Impacts of Near-Term Climate Change and Population Growth on Within-Year Reservoir Systems

Harminder Singh[1]; Tushar Sinha[2]; and A. Sankarasubramanian, M.ASCE[3]

Abstract: Climate change and increased urban demand can significantly stress water supply systems, emphasizing the importance of reallocating reservoir storage for the designed uses. Most studies on climate change assessment have analyzed arid region reservoirs due to high interannual variability in streamflows. This study focuses on a within-year reservoir system, Lake Jordan in North Carolina, from a temperate region that has been experiencing rapid growth since the 1990s. Given the interest in utilizing climate change projections for planning purposes, the current operational policies are evaluated, and revised rules for operating the within-year system over 30 year period (2012–2041) are suggested. Downscaled general circulation model (GCM) projections are used to implement the soil and water assessment tool (SWAT) model for the Upper Cape Fear River basin to estimate changes in mean monthly streamflows during 2012–2041 at Lake Jordan. Projected monthly streamflows from four GCMs indicate wet winter conditions and increased interannual variability. The authors forced the reservoir model with multiple streamflow realizations that preserve the projected changes in monthly streamflow using a stochastic scheme. The within-year reservoir system performance was evaluated under stationary climate, climate change under existing and projected water demands, and by investigating interventions to ensure the design reliability under increased demands. These results indicate that the changes in the reliability due to increased urban demands are small because initial reservoir storage ensure the demand for multiple seasons. However, increases in the urban demand and streamflow variability tend to decrease the reservoir resiliency, forcing the within-year reservoir to behave like an over-year system. This could result in increased period of proactive measures such as restrictions and necessitates periodical reevaluation of drought management plans for better managing existing systems. **DOI: 10.1061/(ASCE)WR.1943-5452.0000474.** © *2014 American Society of Civil Engineers.*

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Introduction

Climate change and increase in water demands impact water infrastructure indicating the need for reallocating reservoir storage for the designed uses (Lettenmaier et al. 1999; Hanak and Lund 2012). Over the last three decades, several studies have analyzed the impact of climate change on United States water resources (Gleick 1987; Lettenmaier et al. 1999; Gleick and Chalecki 1999; McCabe and Wolock 1999; Sankarasubramanian et al. 2003; Sinha and Cherkauer 2010). Most of these studies primarily focus on the changes in the precipitation/streamflow under future climate change scenarios (Christensen et al. 2004, 2007). Very few studies have analyzed the impact of climate change and population growth on reservoir systems using climate change projections (Lettenmaier et al. 1999; Hanak and Lund 2012) and those studies have also predominantly focused on large reservoir systems in the western United States (Vicuna et al. 2010; Hanak and Lund 2012). Given that the western United States (except the Pacific Northwest) is a semi-arid region experiencing higher interannual variability in streamflows (Sankarasubramanian et al. 2002), most reservoirs, excluding those on the Sacramento–San Joaquin Rivers in California, are designed to be over-year systems that can hold multiple years of mean annual flows. Thus, many studies have focused on the reallocation of existing storage in the western United States under different climate change and population growth scenarios (Anderson et al. 2008; Brekke et al. 2009; Rajagopalan et al. 2009; Vicuna et al. 2010; Hanak and Lund 2012). Reallocation of storage typically involves developing a new set of rule curves by repartitioning existing storage within the systems for the intended uses, including flood control. The eastern United States, in contrast, is mostly temperate/humid (Sankarasubramanian et al. 2002) with relatively less variability in annual streamflows, thereby most reservoirs are within-year systems designed to refill allocated storage every year by the beginning of the spring season (Vogel and Bolognese 1995; Vogel et al. 1999). Further, the operational rule curves of these reservoirs are developed by assuming the stationary inflows (Milly et al. 2008). Given the smaller storage capacity of the systems in the East, any potential changes in streamflows under climate change are bound to significantly impact the reservoir management.

Apart from the potential changes in seasonal streamflows due to climate change, increased urban demand over the eastern United States has also been stressing the system operation with recurrent droughts that are partly demand-induced (Lyon et al. 2005; Golemebesky et al. 2009). For instance, despite abundant water resources in North Carolina (Moreau 2006), increase in water supply demand have made the local/regional water supply vulnerable to even moderate changes in inflow conditions (Weaver 2005; Golembesky et al. 2009). This increased demand along with changes in precipitation/streamflow (Boyles and Raman 2003;

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Hayhoe et al. 2007; Peterson et al. 2012 and references therein) in the eastern United States has substantially stressed the operation of reservoir systems over the past decade (Lyon et al. 2005; Weaver 2005; Golembesky et al. 2009; Schnoor 2012). Given that there is no/limited scope for building new reservoirs, existing within-year systems in the eastern United States need to be managed more efficiently to limit frequent shortfalls (drought) and surpluses (floods) under potential climate change and increased urban demand (Peterson et al. 2012). Thus, evaluation of future water demands may necessitate reallocation of storage as well as revisiting existing operational rule curves, since both are developed under the assumption of the stationary inflows.

The main intent of this paper is to analyze the impact of near-term (10–30 years) climate change and increase in urban demand on a within-year reservoir system. The primary limitation in extending such analyses to management options stems from the large uncertainty in the climate change projections, which predominantly arises from the prescribed CO_2 emission scenarios (Hawkins and Sutton 2009). Recently, Hawkins and Sutton (2009) showed that the total uncertainties resulting from climate scenarios, model and internal variability are minimal over the decadal (10–30 years) time scales when considering the entire future climate projections over the 21st century. At 10–30 year time scales, the general circulation models (GCM) exhibit similar changes in projected climate under different emission scenarios (i.e., low scenario uncertainty) while the primary source of uncertainty lies across models (i.e., high model uncertainty). Further, evidence is emerging that the climate system possesses useful predictability on 10–30 year time scales associated with the thermal inertia of the oceans, which can lead to *committed warming* (Meehl et al. 2009). Beyond the decadal time scales, anthropogenic increases in greenhouse forcing dominates (Smith et al. 2007; Keenlyside et al. 2008). Knutti and Sedlacek (2012) indicated that spatial patterns of changes in temperature and precipitation are remarkably similar under Climate Model Intercomparison Project (CMIP) 5 and CMIP3 models. Thus, the analyses presented in this study rely on near-term climate change projections from the CMIP3 models for assessing the performance of existing within-year storage systems in regions experiencing rapid development and urbanization. For this purpose, the authors consider a within-year reservoir system, Lake Jordan, in the Triangle area in North Carolina, which is experiencing frequent shortages in meeting the desired yields from the system due to rapid urbanization and changes in streamflow pattern.

This paper is organized as follows: First, details are provided on the recent droughts experienced by the within-year system as well as in the region followed by the methodology related to obtaining future inflows under near-term climate change. Then the projected inflows under near-term change are described with different scenarios of increased water demands for quantifying the impact on the Lake Jordan system. Finally, the salient findings are summarized from the study on impacts of near-term climate change on within-year storage systems that are experiencing rapid increase in demand due to urbanization.

North Carolina Triangle Area Water Management Challenges and Hydroclimate Data

The objective of this study is to evaluate the performance of a within-year reservoir system, Lake Jordan, in the Upper Cape Fear River Basin [Fig. 1(a)] in delivering the desired yields for water supply and water quality under near-term climate change and increased urban demand. The Triangle area (Wake, Chatham, and Orange Counties) in North Carolina has experienced three severe droughts/water shortages (1998–2002, 2005, and 2007) during the past 15 years due to continually increasing water supply demand, which increased up to 20–62% in different counties in North Carolina (Weaver 2005). Similar experiences of demand-induced water shortages have also been reported for other within-year storage systems, namely the Falls Lake, Kerr-Scott, and Catawba reservoirs, which serve water for rapidly growing counties in North Carolina (Golemebesky et al. 2009). By analyzing the performance of Lake Jordan in the Upper Cape Fear River basin, the authors intend to provide broader framework for improving the management of other within-year storage systems in the region under potential impacts due to climate change and urban water supply demand.

