the four RCPs) twice; once with GROS simulating reservoir operation, and once without GROS to characterize

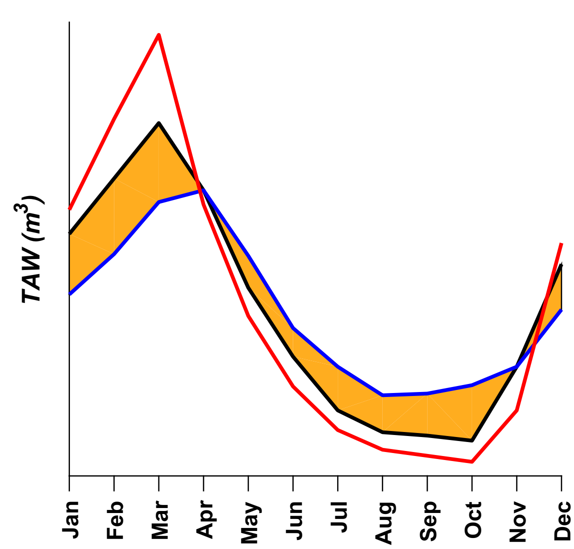

Fig. 3. Effective Degree of Regulation (EDR). The black line on this schematic represents the contemporary naturalized TAW (without dams). The blue line shows the resultant effect of dams on the naturalized hydrograph. The red line illustrates the effect of climate change on the TAW. The orange area is the volume of water that is displaced by dams. EDR_a may be calculated by dividing the orange area, by the area under the black line.

naturalized conditions. To quantify the effects of climate change on the operation of dams, the annual and monthly ΔEDR for each climate scenario were calculated by applying the simulation results to Eqs. (1), (2), and (3).

To assess the effects of climate change on water availability, we calculated ΔTAW as:

$$\Delta TAW_t = \frac{\mathrm{TAW}_{F,t} - \mathrm{TAW}_{C,avg}}{\mathrm{TAW}_{C,avg}} \times 100 \quad (4)$$

where $\Delta \mathrm{TAW_t}$ is the percent change in TAW of a region at any time (month or year) in the future ($\mathrm{TAW}_{F,t}$, i.e., red line in Fig. 3) compared to the average contemporary TAW ($\mathrm{TAW}_{C,avg}$, mean of 1950–1999). Negative ΔTAW indicates that water availability has declined under future climate scenarios (e.g., October in Fig. 3), and positive ΔTAW indicates that more water is projected to be available (e.g., March in Fig. 3).

We investigated the effects of climate change on annual and monthly water supply by comparing the water availability under future climate scenarios to average contemporary conditions using Eq. (4). We repeated these calculations with three hypothetical alternative future dam scenarios to evaluate the effectiveness of dam building as a climate adaptation strategy.

The base dam scenario (DS-0) is a business-as-usual scenario in which the dams currently in place will continue to operate in the future. The first dam scenario (DS-1), is the hypothetical removal of all dams across the region. We assessed the capacity of existing dams to control overall climate change effects on water availability by exploring the difference between DS-1 and DS-0. In the second (DS-2) and third (DS-3) scenarios, we assumed 100% increase in the water storage capacity in the region, with a distinction between the size and the number of new dams in each scenario.

These scenarios are not designed as forecasts of the future per se, but instead to simulate the sensitivity of the Northeast regional water system to the impact of postulated extreme climate conditions/scenarios. We recognize that these significantly increased reservoir storage volumes accompanying anticipated new dam construction in the region may be impossible to realize in practical terms, but nevertheless, hold that the results of these experiments are useful in conceptually bounding the significance of new dam construction. These projections are explored in two ways. In DS-2 the impact of construction of new dams is assessed with similar sizes to the existing population of dams and then by doubling the number of dams compared to the number of currently existing ones. As a result, water storage capacity in the region increases from 71.5 km^3 to 143 km^3. Most of the dams in the region are small. Large reservoirs are flexible means of adaptation to climate change (Gaupp et al., 2015; Giuliani et al., 2016). Scenario DS-3 contrasts water supply resiliency arising from the construction of large dams versus small dams. The largest existing dam in the region has a capacity to store approximately 4 km^3 of water. To keep the total storage in DS-2 and DS-3 the same at 143 km^3, in DS-3, 18 large dams, each with a capacity of 4 km^3 are strategically located and added to the existing dams. Location of these dams (Fig. S 4) is chosen based on statistical analysis of NID, and annual average river flows in the region (Ehsani et al., 2016).

