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Uncertainty in Surface Water Availability Over NC Due to Climate and Land Use Changes

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Abstract
Climate change and population growth can significantly stress water supply systems emphasizing the importance of reallocating reservoir storages for the designed uses. Most studies on climate change assessment analyzed arid region reservoirs due to high interannual variability in streamflows. We focus on a within-year reservoir system, Lake Jordan, NC from a temperate region that has been experiencing rapid growth since 1990s. Given the reduced uncertainty in near-term climate projections, we evaluate the current operational policies and suggest revised rules for operating the within-year system. We used downscaled GCM projections to implement 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. We 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. Our results indicate that the changes in the reliability due to increased urban demands are small since initial reservoir storages 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.
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1. Introduction

Climate change and population growth impact water infrastructure indicating the need for reallocating reservoir storages 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 U.S. water resources (Gleick 1987; Lettenmaier et al. 1992; 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 US (Vicuna et al. 2010; Hanak and Lund, 2012). Given that the western US (exception being Pacific Northwest) is semi-arid experiencing higher interannual variability in streamflows (Sankarasubramanian et al. 2002), reservoirs in the arid west, excluding those on the Sacramento – San Joaquin Rivers in California, are mostly designed to be over-year systems, having the ability to hold multiple years of mean annual flows. Thus, many studies have focused on the re-allocation of existing storages in the western US 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). Eastern US, 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 storages 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 also developed by assuming the inflows being stationary (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 demand due to population growth over the eastern US 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 (NC) (Moreau 2006), increase in water demand due to urbanization, industrial growth and agricultural use have made 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); Hayhoe et al. 2007; Peterson et al. 2012 and references therein) in the eastern US 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 limited scope for building new reservoirs, existing within-year systems in the eastern US needs to be managed more efficiently to limit frequent shortfalls (drought) and surpluses (floods) under potential climate change and increased demand due to population growth (Peterson et al. 2012). Thus, evaluation of future water supply needs may necessitate reallocation of storages as well as revisiting existing operational rule curves, since both are developed under the assumption that the inflows are stationary.

The main intent of this paper is to analyze the impact of near-term (10-30 years) climate change and population growth 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\textsubscript{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 21\textsuperscript{st} century. The general circulation models (GCM) tend to have similar climate projections under different emission scenarios (i.e., scenario uncertainty) with the primary source of uncertainty lying across models (i.e., model uncertainty). There is a growing scientific consensus that at decadal time scales (10-30 years) – an important planning horizon for watershed development – the choice of the scenario for greenhouse-gas emissions contributes little to the uncertainties in climate scenarios generated by different GCMs (Hawkins and Sutton 2009). This partly arises from the thermal inertia of the oceans, which lead to significant “committed warming” on decadal time scales (Meehl et al. 2009). Further, evidence is emerging that the climate system possesses useful predictability on these time scales, associated with the observed state of the ocean circulation and anthropogenic increases in greenhouse forcing (Smith et al. 2007; Keenlyside et al. 2008). Further, decadal time scales are very critical from water resources planning perspective (Milly et al. 2008). The analyses presented in this study primarily rely on these new developments in near-term climate change prediction for assessing the performance of existing within-year storage systems in regions experiencing rapid development and urbanization. For this purpose, we consider a within-year reservoir system, Lake Jordan, in the “research triangle” area in NC which is experiencing frequent shortages in meeting the desired yields from the system due to rapid urbanization and changes in streamflow pattern.

This report is organized as follows: Section 2 presents a detailed background on the recent droughts experienced by the within-year system as well as in the region. Section 3 details the methodology related to obtaining future inflows under near-term climate change. Section 4 combines the projected inflows under near-term change with different scenarios of population growth for quantifying the impact on the Lake Jordan system. Finally, in Section 5, we summarize the salient findings from the study in the context of impact of near-term climate change on within-year storage systems that are experiencing rapid increase in demand due to urbanization.