Study Area

The Upper Cape Fear River basin in the Triangle area is one of the rapidly growing areas in North Carolina, and the population in this basin is expected to grow by 10–20% over the next three decades (Moreau 2006). The Upper Cape Fear basin comprises of two subbasins: (1) Haw River with a drainage area of 3,264 km^2, and (2) Deep River which has a drainage area of 3,671 km^2. The region receives about 107 cm of average rainfall annually with uniform precipitation throughout the year resulting in significant runoff in all months. Typically, monthly air temperature ranges from −1°C in winter to 38°C in summer (North Carolina State Climate Office). Fig. 1(a) shows the location of the Lake Jordan reservoir in the Upper Cape Fear River basin, which is intended to serve water to the cities of Chapel Hill, Cary, and Apex in Chatham, Orange, and Wake Counties. The Lake Jordan reservoir is located downstream of the Haw River watershed about 40 km southwest of Raleigh, North Carolina. The reservoir is primarily used for supplying water to the Triangle area and for downstream water quality and flood protection. Downstream water quality releases ensure the protection of the Cape Fear River estuary and supply water to the cities of Fayetteville and Wilmington.

Streamflow and Observed Climate Data

Observed daily streamflow from two USGS stations, Haw River at Bynum (Station No. 02096960; 1973–to date) and Deep River at Moncure (Station No. 02102000; 1930–to date), were considered as natural inflows because these sites are included in the hydroclimatic data network (HCDN) database (Slack et al. 1993). This database includes stations that are minimally impacted by reservoir operations. These flows were used for the calibration of the soil and water assessment tool (SWAT) model. Net observed inflows at the Lake Jordan reservoir, which include evaporative losses, were obtained from the United States Army Corps of Engineers (USACE) over the 1991–2010 period. The historical climate data (precipitation and maximum and minimum air temperature), available at 1/8° (~14 by 12 km) from 1949 to 2010, were obtained from the national gridded climate data developed by Maurer et al. (2002). This historical time series was used for calibrating the SWAT model at Deep River at Moncure and Haw River at Bynum.

Near-Term Climate Change Projections

Near-term climate change projections were obtained from four different GCMs: (1) BCCR—Bjerknes Centre for Climate Research, version BCM2 0.1 (Déqué et al. 1994; Déqué and Piedelièvre 1995; Royer et al. 2002); (2) CCCMA—Canadian Centre for Climate Modeling and Analysis, version CGCM3 1.5 (Flato et al. 2000); (3) CNRM—Centre National de Recherches Météorologiques, version CM3.1 (Déqué et al. 1994; Déqué and Piedelièvre 1995;

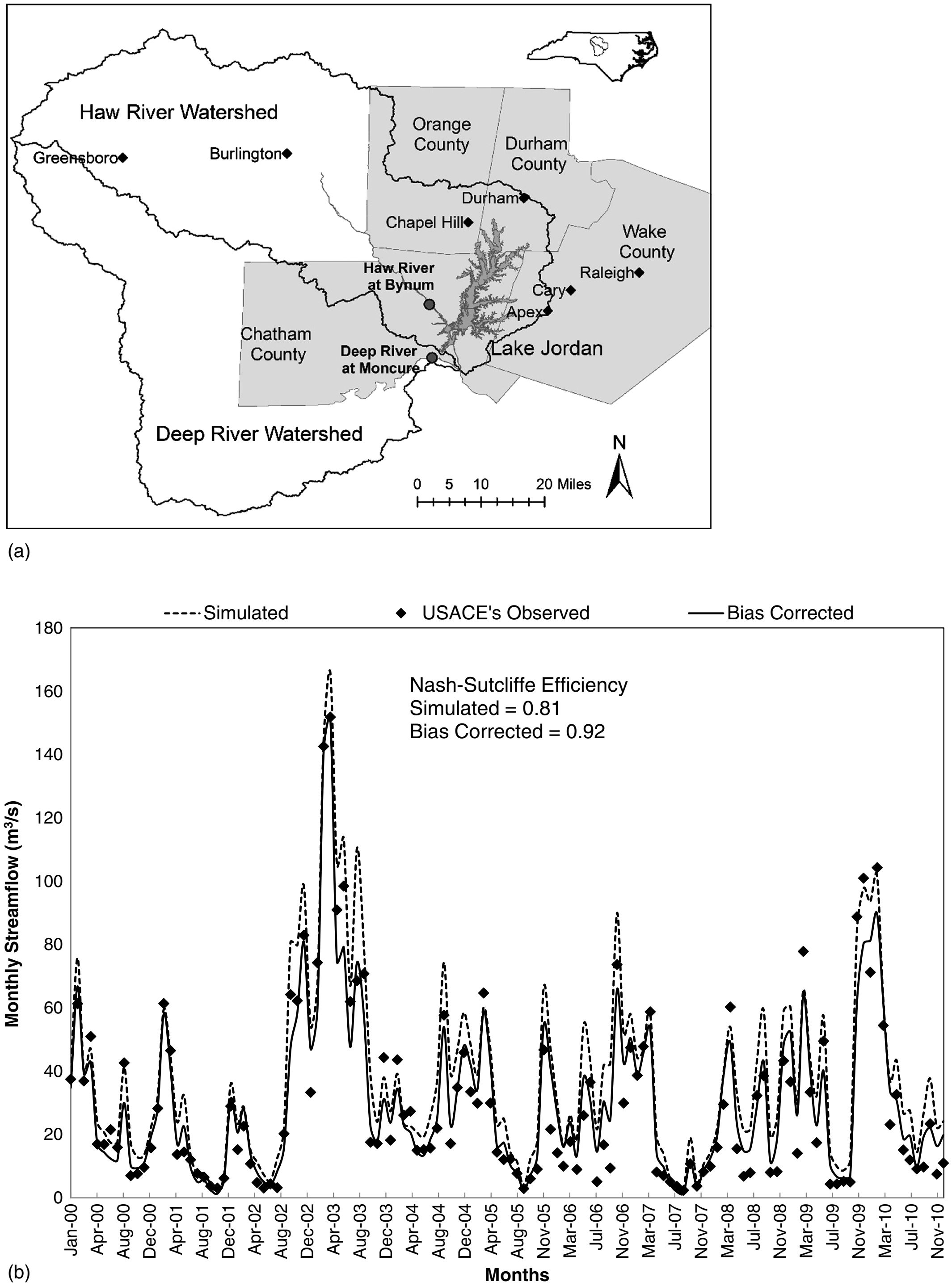


Fig. 1. (a) Location of Lake Jordan Reservoir in the Upper Cape Fear River basin. The shaded areas indicate the four counties that show tremendous population growth over the Triangle area; (b) monthly time series of U.S. Army Corps of Engineers (USACE) observed and soil and water assessment tool (SWAT) model simulated streamflow (original and bias corrected) at the Haw River near Bynum site over the validation period of 2000–2010

Royer et al. 2002); and (4) CSIRO—commonwealth scientific and industrial research organization, version CSIRO MK3 0.1 (Gordon et al. 2002).

These models were chosen based on their ability to capture realistic seasonal precipitation patterns over North Carolina during the 1981–2010 period (not shown) and different resolution in their ocean models (Randall et al. 2007). Downscaled climate change projections for these models over the period 2012–2041 were obtained from World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multimodel dataset (Maurer et al. 2007) under the A1B emission scenario (Nakicenovic et al. 2000 for scenario details). There are three emission scenarios in the CMIP3 projections that have similar levels of uncertainty over the next 10–30 years (Hawkins and Sutton 2009), but the A1B emission scenario was utilized in this study because it considers moderate growth. These downscaled gridded projections of precipitation, and maximum and minimum air temperature are available at 1/8° spatial resolution until 2099 for different scenarios of growth and were downscaled using the quantile mapping bias correction method (see details in Maurer et al. 2007).

Inflow Projections and Reservoir Analyses under Climate Change: Methodology

Fig. 2 provides the overall approach for obtaining changes in inflows and storage for the Lake Jordan reservoir under near-term climate change by using: (a) continuous semi-distributed SWAT model, (b) develop inflows, and (c) the Lake Jordan reservoir model. Because the monthly inflows obtained from the SWAT model by forcing near-term climate change projections provide only a single realization of monthly inflows for the period 2012–2041, a stochastic inflow generation model that utilizes the changes in the moments of the monthly flows for generating multiple traces of multiple inflows was also employed. Both of these modeling segments are described below.