To assess the ability (or inability) of dams in reducing the impact of climate vulnerability and creating resiliency, we compared the effects of hypothetical future dams (DS-1, DS-2, DS-3), and the currently existing dams (DS-0) on water availability and calculated the Climate Effect Alteration index (CEA) as:

$$CEA_t = \frac{\Delta TAW_{(DS-s,t)} - \Delta TAW_{(DS-0,t)}}{\Delta TAW_{(DS-0,t)}} \qquad s = 1, 2 \text{ or } 3 \quad (5)$$

where $\mathrm{CEA_t}$ represents the difference in climate change effects on water availability at time t due to the change in number and/or capacity of dams in the future. Subscript DS-s represents the hypothetical future dam scenario which is compared to the base scenario (DS-0). For such an alternative impoundment scenario, negative CEA means that climate change effects have been dampened, and positive CEA means the reverse.

3. Results and discussion

3.1. Flow regulation by dams in the Northeast

The first step in estimating EDR is to compute naturalized (without dams) and dam-regulated flows. Fig. 4 shows the contemporary EDR for individual states in the region. EDR values in each state reflect the cumulative impact of dams located in that state plus that of, all dams located on upstream river segments that flow into that state. Based on $\mathrm{EDR_a}$ values, the cumulative effect of dams on water resources is smallest in Maryland and the District of Columbia (combined as one region, $\mathrm{EDR_a}$ = 0.05), and is largest in New Jersey ($\mathrm{EDR_a}$ = 0.16) and Pennsylvania ($\mathrm{EDR_a}$ = 0.15). New Jersey, Pennsylvania, and Delaware benefit the most from the operation of dams in the driest month of year when, on average, dams increase water availability in those states by 48%, 45%, and 40% respectively. In the most water-rich month of year, dams in Pennsylvania and New Jersey can store respectively 25% and 23% of the otherwise naturally available water supply, exceeded only by West Virginia, with 30%. The mean contemporary regional $\mathrm{EDR_m}$ is presented in Fig. 7 and state level results are presented in Fig. S6.

3.2. Regional trends in water availability under changing climate

Based on the 1950–1999 means, March and April are the most water-rich months of the year (as expressed as discharge flowing through rivers), and August, September, and October are the most water-scarce months of the year (Fig. 5). Due to the changes in precipitation and temperature, peak streamflows are projected to shift

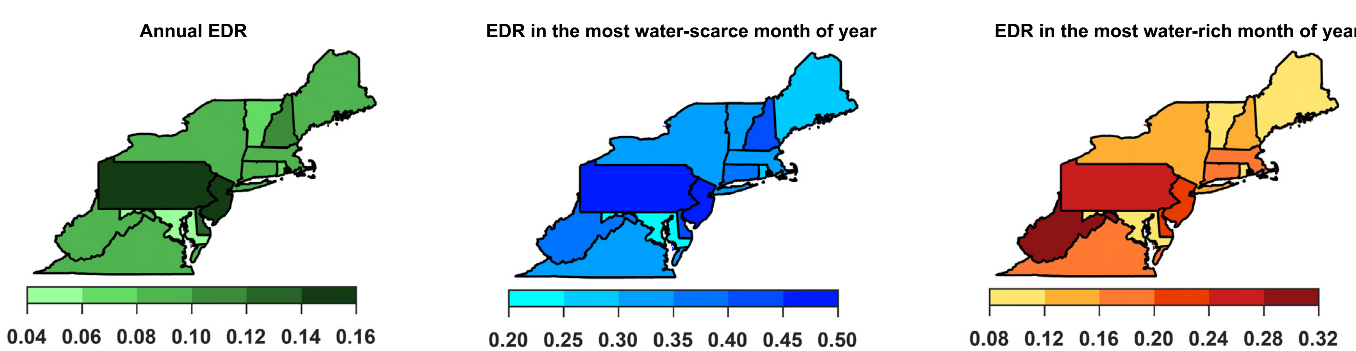

Fig. 4. Dams' contemporary Effective Degree of Regulation in the Northeast (average EDR for 1950–1999).