2. NC Triangle Area Water Management Challenges and Hydroclimate Data

The main objective of this study is to evaluate the performance of a within-year reservoir system, Lake Jordan, in the Upper Cape Fear River Basin (Figure 1) in delivering the desired yields for water supply and water quality under near-term climate change and population growth. The triangle area (Wake, Chatham and Orange counties) in NC has experienced three severe droughts (1998 - 2002, 2005 and 2007) over the past decade due to continually increasing (20%-62%) water supply demand. Five counties (Union, Brunswick, Mecklenburg, Wake and Iredell) from NC were among the top 100 fastest growing counties in the nation during 2000 to 2009 (U.S. Census Bureau 2009). Similar experiences of demand-induced droughts have also been reported for other within-year storage systems: Falls Lake, Kerr-Scott and Catawba reservoirs, which serve water for the above five counties in NC (Golemebesky et al. 2009). By analyzing the performance of Lake Jordan in the upper Cape Fear River basin, we intend to provide broader suggestions for improving the management of other within-year storage systems in NC as well as in the eastern US under potential impacts due to climate change and population growth.
2.1 Study Area

The Upper Cape Fear River basin in the triangle area is one of the rapidly growing areas in NC 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 two sub basins: 1) Haw River with a drainage area of 3,264 km², and 2) Deep River which has a drainage area of 3,671 km². 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 (NC State Climate Office). Figure 1 shows the location of the Jordan Lake reservoir in the Upper Cape Fear River basin intended to serve water to the cities of Chapel Hill, Cary, and Apex, in Chatham, Orange, and Wake counties, respectively. The Jordan Lake reservoir is located downstream of the Haw River watershed about 40 km southwest of Raleigh, NC. 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 Cape Fear River estuary and supply water to the cities of Fayetteville and Wilmington.

2.2 Streamflow and Observed Climate Data

Observed daily streamflow from two USGS stations, Haw River at Bynum (Station No. 02096960; 1973 – till date) and Deep River at Moncure (Station No. 02102000; 1930- till date), were considered as natural inflows for the calibration of the Soil and Water Assessment Tool (SWAT) model. Net observed inflows that include evaporative losses from the Lake Jordan reservoir were obtained from the US Army Core of Engineers (USACE). The historical climate data (precipitation and maximum and minimum air temperature), available at 1/8 degree (~14 km by 12 km) from 1949-2010, was obtained from the national gridded climate data developed by Maurer et al. (2002). This historical time series was primarily used for calibrating the SWAT model at Deep River at Moncure and Haw River at Bynum.

2.3 Near-term Climate Change Projections

Near-term climate change projections were obtained from four different GCMs: 1) Bjerknes Centre for Climate Research (Model: BCM2 0.1) (Déqué et al. 1994; Déqué and Piedelievre 1995, Royer et al. 2002), 2) Canadian Centre for Climate Modeling and Analysis (Model: CGCM3 1.5) (Flato et al. 2000), 3) Centre National de Recherches Météorologiques (Model: CM3.1) (Déqué et al. 1994; Déqué and Piedelievre 1995; Royer et al. 2002), and 4) Commonwealth Scientific and Industrial Research Organization (Model: CSIRO MK3 0.1) (Gordon et al. 2002). These four models were chosen based on their ability to predict variability in observed monthly precipitation over North Carolina over the period 1981-2010 (results not shown). Downscaled climate change projections for these models over the period 2012-2041 were obtained from World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Maurer et al. 2007) under the A1B climate change scenario (See Nakicenovic et al. 2000 for scenario details). A1B climate change scenario is used for this study since the scenario considers moderate growth in emissions although GCMs tend to have similar levels of uncertainty under the three different emission scenarios over the upcoming decadal time scale (Hawkins and Sutton 2009). These downscaled gridded projections of monthly precipitation, and maximum and minimum air temperature, are available at 1/8 degree spatial resolution until 2099 for different scenarios of growth.
3. Inflow Projections and Reservoir Analyses under Climate Change: Methodology