SWAT Model Implementation

The soil and water assessment tool (SWAT) model (Arnold et al. 1998; Srinivasan et al. 1998) is a continuous watershed scale semi-distributed model where a watershed is subdivided into subbasins, with each subbasin comprising of unique combinations of land cover and soil termed as hydrologic response units (HRUs). The SWAT model has been widely implemented to study how climate and land use changes impact water resources at various spatial and temporal scales under different climatic regimes (Arnold et al. 1998; Stone et al. 2001; Zhang et al. 2007; Migliaccio and Chaubey 2008; EPA 2013). In order to run the SWAT model, daily climate data is required along with land cover and soil cover data for the region of interest. The soil data was obtained from the State Soil Geographic (STATSGO) database (Schwarz and Alexander 1995) and the land cover was obtained from 2001 National Land Cover Database (NLCD) (Homer et al. 2007). Because the focus of this study is to evaluate the impacts of near-term climate change and projected water demands on within-year reservoirs, the authors did not consider the effects of dynamic (or projected) land use changes on water supply. Further, several studies indicate that the sensitivity of streamflow to climate change is much higher than slight to moderate changes in land use (EPA 2013; Touma 2013). Touma et al. (2013) showed that under the EPA land-use change projections from 2011 to 2040 in the northeast Cape Fear basin, mean flows did not change significantly while only peak flows were impacted.

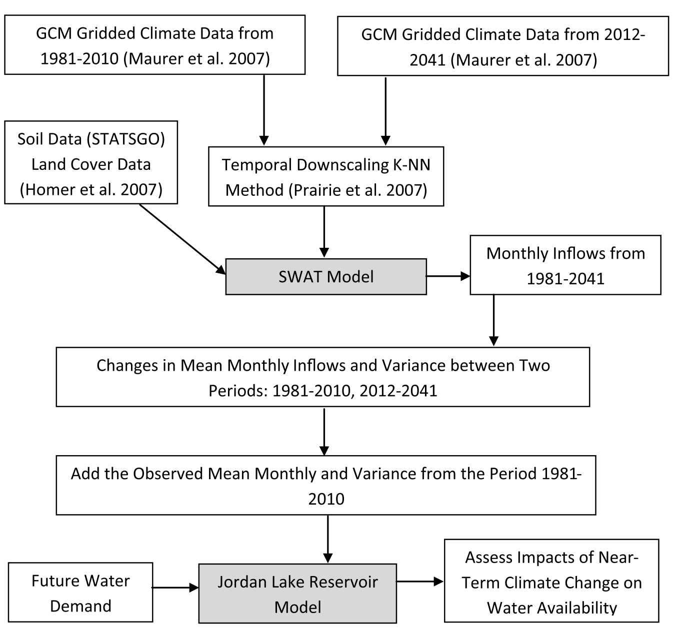


Fig. 2. Schematic diagram for evaluating the impacts of near-term climate change and increased water supply demand on the Lake Jordan reservoir

First, the SWAT model parameters were calibrated for the Deep River during 1981–1990 to monthly observed streamflow and then validated for the Haw River using observed gridded data of precipitation and air temperature (Maurer et al. 2002) [Fig. 1(b)] given that these two neighboring watersheds are similar in hydroclimatic conditions and projections of population growth (United States Census Bureau 2009). Both calibration and validation were performed by forcing the SWAT model with historical (observed) gridded climate data at the daily time scale. The Nash-Sutcliffe efficiency of SWAT model simulated monthly flows for the Haw River was 0.81 when implemented with observed forcings [Fig. 1(b)]. The calibrated SWAT model for Haw River was then forced with temporally disaggregated gridded climate data from the four GCMs to estimate streamflow from the observed period 1981–2010 as well as over the future period 2012–2041. The authors performed temporal disaggregation (Prairie et al. 2007) to convert the monthly precipitation and temperature time series to daily time scale for forcing the SWAT model (see details in Sinha and Sankarasubramanian 2013; Sinha et al. 2014).

Numerous studies focusing on estimating climate change impacts on water resources suggest that the only skills available in streamflow projections under GCMs are in capturing mean and variability over a 20–30 year time scale rather than capturing the temporal variability in observed streamflow (Gangopadhyay et al. 2005; Christensen et al. 2007; Vicuna et al. 2010; Hanak and Lund 2012). Thus, only changes in the mean monthly streamflows and the variance of monthly streamflows between the periods 1981–2010 and 2012–2041 were considered for analyzing the performance of a within-year reservoir under climate change (Brekke et al. 2009; Anderson et al. 2008; Vicuna et al. 2010).

Net-Inflow Generation Scheme for Reservoir Analyses

To analyze the performance of Lake Jordan under climate change, the SWAT model projected changes in both mean and standard deviations of monthly flows are combined with the respective observed net-inflows to obtain the projected changes in the distribution of monthly flows. By assuming the changes in the covariance structure primarily arise from the changes in the monthly net-inflows variance, multiple realizations are generated of monthly net-inflows based on multivariate normal distribution to analyze the performance of Lake Jordan under climate change and increased urban demand. Detailed steps on net-inflows generation scheme for each GCM are described below.

1. Obtain monthly mean, $\mu_i^{1981-2010}(\mu_i^{2012-2041})$, and standard deviation, $\sigma_i^{1981-2010}(\sigma_i^{2012-2041})$, of the SWAT model simulated inflows when ingested with each selected GCM climate forcings for the Haw River at Bynum over the observed (projected) time period 1981–2010 (2012–2041).
2. Obtain changes in mean monthly streamflow ($d\mu_i$) and changes in standard deviation of monthly streamflow ($d\sigma_i$) for each GCM over the two periods (1981–2010 minus 2012–2041), where

$$d\mu_i = \mu_i^{1981-2010} - \mu_i^{2012-2041} \quad (1)$$

$$d\sigma_i = \sigma_i^{1981-2010} - \sigma_i^{2012-2041} \quad (2)$$

3. Add, $d\mu_i$ and $d\sigma_i$, from Step 2 under each GCM to the USACE observed mean monthly net-inflows (μ_i^{ni-o}) and standard deviation (σ_i^{ni-o}) of monthly net-inflows at Lake Jordan, respectively, over the 1991–2010 period to obtain the projected mean monthly net-inflows (μ_i^{ni-pr}) and standard deviation of monthly net-inflows (σ_i^{ni-pr}) for the period 2012–2041

$$\mu_i^{ni-pr} = d\mu_i + \mu_i^{ni-o} \quad (3)$$

$$\sigma_i^{ni-pr} = d\sigma_i + \sigma_i^{ni-o} \quad (4)$$

4. Assuming the changes in the covariance structure of the projected net-inflows primarily arise from the changes in the standard deviation of monthly net-inflows, the covariance of the projected flows is estimated using Eq. (5), where Q_j^{ni-pr} and Q_k^{ni-pr} denote projected monthly net-inflows with ρ_{jk} denoting the correlation between the observed monthly net-inflows, Q_j^{ni-pr} and Q_k^{ni-pr}, for two different months j and k. For $j = k$, i.e., for the same month ρ_{jk} is 1, the covariance basically denotes the variance of the projected monthly net-inflows

$$\mathrm{Cov}(Q_j^{ni-pr}, Q_k^{ni-pr}) = \rho_{jk} \cdot \sigma_j^{ni-pr} \cdot \sigma_k^{ni-pr} \quad (5)$$

5. Given the projected mean monthly inflows, μ_i^{ni-pr}, and the covariance matrix, $\mathrm{Cov}(Q_j^{ni-pr}, Q_k^{ni-pr})$, multiple realizations of monthly net-inflows over the period 2012–2041 are generated by assuming the net-inflows follow multivariate normal distribution. The generated streamflow traces not only preserves the mean and variance of the monthly flows but also maintains the month-to-month correlation exhibited in the observed net-inflows. Based on this procedure, 50 realizations of the streamflow traces are generated using the three parameters—mean, variance, and covariance matrix—with each realization having 30-year length.