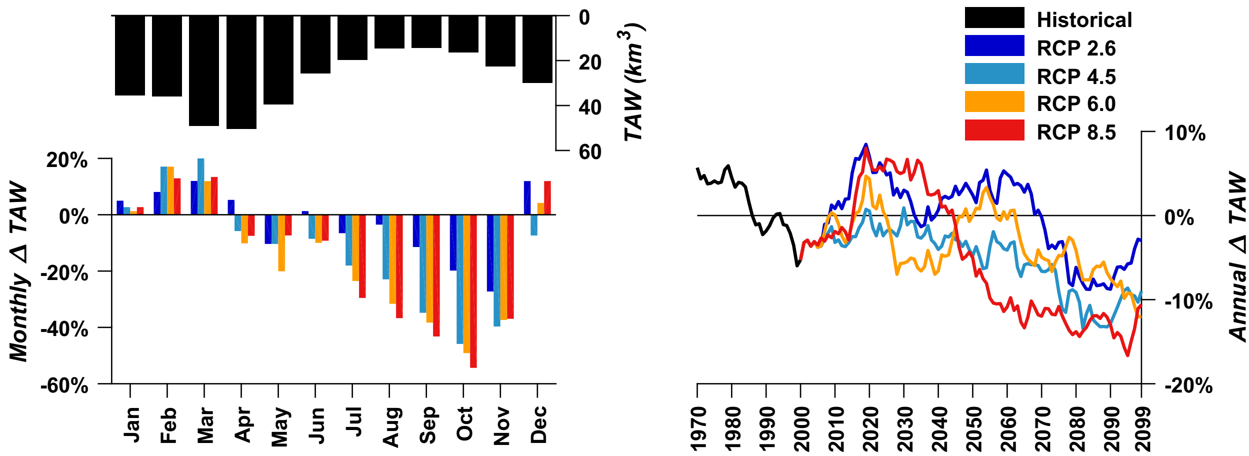

Fig. 5. Climate change effect on water availability in the Northeast. (Left) Monthly historical TAW (average of 1950–1999) and ΔTAW under climate change scenarios (average of 2080–2099). (Right) the 20-year moving average of annual ΔTAW.

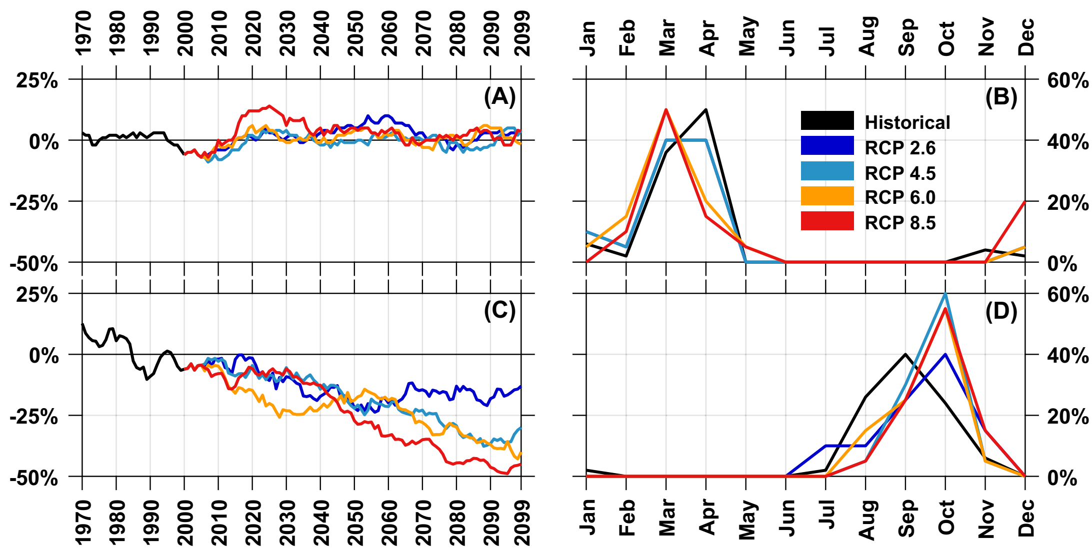

Fig. 6. On the left, 20-year moving average of ΔTAW in the Northeast for the most water-rich (A) and the most water-scarce (C) months of year. On the right, the relative frequency of occurrence of the maximum (B) and minimum (D) monthly water availability in each month. In graphs B and D, RCP values are based on 2080–2099 simulations, and historical values are calculated for the period of 1950–1999.