Since the downscaled climate change projections from Maurer et al. (2007) are available only at the monthly time scale, we 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. Figure 2 provides the overall approach for obtaining changes in inflows and storages for the Jordan Lake reservoir under near-term climate change by using a: a) continuous semi-distributed SWAT model and b) the Jordan Lake reservoir model. First, the SWAT model parameters were calibrated for the Deep River during 1981 to 1990 using observed streamflow and then validated for the Haw River using observed gridded data of precipitation and air temperature (Maurer et al. 2002) given that these two neighboring watersheds are similar in hydroclimatic conditions and projections of population growth. Then, the SWAT model was forced with spatially downscaled (Maurer et al. 2007) and temporally disaggregated climate data obtained over the period 1981 to 2041. The projected changes in mean monthly inflows from the SWAT model under each GCM were used with a statistical generation scheme (discussed in detail in Section 3.2) to obtain 50 realizations of monthly inflows to analyze the performance of Jordan Lake under different scenarios of increased water demands due to population growth. The next sub-sections describe the details related to each of the above modeling segments.

3.1 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 sub-basins with each sub-basin comprising unique combinations of land cover and soil termed as Hydrologic Response Units (HRUs). The SWAT model is useful to predict impacts of land management practices on water, sediments, and chemical transport in watersheds under varying soils, land use and topographic conditions. It has been implemented 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). 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 STATSGO database and the land cover was obtained from 2001 National Land Cover Data (NLCD). Since the focus of this study is to evaluate the impacts of near-term climate change and projected water demands on within-year reservoirs, we did not consider the effects of dynamic (or projected) land use changes on water supply. Further, land-use changes impact peak flows (Touma et al., 2013), which obviously has minimal impacts on the reservoirs due to the allocated space for flood storage.

The SWAT model was calibrated using the historical gridded daily precipitation and temperature data available at 1/8 degree by 1/8 degree (Maurer et al. 2002) over the Deep River watershed for the period 1981-1990. Using the calibrated model parameters, the performance of the SWAT model was validated in predicting the monthly streamflows over the Haw River watershed. Both calibration and validation were performed by forcing the SWAT model with historical (observed) gridded climate data at the daily time scale. The SWAT model estimated flows were then bias corrected on a monthly basis using the USACE’s observed net inflows available at the Jordan Lake reservoir. 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.
Table 1 shows the performance of the SWAT model in simulating monthly flows at Haw River watershed under observed climate data and projected climate data from four different GCMs for the period 1981-2010. The SWAT model, upon forcing with observed climate data, was able to capture USACE’s observed streamflow variability during 1981-2010 with a correlation coefficient of 0.94. However, when the calibrated SWAT model was forced with bias corrected (Maurer et al. 2007) and temporally disaggregated GCM forcings over the same historical period (1981-2010), the correlations of simulated streamflow are very low in comparison to USACE’s observed streamflow (see Table 1). Although the SWAT estimated streamflow under the four GCMs were bias corrected to match long term USACE’s observed mean flows, the absolute percentage bias from all the four GCMs are about 2.5 times that of the SWAT streamflow resulted from observed climate forcings. All the four GCM-based SWAT flows indicated poor skills in simulating USACE’s historical monthly flows. This is consistent with the findings of Kyriakidis et al. (2001) and Gangopadhyay et al. (2005) who indicated that streamflow obtained from hydrologic models with simulated/projected climate forcings from GCMs does not provide useful information in predicting the observed streamflows. Hence, we considered only the changes in mean monthly streamflow and standard deviations of monthly streamflows between the periods 1981-2010 and 2012-2041 for performing the reservoir analyses.