The primary advantage in using the stochastic generation scheme for obtaining the net-inflows is in developing multiple realizations based on the expected changes in mean and variance in monthly streamflows. The proposed generation scheme relies on the basic premise that multiple realizations of streamflow should be considered in reservoir design and developing operational policies (Vogel and Stedinger 1987). On the other hand, utilizing the monthly inflows obtained from the SWAT model provides only single realization of monthly inflows for the period 2012–2041. Since it is assumed that monthly net-inflows follow multivariate normal distribution, it even allows the small probability of negative flows that can happen in very dry summer months. These 50 realizations of 30 year monthly net-inflows were generated over the period 2012–2041 and fed to the Lake Jordan reservoir model to obtain statistically significant results.

Lake Jordan Reservoir Model

Net-inflows from the statistical flow generation scheme were used with the Lake Jordan reservoir model to assess the impacts of near-term climate change on water availability and reservoir reliability to meet future water demands. The reservoir model was originally developed by Sankarasubramanian et al. (2009) and is used to developing storage forecasts for major reservoirs in North Carolina. Fig. 3 provides pertinent details regarding the Lake Jordan system which are obtained based on the USACE guidelines of operating Lake Jordan. Most of the reservoirs in North Carolina explicitly partition the conservation storage for downstream water quality and for water supply. The fractions, f_{WS} and f_{WQ}, specify how the conservation storage are allocated for water supply and water quality purposes. Given the initial end of the month storage, S_{t-1}^{WQ} and S_{t-1}^{WS}, for water quality and water supply, respectively, and the generated net-inflows, Q_t^*, for month t under a given realization for a GCM, the end of the month storage, S_t^{WQ} and S_t^{WS}, for water quality and water storage were obtained by allocating the release, R_t^{WQ} and R_t^{WS}, for both uses. The previous month storage (S_{t-1}) is allocated by using fraction of 0.64 for water quality ($f_{WQ} = 0.64$) and 0.36 for water supply ($f_{WS} = 0.36$) based on the USACE guidelines. The inflows are also divided among the subsystems using the same factors as storage, while the downstream water quality releases and water supply releases are changed according the scenarios of growth and analyses. The normal operating level for Lake Jordan is 65.84 m (216 ft) above mean sea level (MSL). Storages between 61.57 m-MSL ($S_{\min}$) to 65.84 m-MSL and 65.84–73.15 m-MSL ($S_{\max}$) are considered to be the conservation and controlled flood storage, respectively (USACE). Thus, if the reservoir level is above 73.15 m-MSL, spill is estimated as per Eq. (10) while deficit is estimated using Eq. (11) if the reservoir level is below 61.57 m-MSL. The spill is added to the downstream water quality release to determine whether it would result in downstream flooding. Based on preliminary analysis of flood crest level

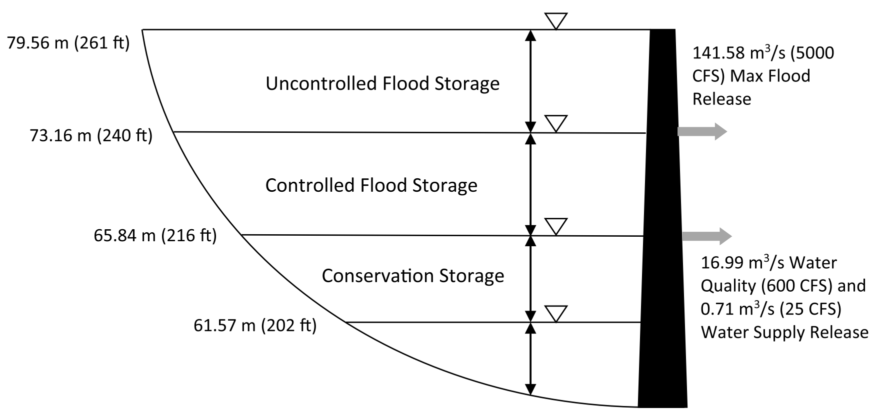


Fig. 3. Pertinent data relevant to Lake Jordan reservoir

at Fayetteville, which is an urban center downstream of Lake Jordan, a release of 141.58 m^3/s from the reservoir would result in significant flood damage downstream

$$S_{t-1} = S_{t-1}^{WQ} + S_{t-1}^{WS} \tag{6}$$

$$S_t^{WS} = S_{t-1}^{WS} + f_{WS}Q_t^* - R_t^{WS} \tag{7}$$

$$S_t^{WQ} = S_{t-1}^{WQ} + f_{WQ}Q_t^* - R_t^{WQ} \tag{8}$$

$$S_t = S_t^{WQ} + S_t^{WS} \tag{9}$$

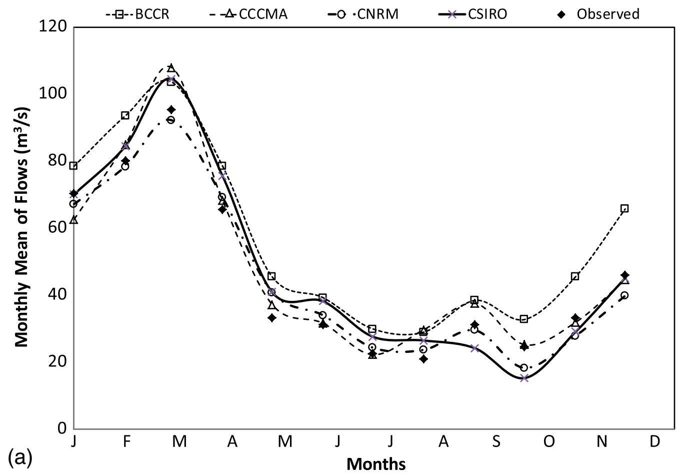
$$SP_t = \max(0, S_t - S_{\max}) \tag{10}$$

$$D_t = \min(0, S_{\min} - S_t) \tag{11}$$

The above model was run for 50 realizations of monthly net-inflows for the period 2012–2041 for each GCM under different scenarios of water supply demand. The net-inflows were used to implement the reservoir model which also accounts for evaporation losses from the reservoirs. The deficit (D_t), excess release above the desired water quality releases (16.99 m^3/s) and flood release above 141.58 m^3/s was noted for each month and their corresponding probabilities were calculated by simply dividing the total number of occurrences by the total months (360) in a realization. The averages of those probabilities were reported under each GCM. The averages and standard deviations of calculated deficit, excess release (above 16.99 m^3/s) and flood release (> 141.58 m^3/s) were also calculated over 50 realizations for a given GCM under different scenarios of water supply demand.

Impact of Near-Term Climate Change on Monthly Streamflow into Lake Jordan

To understand the impacts of near-term climate change, the authors analyzed the changes in the mean and standard deviation of monthly streamflow under each GCM over the two 30 year periods 1981–2010 and 2012–2041 (Fig. 4). These changes in climate signals, i.e., mean and standard deviation of monthly simulated streamflow from the four GCMs during 2012–2041 were added to the mean and standard deviations of USACE's observed monthly net-inflows during 1991–2010, respectively, using Eqs. (3) and (4). Most of the GCMs indicate wetter winter (January–March) and spring (April–June) months with increased mean monthly flows [Fig. 4(a)]. However, during summer and fall, the projected changes in mean monthly streamflows by all four GCMs are just around the observed mean monthly streamflows indicating no clear trend. The potential increase in winter and spring months could result in significant downstream releases above 16.99 m^3/s. The interannual variability of monthly net-inflows is also projected to decrease during the winter months and increase during the spring months [Fig. 4(b)]. This indicates that limited variability is expected with the expected changes in wetter winter conditions under near-term climate change. During spring months, the increased variability in monthly flows would potentially offer more challenges for managing the water supply during the summer months due to increased uncertainty in the initial storage conditions for summer. Based on Fig. 4(b), the authors do not infer any significant changes in the standard deviation of monthly net-inflows during summer and winter months. Thus, the projected net-inflows indicate increased and frequent wetter conditions during the winter, whereas the spring flows indicate increased wetter conditions along