from spring toward winter. Fig. 5 shows the seasonal and annual trends of climate impact on water availability in the region. Despite increased precipitation across the region, annual water availability declines under all future climate scenarios mostly due to the increase in evapotranspiration. For the period of 2080–2099 and for the four RCPs used in this study, climate change may result in 3% to 12% decline in annual water availability throughout the region.

Increased precipitation (and also more rain instead of snow) in winters and earlier snowmelt in spring increases the aggregate regional TAW by up to 22% from December through March. In other months, reduced precipitation and increased potential evapotranspiration combine with reduced recharge (from the shift in spring snowmelt and smaller snowpack) to decrease water availability by up to 54%. These results imply that the existing dams and reservoirs in the region are incapable of storing the added water in the wet season to supplement lower flows in dry months.

At the state level, water availability is expected to increase considerably between December and March in Maine, New Hampshire and Vermont (Fig. S 5). Massachusetts, Connecticut, Rhode Island, and New York are also projected to experience an increase in water availability in those months, but to a lesser extent. For the Middle Atlantic States of New Jersey, Pennsylvania, and Delaware, the expected change in water availability is not significant. For the southern part of the region (Maryland, Virginia, and West Virginia) a decline in water availability is expected in those months. Water availability is projected to decrease everywhere across the Northeast in July, August, September, October, and November. The decline is projected to be larger in the most southerly states and late fall (Fig. S 5).

Fig. 6 shows the shift in timing and magnitude of available water in the most water-rich and water-scarce months of year caused by climate change. Available water supply in the most water-rich month of year (Fig. 6A) is not expected to change significantly (ΔTAW between −2% and +4%). Because more precipitation is projected to fall during the warmer winters, the peak occurrence of the maximum water availability (Fig. 6B) shifts to earlier dates (from April to March). The regional water availability in the most water-scarce month of year (Fig. 6C) is expected to decline (ΔTAW between −13% and −45%), and the peak time of occurrence of the most water-scarce month of year shifts from September to October (Fig. 6D). These results are consistent with observations of shifts in flow patterns in the past few decades caused by temperature and precipitation changes within the region (Hodgkins et al., 2003). Hodgkins et al. (2003) focused on rivers in New England with long-term data that drain unregulated basins with stable land use.

ΔTAW patterns at the state level (Fig. S 5) follow the general precipitation anomaly patterns. Water availability declines in July through November in all states. The combined effects of increased rainfall in winter and earlier snowmelt in the spring increases the available water supply in the northern states in December through March (More than 100% increase in February in Maine, New Hampshire, and Vermont (Fig. S 5)). On the other hand, the more southern states with small increases (or declines) in precipitation, are expected to have less water available in most months. For example, the available water resources in Virginia and West Virginia decrease in all months, up to 75% in October and November.

For the southern states (West Virginia, Virginia, Maryland & D.C. Delaware, and Pennsylvania) peak occurrence of the most water-rich month of year is in March, and climate change is not expected to impact this pattern significantly (Fig. S 6). In the northern part of the region where snow and ice have a more significant impact on hydrology (New York, Connecticut, Massachusetts, Vermont, New Hampshire, and Maine), under the two warmer scenarios (RCP6.0 and RCP8.5), peak time of occurrence of the most water-rich month of year shifts from April, to March and February (Fig. S 6).