3.2 Net-inflow Generation Scheme for Reservoir Analyses

Since the skill of GCMs in predicting monthly streamflow is very low over 1981-2010 (Table 1), we propose a net-inflow generation scheme that considers only the changes in mean monthly streamflows and variance of monthly streamflows for performing reservoir analyses. Previous studies have considered only the mean monthly streamflows and the variance of monthly streamflows for analyzing the performance of reservoirs under climate change (Brekke et al. 2009; Anderson et al. 2008; Vicuana et al. 2009). To analyze the performance of reservoirs under climate change, we combine the projected changes in mean monthly net-inflows and standard deviation of monthly net-inflows with the respective observed net-inflow values to obtain the projected changes in the distribution of monthly flows. By assuming that the changes in the covariance structure primarily arise due to the changes in the variance of the monthly net-inflows, we generate multiple realizations of monthly net-inflows based on multivariate normal distribution to analyze the performance of Lake Jordan under climate change and population growth. 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 inflows from the SWAT model ingested with climate forcings from each selected GCM for Haw River at Bynum for the observed (projected) period using simulated inflows for each GCM from the period 1981-2010 (2012-2041).

2) Obtain changes in mean monthly streamflow (equation 1) and changes in standard deviation of monthly streamflow (equation 2) for each GCM over the two periods (1981-2010 minus 2012-2041), where:

   \[
   d\mu_{i} = \mu_{i}^{1981-2010} - \mu_{i}^{2012-2041} \quad \ldots(1)
   \]

   \[
   d\sigma_{i} = \sigma_{i}^{1981-2010} - \sigma_{i}^{2012-2041} \quad \ldots(2)
   \]

3) Add, \( d\mu_{i} \) and \( d\sigma_{i} \), available for Haw River at Bynum from each GCM with the observed mean monthly net-inflows \( (\mu_{i}^{ni-o}) \) and standard deviation \( (\sigma_{i}^{ni-o}) \) of monthly net-inflows.
at Lake Jordan to obtain the projected mean monthly net-inflows ($\mu_i^{ni-pr}$) and standard deviation of monthly net-inflows ($\sigma_i^{ni-pr}$) for the period 2012-2041.

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

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

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, we estimate the covariance of the projected flows using equation 5, where $Q_j^{ni-pr}$ and $Q_k^{ni-pr}$ denote projected monthly net-inflows with $\rho_{jk}$ 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 $j=k$, it basically denotes the variance of the projected monthly net-inflows.

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

5) Given the projected mean monthly inflows, $\mu_i^{ni-pr}$, and the covariance matrix, $\text{Cov}(Q_j^{ni-pr}, Q_k^{ni-pr})$, we generate 50 realizations of monthly net-inflows over the period 2012-2041 by assuming the net-inflows follow a multivariate normal distribution.

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, if we were to use the bias-corrected monthly net-inflows obtained from SWAT model, then we would have had just only one realization of monthly inflows for the period 2012-2041. Since we assume 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 over the period 2012-2041 were fed into the Lake Jordan reservoir model for further analyses.

3.3 Jordan Lake Reservoir Model

Net-inflows from the statistical flow generation scheme were used with Jordan Lake reservoir model in order to assess the impacts of near-term climate change on water availability and reservoir reliability to meet future water demands. Figure 3 provides pertinent details regarding Lake Jordan system. Most of the reservoirs in NC explicitly partition the conservation storage for downstream water quality and for water supply. The fractions, $f_{WS}$ and $f_{WQ}$, specify how the conservation storages being allocated for water supply and water quality purposes. Given the initial end of the month storages, $S_{t-1}^{WQ}$ and $S_{t-1}^{WS}$, for water quality and water storage respectively and the generated net-inflows, $Q_t^r$, for month ‘r’ under a given realization for a GCM, we obtained the end of the month storages, $S_t^{WQ}$ and $S_t^{WS}$, for water quality and water storage 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 ($f_{WS} = 0.36$). The inflows are also divided among the sub-systems using the same factors as storage, while the downstream water quality releases and water supply releases are changed according to the scenarios of growth and analyses. The normal operating level for Jordan Lake is 216 ft above Mean Sea Level (MSL). Storages between 202 ft-MSL ($S_{min}$) to 216 ft-MSL and
216 ft-MSL to 240 ft-MSL \( (S_{\text{max}}) \) are considered to be the conservation and controlled flood storages, respectively. Thus, if the reservoir level is above 240 ft-MSL, spill is estimated as per equation (10) while deficit is estimated using equation (11) if the reservoir level is below 202 ft-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 releases from the Lake Jordan system, a release of 5000 cubic feet per second (CFS) from the reservoir would result in significant flood damage downstream.