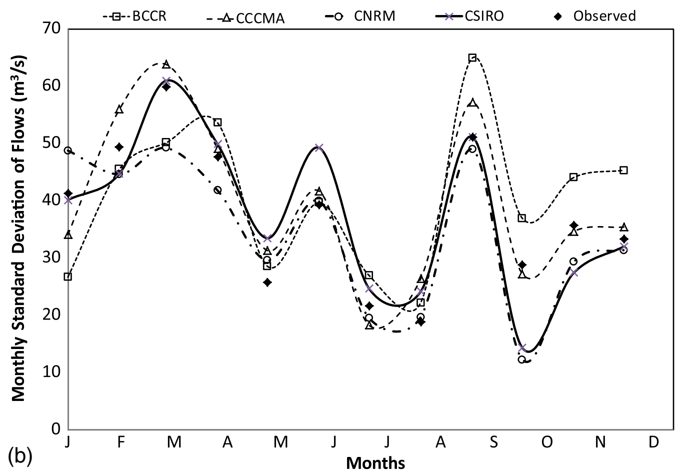


Fig. 4. Projected changes in mean monthly streamflow and standard deviation of monthly streamflows between the period 2012–2041 and 1981–2010 based on four different GCMs in (a) mean; (b) standard deviation of streamflow

with pronounced variability in net-inflows. These two projected changes could significantly impact the operation of the reservoir because the within-year system is expected to refill by April 1 to meet the summer demand. Under current operational management, the required release is set to 17.70 m^3/s including 16.99 m^3/s for water quality and 0.70 m^3/s for water supply. Comparing the average monthly releases above 17.70 m^3/s over the period 1991–2010 during the observed period with the projected average monthly releases in m^3/s from GCMs (Table 1: Row 7), it can be inferred that models with increased net-inflows release more volume (and with higher likelihood of being above 17.70 m^3/s) to ensure the current operational pool level of 65.84 m-MSL. The next sections evaluate the performance of the Lake Jordan reservoir system under different scenarios of increased demand under near-term climate change projections.

Results and Analysis

This section focuses on the management of Lake Jordan based on the projected changes in net-inflows arising from near-term climate change by (1) quantifying the uncertainty in meeting the current allocation/demand for the intended uses (water supply, water quality, and flood control); (2) analyzing the impact of increased water supply demand on delivering the desired reliabilities on

Table 1. Baseline Flood/Surplus and Drought Risks for Lake Jordan Based on USACE's Observed Net-Inflows during 1991–2010 and Inflows Generated Based on the Projected Precipitation from Different GCMs during 2012–2041 in Meeting Water Quality and Water Supply Demands; Probability of Flood Risk Is Assessed Based on Monthly Releases above 141.58 m^3/s

Streamflow attributes	Observed	Stochastic generation model			
		BCCR	CCCMA	CNRM	CSIRO
Mean annual flow (m^3/s)	46.24	56.69	48.65	45.45	48.44
Coefficient of variation in annual flow	0.36	0.37	0.39	0.61	0.46
Months with release >17.70 m^3/s	0.658	0.745	0.669	0.648	0.648
Months with release <17.70 m^3/s	0.02	0.008	0.017	0.015	0.015
Months with no release	0.005	0.002	0.005	0.003	0.004
Months with release >141.58 m^3/s	0.047	0.063	0.063	0.035	0.06
Average monthly release >17.70 m^3/s	65.81	72.63	68.10	63.63	69.09
Average monthly release <17.70 m^3/s	7.48	8.33	8.35	9.26	9.23
Average monthly release >141.58 m^3/s	35.31	37.49	47.26	33.75	42.73

Note: Water quality and water supply demands are 16.99 m^3/s, 600 CFS and 0.71 m^3/s, 25 CFS, respectively; monthly releases above 141.58 m^3/s = 5,000 CFS.

the intended uses based on the current rule curves; and (3) identifying the revised operational policies for ensuring current reliabilities on the intended uses even under increased water supply demand. This respectively results in three scenarios: (1) climate change impact alone with no increase in demand, (2) climate change impacts under increased demand with no reallocation strategies, and (3) climate change impacts under increased demand by considering reallocation. To address the first scenario, the authors first implemented the SWAT model under near-term climate change projections from four different GCMs (Maurer et al. 2007) and stochastically generated net-inflows over the 2012–2041 period. These net-inflows were then input into the Lake Jordan reservoir model under current reservoir operation policy with no anticipated increase in water demand. Under Scenario 2, the performance of current operational policies was analyzed with increased water supply demand with the same stochastically generated net-inflows. Finally, under Scenario 3, the analyses focused on identifying revised allocation strategies that ensure current risk-levels for flood control, water supply delivery, and water quality protection under near-term climate change and increased water supply demand.

Before the analyses on the impact of near-term climate change on Lake Jordan are presented, a baseline estimate of current flood/surplus and drought risks for the period 1991–2010 is provided. For this purpose, the Lake Jordan reservoir model is implemented by forcing the reservoir model by the observed monthly net-inflows from 1991 to 2010. The drought and flood risks are evaluated by considering whether the model suggested releases satisfy the required releases. The first attribute of drought risk is the number of months in which the monthly release is less than the required release (17.70 m^3/s), which is the sum of water supply and water quality releases. The second attribute is the number of months in which the monthly release is zero, which indicates a severe drought condition. For surplus release risk, first the number of months in which the monthly release is greater than the required release (17.70 m^3/s) is estimated, which indicates additional release to adhere to the operational rule curve of 65.84 m-MSL. Following that, extreme flood risk is quantified based on the number of months the monthly release exceeds the allowed flood release of 141.58 m^3/s. Both the flood/surplus and drought risk attributes for the baseline period as well as under the near-term climate change period for each GCM are expressed as a probabilities based on the total number of event occurrences to the total months over the analyses period (240 months). Apart from the probabilities, the average and standard deviation of monthly releases are also quantified if the adjusted releases in a given month are above/below 16.99 m^3/s. Similar information is also provided if the monthly releases are above 141.58 m^3/s.

Baseline Flood and Drought Risks

Table 1 provides the baseline estimates of current flood/surplus and drought risks under existing operational policies. Based on this, the probability of meeting required releases of 17.70 m^3/s is about 66% while the probability of flood releases, i.e., releases greater than 141.58 m^3/s, is 4.7%. These two attributes quantify the current flood/surplus risk at Lake Jordan. Looking at the drought risks, the probability when model release is less than the required release of 17.70 m^3/s is 2% while there is only 0.5% probability when monthly releases are zero. Although the drought risk seems to be small under existing demand, it could change significantly under near-term climate change in meeting the existing demand. This scenario is evaluated next.

Flood/Surplus and Drought Risks under Near-Term Climate Change (Scenario 1)

Under this scenario, the performance of Lake Jordan is evaluated based on the projected net-inflows from each GCM over the period 2012–2041 in meeting the existing demand to understand the impact of climate change alone without modifying existing operational rules. For comparison, the authors also forced the reservoir model with the net-inflows being generated based on the USACE's observed mean monthly streamflow statistics over the period 1991–2010. For GCM, the net-inflows were obtained from the statistical scheme that utilizes projected monthly mean and monthly covariance structure of net-inflows. Table 1 shows changes in the flood and drought risks under USACE's observed net-inflows (1991–2010) and for each GCM under near-term climate change (2012–2041) in delivering the current demand. Based on the projected monthly net-inflows, there is no consistent trend by the four GCMs in changes in the probability when monthly releases > 17.70 m^3/s. It can be inferred from Table 1 that all four GCMs indicate reduction in the probability of failure to meet the target release of 17.70 m^3/s. This could be due to the potential increase in mean annual inflows, which occurs primarily due to increase in mean monthly flows during winter and spring (Fig. 4) resulting in lesser number of months experiencing shortfall in meeting the demand. There does not seem to be any appreciable difference in the probabilities of months with zero releases obtained based on the observed flows and GCM-projected net-inflows. However, there is a clear increase in the average monthly releases greater than