Freezing temperatures and low precipitation rates (mostly as snow) under contemporary conditions make January one of the months with the lowest levels of water availability, especially in northern states like Maine, New Hampshire, Vermont, and New Jersey. Under future climate scenarios, winter precipitation and temperature are projected to increase (Fig. S 3), which means a larger portion of winter precipitation will be in the form of rain instead of snow. As a result, water availability in January will increase (Fig. S 5). On the other hand, September, October or November are projected to more often become the most water-scarce month of year. The most water-scarce month of year in southern states is expected to shift to one month later (Fig. S 7).

The seasonality shift accompanied by increasing winter streamflows requires maintaining flood control storage in high flow seasons even though the ability of dams to refill their reservoirs in spring is diminished. Decreasing summer inflows and expected increased water demand caused by population growth, warmer temperatures, and increased evapotranspiration rates would further aggravate the reduced reservoir refill capacity. These shifts will affect the ability of the system to meet human and environmental water demand as well as hydropower production targets and thermoelectric generation (Madani and Lund, 2010; Miara et al., 2013; Payne et al., 2004). Moreover, the need to release otherwise valuable winter-derived runoff to maintain flood control storage means that the vulnerability of the water resources systems to drought will increase which draws the attention to the water storage capacity of the region as a key limitation toward meeting the future demand of dense population centers (Stakhiv et al., 2016).

Simulation results are influenced by uncertainty in the data, model parameters, and model structure. The use of calibrated parameters provides a large degree of uncertainty in the ability of models to be climatically transferable (Leavesley, 1994). For the sake of consistency, we have used the same GCM climate forcings for both historical and future scenarios. As a result, we do not expect the streamflow simulations to match observations any better than downscaled GCMs matching day-to-day climate observations. Tuning the model parameters by calibrating the simulated flows that are based on the application of GCM forcings to observation data may lead to bias for climate impact projections (Tebaldi and Knutti, 2007; Xiong et al., 2016). Uncertainty from this calibration procedure may be comparable in size to emission scenarios uncertainties (Kay et al., 2009). On the other hand, calibration and validation of regional and global hydrological models usually only includes pristine streams and/or long-term average annual flows; simply because global and regional models are not able to accurately simulate daily and monthly stream flows of vast and diverse landscapes particularly where reservoirs exist. The main focus of this work is the regional impact of dams on seasonal variations of flow; exactly where most other hydrological studies avoid. Besides, access to reservoir operation data is highly restricted; especially for a macro-scale study like this with thousands of dams involved. We believe that for this study calibration of model outcomes to observed data would be unrealistic as it creates a fit only by mathematical manipulation of model parameters and results while ignoring fundamental differences between the model results and GCM climate data, and the real world observations (Kirchner, 2006). As a result, we opted to use the default model parameters (Wisser et al., 2010) and have not calibrated our model further for this study.

3.3. Changes in the flow regulation by existing dams

The change in EDR for existing dams is presented based on four future RCPs to project how climate change may affect the operation of dams (Fig. 7). For the period of 2080–2099 under RCP 2.6, the average annual EDR does not significantly change. However, the average annual EDR significantly increases for other RCPs. Under RCP4.5 and RCP6.0 average annual ΔEDR is +28% and for RCP8.5 it is +47%. The largest increase in EDR occurs in September and October (Fig. 7) when the largest relative decline in water availability is also expected (Fig. 5).

Under RCPs 4.5, 6.0, and 8.5 the annual EDR increases (positive ΔEDR) in all states except Maine and Rhode Island (Fig. S 8). Under RCP 2.6 some states have a small decrease in EDR (negative ΔEDR). ΔEDR is especially high in late summer and fall when natural streamflows are low, and may in fact, exceed +350% (i.e., October in New Hampshire and Vermont under RCP 8.5 (Fig. S 8)). As a result, environmental resources managers in water-dependent systems, in particular, have to increasingly rely on water provided by dams to stay under 'safe yield' limits in late summer and fall.