\[
S_{t-1} = S_{t-1}^{WQ} + S_{t-1}^{WS} \quad \ldots(6)
\]
\[
S_{t}^{WS} = S_{t-1}^{WS} + f_{WS}Q_{t}^{*} - R_{t}^{WS} \quad \ldots(7)
\]
\[
S_{t}^{WQ} = S_{t-1}^{WQ} + f_{WQ}Q_{t}^{*} - R_{t}^{WQ} \quad \ldots(8)
\]
\[
S_{t} = S_{t}^{WQ} + S_{t}^{WS} \quad \ldots(9)
\]
\[
SP_{t} = \max(0, S_{t} - S_{\text{max}}) \quad \ldots(10)
\]
\[
D_{t} = \min(0, S_{\text{min}} - S_{t}) \quad \ldots(11)
\]

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. We used the net-inflows 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 (600 CFS) and flood release above 5000 CFS 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 600 CFS) and flood release (> 5000 CFS) were also calculated over 50 realizations for a given GCM under different scenarios of water supply demand.

### 3.4 Impact of Near-term Climate Change on Monthly Streamflow into Lake Jordan

In order to understand the impacts of near-term climate change, we analyzed the changes in the mean monthly streamflows and standard deviation of monthly streamflow under each GCM over the two 30 year periods 1981-2010 and 2012-2041 (Figure 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 1981-2010 respectively using equations (3) and (4). Most of the GCMs indicate wetter winter (January to March) and spring months (April to June) with increased mean monthly flows (Figure 4a). 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 fall and winter months could result in significant downstream releases above 600 CFS. The interannual variability of monthly net-inflows also is projected to decrease during the winter months and increase during the spring months (Figure 4b). This indicates that wetter winter conditions will be more common under near-term climate change, since the mean monthly streamflows are also expected to increase during winter. 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 Figure 4b, we don’t 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 with pronounced variability in net-inflows. These two projected changes could significantly impact the operation of the reservoir, since the within-year system is expected to refill by April 1 for ensuring the summer demand. Comparing the average monthly releases above 625 CFS over the period 1981-2010 (2324 CFS) with the projected average monthly releases from GCMs (BCCR: 2565 CFS, CCCMA: 2405 CFS, CNRM: 2247 CFS, CSIRO: 2440 CFS), all models indicate an increased scenario of net-inflows into the Lake, which could in general result in an increased downstream releases (> 625 CFS) to ensure the current operational pool level of 216 ft-MSL. Since the projected increases in water demand would result in tapping more water from the conservation storage (202 ft to 216 ft-MSL), this may result in demand-induced droughts since the operational rule curves maintaining 216 ft-MSL. The next section evaluates different scenarios of increased demand for improving the operation of Lake Jordan reservoir system utilizing the generated net-inflows obtained from near-term climate change projections.