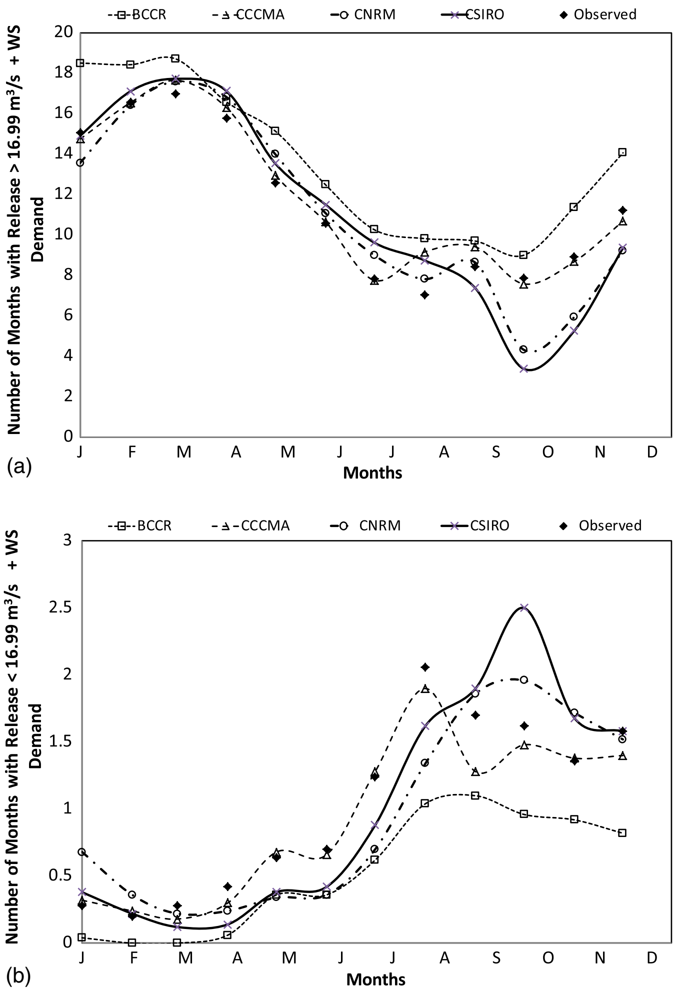


Fig. 5. Number of months with water supply and water quality releases: (a) greater than the target releases; (b) lesser than the target releases, which are 16.99 m^3/s for water quality releases and 0.71 m^3/s for water supply releases for the current operational rule curve of 65.84 m level

17.70 m^3/s as well as lesser than 17.70 m^3/s. On the flood risk, it can be inferred that that three models except the CNRM model indicate increased flood risk with more months having greater than 141.58 m^3/s. This is consistent with the increase in the average releases above 141.58 m^3/s by the above three models.

To understand which months/seasons experience pronounced changes with releases greater (lesser) than 17.70 m^3/s, the seasonality of release patterns is shown in Figs. 5(a and b). It is clear that the winter and spring months experience a more pronounced increase in releases > 17.70 m^3/s [Fig. 5(a)], whereas releases lesser than 17.70 m^3/s are experienced more in the spring and summer months (April–August). The surplus releases (release > 17.70 m^3/s) are also more pronounced in the winter and spring months. Thus, the overall increase in net-inflows seems to increase flood risk and more variability in allocation.

Flood and Drought Risks with Increased Water Demand (Scenario 2)

Given that the water supply demand in the Triangle (Raleigh-Durham-Chapel Hill) area have grown up by 20–60% during 1995–2000 (Weaver 2005), a moderate 30% increase in water supply demand was assumed for every five years for the Triangle area as well as for the downstream cities (Fayetteville and Wilmington) over the period 2000–2041. This implies that the water supply demand of 0.71 m^3/s in 2,000 could increase up to 5.80 m^3/s by 2,041 over the eight, five-year periods. The other reason to consider such a high potential demand scenario is due to opportunities for interbasin transfer (Characklis et al. 2006; Li et al. 2011). Lake Jordan has more water supply storage space compared to the Falls Lake (in the Neuse River basin) that supply water to the city of Raleigh. Thus, any potential increase in water demand across the Triangle area needs to be met by Lake Jordan, since the Falls Lake is already stressed in delivering the water supply demand for its municipalities (Li et al. 2011). Hence, several studies have focused on interbasin transfer between these two lakes so that the potential increase in demand over the entire Triangle area could be met with high reliability (Characklis et al. 2006; Palmer and Characklis 2009; Li 2011). Thus, a sustained 30% increase for every five years could be considered as an upper bound on the potential increase in water demand that could be supplied by Lake Jordan over the next 30-year planning period. This potential increase in water supply release also needs to be met along with the required downstream water quality protection release of 16.99 m^3/s. The reservoir model is evaluated with the generated net-inflows using the observed monthly statistics over the period 1991–2010 and using the projected monthly statistics over the period 2012–2041.

Figs. 6(a and b) shows the probability of surplus releases (probability of flood release > 141.58 m^3/s) as a function of different target releases. With increased water supply demands, the probability of surplus releases [Fig. 6(a)] decreases under all GCMs. This is natural to expect because increased demand will stress the conservation storage more resulting in decreased surplus releases. This decline is present across all GCMs with a decrease of about 8.3% (20 out of 240 months) in which the model-suggested releases exceed the required release. BCCR is the only GCM that stand out from the other models due to its relatively wetter projections of near-term climate change. In contrast, there is no significant decline in the months with release at the maximum flood level [Fig. 6(b)].

As expected, the drought risk on both attributes—the probability of deficit in meeting the target releases [Fig. 7(a)] and the probability of zero release under increased water supply demand [Fig. 7(b)]—increases as the water supply demand increases under each GCM. Also provided for comparison are the estimated drought risk under current inflow conditions, which do not consider projected climate change. Because that the net-inflows are expected to increase under climate change, for a given water supply demand, the drought risk estimated by the net-inflows decrease in comparison to the drought risk for the current inflow conditions. Most of the shortfalls typically occur in the summer and fall months, because the projected net-inflows are lower during those months. The change in the seasonality in shortfalls remains the same between the observed and the projected inflows. In the next section, the authors evaluate whether the increased drought risk under potential increase in urban demand can be offset by altering operational strategies utilizing the projected inflows based on near-term climate change projections.

Intervention: Reallocation of Existing Storages (Scenario 3)

The current practice is to keep the conservation storage, which comprises allocations for water quality and water supply, at an operating level of 65.84 m-MSL. One way of reducing the drought risk is to increase the conservation storage in the reservoir so that

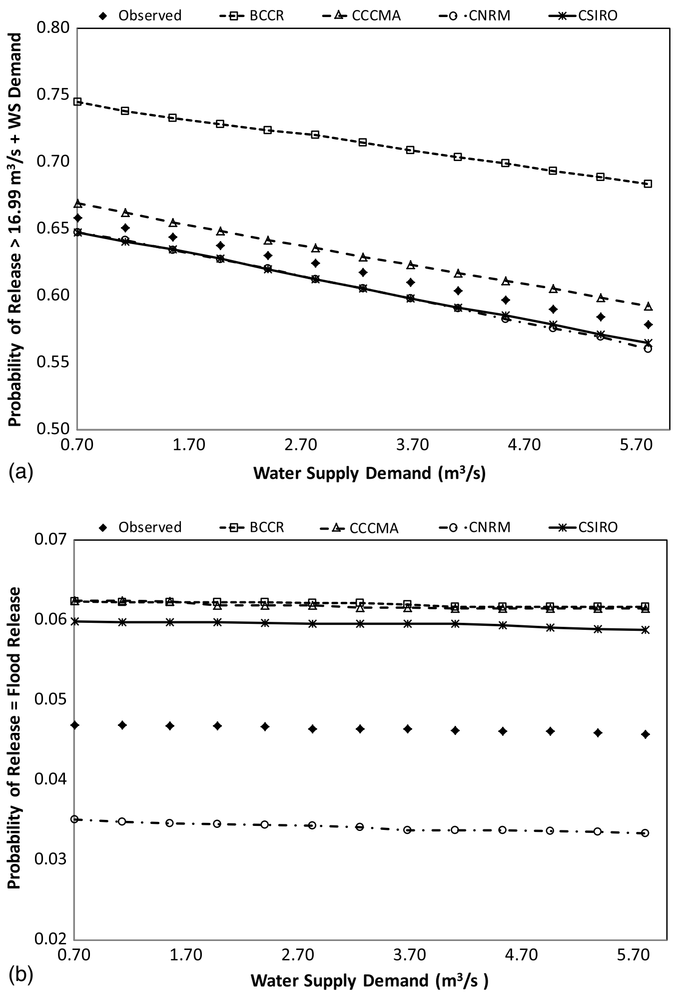


Fig. 6. Impacts on flood/surplus risk under near-term climate change and increased water supply demand for the existing operating rules with (a) probability of exceeding the projected required water supply release and target water quality release; (b) probability of occurrence of maximum allowed flood release