3.4. Role of dams in Mitigating the effects of climate change on the water resources

To assess the effectiveness of dams in creating climate change resiliency in the future, we simulated the climate change effects on water availability in the region under the three hypothetical dam scenarios presented earlier (Section 2.4). Fig. 8 shows the average ΔTAW and the CEA factor under RCP8.5 for scenarios DS-1, DS-2, and DS-3 for the period of 2080–2099. Results for the other RCPs show a similar pattern (Fig. S 9). Recall that if the alternate future dam construction scenario intensifies the climate change effect on the availability of water, CEA will be positive, but if it dampens the effect, CEA will be negative (see Section 2.4). If all existing dams in the region are removed (Fig. 8, DS-1), climate change effects on water availability will intensify (positive CEA) in most months and under all climate scenarios. Doubling the number of dams (Fig. 8, DS-2) moderately reduces the climate change effects (negative CEA) in most months. When 18 large dams are added to the existing dams in the region (Fig. 8, DS-3) climate change effects on water availability will significantly decline (negative CEA).

Solely as a result of climate change, water availability is expected to increase in February and March under RCP8.5 (Fig. 8, positive ΔTAW). For DS-1, average CEA of February and March is +0.49 (Fig. 8) indicating that increased streamflows under this scenario are exacerbated due to the lack of streamflow regulation if all

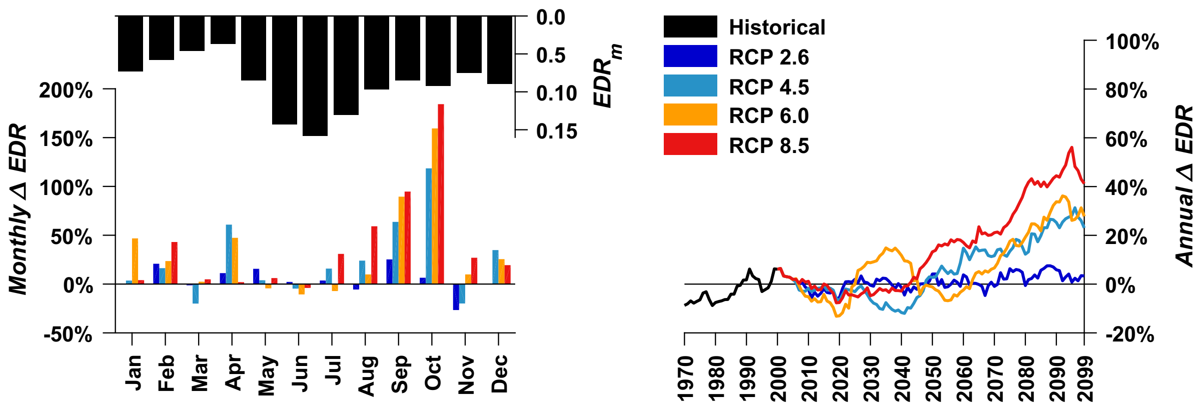

Fig. 7. (Left) The monthly Effective Degree of Regulation for the dams in the region (mean for 1950–1999) and its change under future climate scenarios (mean for 2080–2099). (Right) the 20-year moving average of the change in annual Effective Degree of Regulation for the dams in the region.

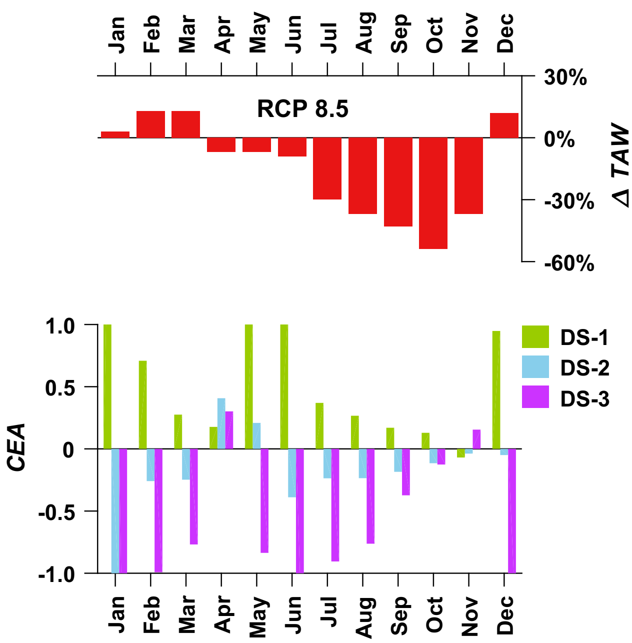

Fig. 8. The effectiveness of dams in reducing the climate change effects on water availability. The top panel shows the ΔTAW under RCP8.5. The lower panel shows the CEA factor for the three dam scenarios under RCP8.5. For illustrative purposes, we have limited the CEA values on the graph to −1 and +1. A CEA value equal to −1 means that the effect of climate change is completely mitigated. A CEA value equal to +1 means that the effect of climate change is doubled (intensified).