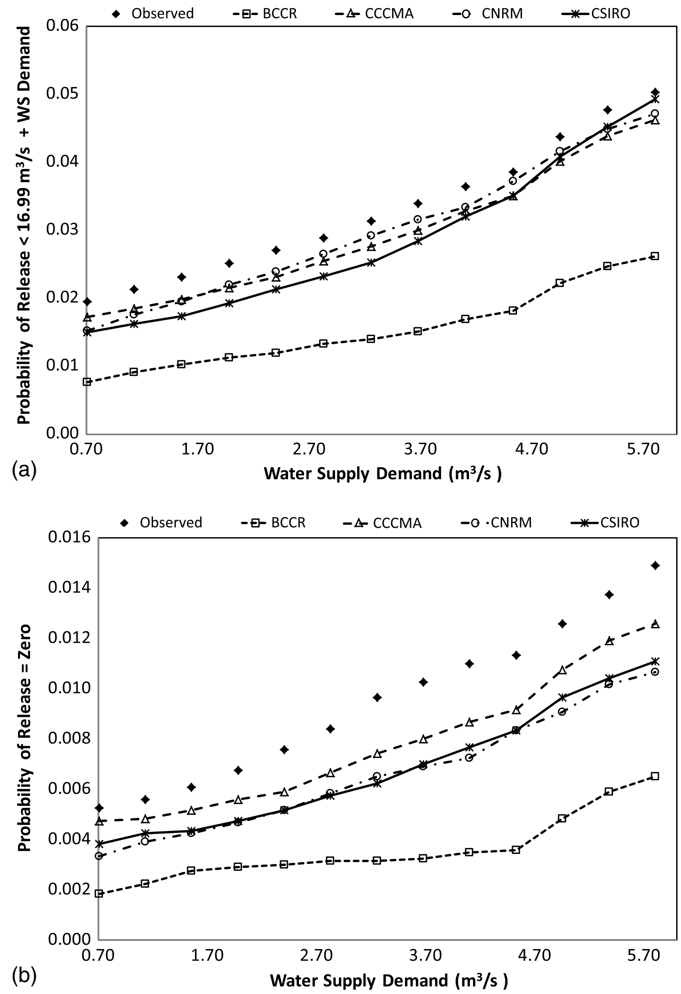


Fig. 7. Impacts on drought risk under near-term climate change and increased water supply demand for the existing operating rules with (a) failure probability in meeting the projected required water supply release and the target water quality release; (b) probability of occurrence of no releases for both water supply and water quality uses

the resulting risk remains the same as that of current risk for the desired yield of 17.70 m^3/s. However, this increased water supply allocation should not result in any increased downstream extreme flood risk (i.e., probability of release = 141.58 m^3/s). Similarly, increasing the water supply allocation alone is bound to increase the probability of shortfalls on water quality releases (16.99 m^3/s) for a given set of net-inflows if the operating rule curve is fixed. Hence, it can be ensured that both the probability of extreme flood risk (141.58 m^3/s) and the probability of shortfalls on water supply and water quality releases (16.99 m^3/s) remain as that of current risk reported in Table 1 for a given set of inflows. Because changing the rule curve from 65.84 to 67.06 m-MSL did not change the probability of no release under observed flows as well as under GCM projected net-inflows, that criterion was dropped from the analyses. Further, the probability of surplus releases beyond water supply and water quality releases is naturally expected to go down by increasing the operational rule curve, because the reservoir can hold additional water as conservation storage. Hence, that metric is also not considered here. The goal here is to find increased water supply releases (Table 2) that is permissible under various operating levels such that the extreme flood risk and the probability of shortfalls on increased water supply and water quality releases remain as that of current risk (Table 1) for a given set of net-inflows.

Table 2 provides the permissible water supply releases under different operating levels (ranging from 65.84 to 67.06 m-MSL) for both observed net-inflows (i.e., no climate change impacts) as well as under GCM-projected net-inflows for the period 2012–2041. Under the observed inflow pattern, which assumes no climate change impacts, the existing operating rule curve at 65.84 m-MSL has to be increased for potential water supply allocation due to

Table 2. Increased Water Supply Releases under Different Operating Levels for Observed Flows and GCM-Projected Net-Inflows over the Planning Period 2012–2041

Elevation [m (ft)]	Observed (m^3/s)	BCCR (m^3/s)	CCCMA (m^3/s)	CNRM (m^3/s)	CSIRO (m^3/s)
65.84 (216)	0.71	4.67	1.56	1.56	2.12
66.14 (217)	1.98	5.80	2.83	2.41	3.26
66.45 (218)	3.26	5.80	3.68	3.68	4.25
66.75 (219)	4.53	5.80	4.67	4.96	5.38
67.06 (220)	5.38	5.80	5.80	5.80	5.80

J. Water Resour. Plann. Manage.

future increase in urban demand particularly to ensure that the probability of shortfalls on water supply and water quality releases remain at the current risk level (0.020) in Table 1. Information in Table 2 could also be employed for adaptive planning depending on the potential increase in urban demand in the area. Thus, as the population grows in the Triangle area, water managers could potentially utilize a change in the rule curve that ensures the current level of probability of shortfalls and flood risk. Based on this, it is inferred that by increasing the rule curve to 67.06 m-MSL, a total of 5.38 m^3/s could be allocated to water supply release for ensuring current flood and drought risks.

By considering climate change impacts, the GCM-projected net-inflows suggest additional allocations since the net-inflows are in general expected to increase. The maximum allocation that would be required for water supply release has been capped at 5.80 m^3/s due to increase in urban demand. With the exception of GCM BCCR, which shows increased net-inflows (Fig. 5), the rest of the GCMs show consistent allocation pattern for water supply release under different operational rule curves. By increasing the rule curve to 67.06 m above MSL, an increased allocation up to 5.80 m^3/s could be accommodated for water supply releases without increasing the downstream extreme flood risk and the probability of shortfalls on water supply and water quality releases. Given the overall increases in net-inflows, GCMs suggest increased allocation for water supply releases as opposed to the allocation suggested by the stationary net-inflows assumption (i.e., observed inflows). Results in Table 2 could also be employed adaptively as the water supply demand continues to increase during the considered planning horizon 2012–2041. Such adaptive planning considerably reduces the uncertainty in demand that could arise due to future development and urbanization in the region.

Discussion

One allied goal of this paper is to offer additional insights on the behavior of within-year reservoir system under near-term climate change. Within-year (over-year) reservoir systems are more common in the humid (arid) eastern (western) United States due to the smaller (larger) interannual variability in streamflows. For this purpose, the resilience index, m, of a reservoir system is considered (Vogel and Stedinger 1987; Vogel and Bolognese 1995)

$$m = (1 - \alpha)/Cv \qquad (12)$$

where α denotes the total yield/release from the reservoir as a fraction of the mean annual inflow into the reservoir and Cv is the coefficient of variation of annual inflows (Table 1). For over-year systems, m ranges from 0 to 1, whereas for within-year systems, m is greater than 1 (Vogel and Bolognese 1995). Resilience index, m, indicates that over-year (within-year) systems requires more (less) time to recover from failure due to higher (lower) interannual variability in flows. The value of m was computed for both observed inflows and for the four GCM-projected inflows (Table 1) for a water quality release of 16.99 m^3/s and for 13 different values of water supply releases from 0.71 to 5.80 m^3/s with an increment of 30% every 5 year. The total yield from the system for calculating m is considered as the sum of the water quality release and the desired water supply release between 0.71 and 5.80 m^3/s. Thus, using the mean annual inflows for both observed and GCM-projected inflows (Table 1), 13 different values of m were computed for a given inflow scenario. For each of the 13 different yields, the failure probability of total yield [i.e., probability of total yield < (16.99 m^3/s + water supply release in m^3/s)] was also obtained for each set of inflow scenario (Fig. 8).

Fig. 8 shows the failure probability of releases as a function of system resilience for both observed inflows and GCM-projected inflows under two different operating levels of 65.84 m [Fig. 8(a)] and 67.06 m above MSL [Fig. 8(b)]. For a given set of inflows, as the water supply demand increases from 0.71 to 5.80 m^3/s, the failure probability increases. However, with the exception of BCCR model, the failure probability obtained based on observed inflows and the rest of the three GCM-projected inflows do not differ much over the increased demand of $0.71 - 5.80$ m^3/s. Because BCCR estimates high mean annual inflows, its failure probability is much lower than the rest of the flow scenarios. Perhaps the most important information from Fig. 8 is the variability in the system resilience (m), which arises due to the difference in CV of annual flows. Each value of m corresponds to the total yield (water quality release + increased water supply release) from the system for a given coefficient of variation of flow estimated by the inflow scenario. Thus, resilience is a function of both inflow characteristics as well as the total yield expected from the system. Even though the failure probability of yield remains the same between the observed inflows (i.e., no climate change impacts) and the GCM-projected inflows, the impact of climate change is more on reservoir resilience. The relatively smaller change in the failure probability across

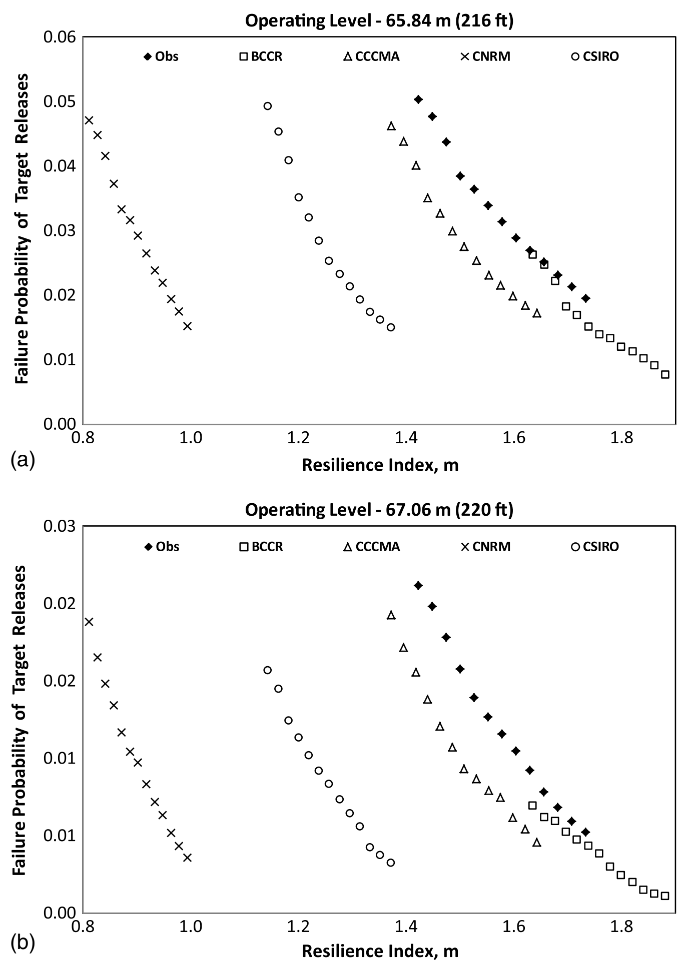


Fig. 8. Relationship between failure probability of target releases (water supply and water quality) and reservoir resilience under climate change and urbanization under operating rule–curve: (a) 65.84 m; (b) 67.06 m

the inflows is due to the ability to supply water purely from the initial storage. This is consistent with the findings of Lettenmaier et al. (1999) over few selected reservoirs in the eastern United States, but the primary impact of climate change is on reducing the resiliency of within-year reservoir systems, which forces the system behavior to be a more over-year system.

Thus, reservoir systems will take more time to recover as both the coefficient of variation of projected inflows and the fractional yield, α, increase. The observed coefficient of variation (CV) of annual streamflows ranges between 0.2 and 0.4 for the eastern United States with smaller CV being observed over the northeast and higher CV being observed in the temperate southeast (Vogel et al. 1998). Recent studies on the impact of climate change on the eastern United States has suggested increase in the coefficient of variation of runoff over the southeastern United States by 1.5–2 times (Milly et al. 2005; Hayhoe et al. 2007; Lettenmaier et al. 2008) though considerable differences lie across the models. The findings are consistent with the above studies, suggesting increased winter flows and reduced summer flows resulting in overall increased coefficient of variation of annual flows. Depending on the magnitude of the changes in CV of annual flows, the behavior of the within-year reservoir system could approach towards that of over-year reservoir system which could result in reduced resiliency of the system. Given that the eastern United States is mostly a humid region and most reservoirs are within-year storage systems, it is natural to expect the findings are applicable for systems facing similar stress. Thus, a clear understanding of the change in the CV of annual flows at hydrologic unit code (HUC)-8 level over the eastern United States will provide the information on the potential stress that could be expected on the reservoir systems. The authors will focus future efforts on quantifying the changes in the coefficient of variation of annual flows based on the recent generation intergovernmental panel on climate change's (IPCC) fifth assessment report (AR5) climate model runs.

Concluding Remarks

Most studies on climate change impact assessment focus on the sensitivity of the system changes to inflow characteristics on over-year reservoir systems. In this study, the impact of climate change on a within-year reservoir system serving a rapidly growing urban population (Lake Jordan in North Carolina) was evaluated. For this purpose, the downscaled GCM projections were forced with the SWAT model to obtain the changes in mean monthly streamflows between the periods 1981–2010 and 2012–2041. These results are similar to other findings (Milly et al. 2005) indicating wet winter conditions and also increased interannual variability in streamflow. Instead of using the actual projected monthly inflows, the study employed a stochastic streamflow generation model that preserves the changes in the mean monthly inflows and the standard deviation of the monthly inflows under climate change. By generating the inflows using the stochastic streamflow generation model, the reservoir model was forced with multiple realizations of streamflow traces that preserve the projected changes in monthly streamflow statistics.

Our results indicate that under near-term climate change alone with no increase in water supply demand in a within-year reservoir system, Lake Jordan, there is no consistent trend in the probability of surplus releases ($> 17.70\ m^3/s$) by the four GCMs considered in this study while there is a decrease in shortfall releases ($< 17.70\ m^3/s$) due to increase in net-inflows during winter and spring months. Under both climate change and projected water supply demand over 2012–2041, drought risk (probability of releases $< 16.99\ m^3/s$ + water supply demand and probability of zero releases) increases while there is a decrease in risk associated with surplus releases ($> 16.99\ m^3/s$ + water supply demand). This is expected because an increase in water demands will stress the conservation storage. In particular, there is no significant decrease in maximum flood release of greater than $141.58\ m^3/s$. Thus, increase in water supply demands from 0.71 up to $5.80\ m^3/s$ could be offset by increasing the rule curve from 65.84 to 67.06 m-MSL without changing the observed flood and drought risks under existing operations even under the net-inflows projected under near-term climate change.

The performance of the within-year reservoir system was evaluated under stationary climate and under projected monthly inflows due to near-term climate change considering both current demand and future urban demand. By constraining that the downstream flood risk will not change, the study investigated allowable releases for urban demand which could be met by increasing the conservation pool (65.84–67.06 m-MSL) storage. Based on the analyses, the authors clearly infer that the changes in the reliability of supply (i.e., 1—failure probability) due to increased urban demand seem to be small. This is primarily due to the inherent reason that initial storage in the reservoir ensure the demand for more than a season. However, increases in the urban demand and the coefficient of variation of annual inflows tend to significant decrease the reservoir resiliency, thereby forcing the within-year reservoir system to behave more like an over-year system. This indicates that it will take longer for the reservoir to reach its operating level, which could result in an increased period of proactive measures such as restrictions and trading between the uses. This necessitates periodical reevaluation of drought management plan and other response measures. Given that the AR5 Climate Model Intercomparison Project (CMIP5) supports 30-year hind casts and every five-year updated hind casts for 10 years, one could utilize them in developing relevant drought management plan with stakeholder participation. Future studies will rigorously evaluate the proposed intervention measures for within-year reservoir systems using AR5 hind casts available from CMIP5.

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