dams were removed. Under DS-2, the average CEA is −0.25 which shows dams in this scenario have moderately dampened the climate change impact on streamflows by storing a portion of the extra flow. Under DS-3, the average CEA is −0.88 which shows large dams in this scenario store most of the extra flow and are able to dampen the climate impact to a much larger extent. On the other hand, from July through November, climate change is expected to decrease water availability throughout the region (Fig. 8, negative ΔTAW). Under RCP8.5 for DS-1, average CEA for July through November is +0.17 (Fig. 8). As a result of the lack of streamflow regulation by dams, lower streamflows resulted from climate change cannot be compensated for by the release of water that could be otherwise collected during the wet months. Under DS-2, the average CEA is −0.16, which shows dams in this scenario were able to moderately dampen climate change impacts on streamflows by releasing the water they had stored in the wet months. Under DS-3, the average CEA in July through November is −0.40. The water that is released from the large dams in this scenario offsets most of the climate change impacts on water supply availability in summer months.

Figs. S 10 through S 13 show results for the three dam scenarios for individual states across the different RCPs. There will be a reduction in water availability in all states during summer and fall because of climate change (Fig. S 5). Removing the existing dams (DS-1) intensifies the decline in water availability in those months (positive CEA). Doubling the number of dams (DS-2) does not considerably dampen the climate change effects on available water resources. In the case of adding 18 large dams to the region (DS-3), these new large facilities can significantly reduce the negative impact of climate change on water availability, and in many instances, the adverse hydrologic effects of climate change will be reversed. In other words, small storage capacity reservoirs are not nearly as effective in regulating extreme hydrologic flow variability as large capacity reservoirs.

Dams are expected to remain an essential component of the water resources systems of the Northeast in the future. Building more dams in the region can provide some climate change resiliency. Most of the existing dams in the region are small. The contrast between results from scenarios DS-2 and DS-3 may be an indication that the size (and maybe location) of the existing dams in the region are not optimal to mitigate climate change effects on water resources. Larger dams located on major rivers have the ability to attenuate the potential effects of climate change on regional water availability.

4. Conclusion

We find that both the annual and seasonal changes projected under future scenarios will provide important challenges to water managers across the Northeast U.S. Despite increased precipitation across the region, annual water availability declines under all future climate scenarios mostly due to the increase in evapotranspiration. Seasonality adds an important dimension to these results. Warmer temperatures that result in a shorter freezing season, as well as earlier snowmelt and larger evapotranspiration rates, will combine with changes in precipitation patterns to increase water availability in winters and reduce the availability of water in warm and dry months in the Northeast United States. The timing of the most water-rich month of year in the region shifts to one month earlier while the most water-scarce month of year shifts to one month later. Results are confirmed by earlier assessments of the influence of global climate change on the key climate and hydrological indicators across the US Northeast using nine GCMs (Hayhoe et al., 2007). Using high-resolution Regional

Climate Models (RCMs) instead of downscaled GCMs can improve climate representation at this scale.

Changes in hydrograph and precipitation patterns in the region affect the design capacity and operating characteristics of dams compared to their current conditions. These changes will affect the ability of the system to meet human and environmental water demand as well as hydropower production targets and thermoelectric generation (Madani and Lund, 2010; Miara et al., 2013; Payne et al., 2004). Moreover, the need to release otherwise valuable winter-derived runoff to maintain flood control storage means that the vulnerability of the water resources systems to drought will increase. This draws the attention to the water storage capacity of the region as a key limitation toward meeting the future demand of dense population centers (Stakhiv et al., 2016). Our findings suggest that the necessity and importance of dams in providing water security will increase across the Northeast United States.

We base this assertion on our key findings. For example, our analysis of the Effective Degree of Regulation by dams (EDR) on water resources shows that there will be an expected increase in the impact of dams on downstream flows in the future, particularly in drier months of year. To compensate for the larger imbalance between water availability in wet versus dry months, dams need to retain a larger portion of the rivers' naturally available water in the wet season and release a larger portion of their storage in the dry season. This means that the differences between peak storage level in winter/spring and the minimum storage in summer/autumn will increase and water managers need to reconsider the trade-offs between having a flood and drought resilient system and meeting downstream water demands as they compete to utilize the same limited reservoir storage. Particularly in water-dependent systems, environmental resources managers, have to increasingly rely on water provided by dams to stay under 'safe yield' limits in late summer and fall.

Moving toward a holistic and integrated water supply/use management and reducing water demand by improving water use efficiency is essential for any drought preparedness planning under highly uncertain future climate change scenarios. However, this analysis suggests that conservation alone cannot satisfy the future storage capacity and system safe yield requirements that are needed to meet future water demands of rapidly growing metropolitan populations (Stakhiv, 2011). Insufficient storage capacity increases the vulnerabilities of water and hydroelectric systems to changes in hydrologic timing associated with climate change (Connell-Buck et al., 2011; Mimikou et al., 1991; Vicuna et al., 2008). The effectiveness of increasing storage capacity in the region by building new dams as an adaptation option to create a climate change resilient water supply system was investigated and shown to be viable, but the spatial and storage "architecture" of such infrastructure deployments are important. Our findings show that increasing the water storage capacity of the region by building more dams can ameliorate the impact of climate change on water resources in the region. Furthermore, results show that small storage capacity reservoirs are not nearly as effective in regulating extreme hydrologic flow variability as large capacity reservoirs

Macro-scale approaches toward water management and planning can yield more comprehensive and sustainable solutions with multiple beneficial outcomes for society and the environment (Vörösmarty et al., 2015). Any decisions about the construction of dams should be based on substantive feasibility and cost-benefit analyses aimed at maximizing benefits of dams and minimizing their drawbacks locally and regionally. The effectiveness of alternative options for increasing water storage capacity (i.e., aquifer recharge) should also be considered. Our work presents a framework for analyzing such strategies. Our findings here, based on purely physical effects, is that a single large dam may be more beneficial and effective (Fiering, 1982; Giuliani et al., 2016; Hashimoto et al., 1982; Poff and Hart, 2002) than many small ones. More than three-quarters (77%) of all dams and reservoirs in the Northeast US have a capacity smaller than 10^6 m^3. Many of those are aging and classified as high hazard potential dams (FEMA, 1998). The current trend for removal of hazardous and unpopular dams may impact regional surface and groundwater, food and energy production, migration, and urban growth (Ho et al., 2017). Provided that suitable dam building sites exist, replacing these aging smaller and less effective dams with new larger dams may be one way to lessen some of their undesirable impacts by reducing the level of river fragmentation (Ehsani et al., 2016; Grill et al., 2014), which has important impacts on aquatic biota (Dynesius and Nilsson, 1994), while improving climate resiliency (Gaupp et al., 2015). Dams will be more efficient in the northern parts of the region where water availability increases in some months. In the more southern areas of the region (e.g., Maryland, Virginia, and West Virginia), where water availability is expected to decline in all months, existing dams will become less efficient and less reliable. However, this suggests that more water storage facilities may be required in those states in the future to retain current levels of service and reliability.

This study indicates that the trade-offs between reservoir releases to maintain flood control storage and drought resilience, ecological flow, human (domestic, agricultural, and industrial) water demand, and energy production (both thermoelectric and hydroelectric) will increasingly need to be reconsidered in light of climate change, population growth, and water technology deployments. The projected increases in the frequency and intensity of floods and droughts combined with the reduced drought and flood storage buffering capacity of dams under a changing climate may have critical implications for the region's water supply and economy. Increasing the size and number of dams in addition to "dam reoperation" (i.e., modifying dam operations) (Watts et al., 2011) may be necessary to offset the climate change impacts on flooding and drought vulnerability even without considering the likely increase in future water demand (Ho et al., 2017), especially in the high population density regions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jhydrol.2017.09.008.

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