4 Results and Analyses

The proposed study focuses on water management of the within-year system, Lake Jordan, over the next 10-30 years 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 water supply, water quality and flood control (Scenario 1: climate change impact alone with no increase in demand); 2) analyzing the impact of increased water supply demand on delivering the desired reliabilities on water supply, downstream water quality protection and flood control based on the existing operational policies as specified by the rule curves (Scenario 2: climate change impacts under increased demand with no reallocation strategies) and 3) identifying the revised operational policies for ensuring current reliabilities on water supply, water quality and flood protection even under increased water supply demand (Scenario 3: climate change impacts under increased demand by considering reallocation). To address the first scenario, we first obtained changes in the mean monthly inflows over the next 30 years by forcing downscaled near-term climate change projections from four different GCMs (Maurer et al. 2007) on the calibrated SWAT model for the upper Cape Fear River basin. The SWAT predicted inflows over the period 2012-2041 were then input into the Jordan Lake 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 inflows obtained from the SWAT model. 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 we present our analyses on the impact of near-term climate change on Lake Jordan, we first provide a baseline estimate of current flood/surplus and drought risks for the period 1991-2010. For this purpose, the Jordan Lake reservoir model is implemented by forcing the reservoir model by using the observed monthly net-inflows from 1991-2010. 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 (625 CFS), 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, we first estimate the number of months in which the monthly release is greater than the required release (625 CFS), which indicates additional release to adhere to the operational rule curve of 216 ft-MSL. Following that, we also quantify extreme flood risk based on the number of months in which the monthly release exceeds the allowed flood release of 5000 CFS. Both the flood/surplus and drought risk attributes for the baseline period as well as each GCM under the near-term climate change period are expressed as probabilities based on the total number of event occurrences to the total months over the period of analyses (240 months). Apart from the probabilities, we also quantify the average and standard deviation of monthly releases if the adjusted releases in a given month are above/below 600 CFS. Similar information is also provided if the monthly releases are above 5000 CFS.

4.1 Baseline Flood and Drought Risks

Under current operational management, the required release is set to 625 cubic feet per second (CFS) including 600 CFS for water quality and 25 CFS for water supply. Table 2 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 625 CFS is about 66% while the probability of flood releases, i.e. releases greater than 5000 CFS, is 4.7%. These two attributes quantify the current flood/surplus risk at the Jordan Lake. Looking at the drought risks, the probability when model release is less than the required release of 625 CFS is 2%. This indicates that reservoir released the exact release of 625 CFS in 32% of months. We also noted that 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. We evaluate this scenario next.

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

Under this scenario, we evaluated the performance of Lake Jordan 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, we 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 each GCM, the net-inflows were obtained from the statistical scheme that utilizes the projected monthly mean and monthly covariance structure of net-inflows. Table 2 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, we infer that there is no consistent trend by the four GCMs in terms of increase in the probability of occurrence of having monthly releases > 625 CFS. On failing to release 625 CFS, almost all four GCMs indicate reduction in the probability of not meeting the target release of 625 CFS. This could be potentially due to the potential increase in mean annual inflows, which occurs primarily due to increase in mean monthly flows during winter and spring (Figure 4) resulting in fewer months experiencing shortfall in meeting the demand. There doesn’t 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. Though there is no increase in the probability of zero releases, there is a clear increase in the fraction of months with average monthly releases greater than 625 CFS and also a reduction in the fraction of months with average monthly releases lesser than 625 CFS. On the flood risk, we infer that
almost three models except the CNRM model indicate increased flood risk with more months having greater than 5000 CFS. This is also further confirmed with the increase in fraction of months with average releases above 5000 CFS by the above three models.

To understand which months/seasons experience pronounced changes with releases greater (lesser) than 625 CFS, we show the seasonality of release patterns in Figure 5a (Figure 5b). It is clear that the winter and spring months experience a more pronounced increase in releases > 625 CFS (Figure 5a), whereas releases lesser than 625 CFS are experienced more in the spring and summer months (April to August). The surplus releases (release greater than 625 CFS) 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.

4.3 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), we assumed a moderate 30% increase in water supply demand for the Triangle area as well as for the downstream cities (Fayetteville and Wilmington) for every five years over the period 2012 to 2041. This implies that the water supply demand of 25 CFS in 2012 could increase up to 205 CFS by 2041. This water supply release needs to be met along with the required downstream water quality protection release of 600 CFS. 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. Figure 6 shows the probability of surplus releases (probability of flood release > 5000 CFS) as a function of different target releases. With increased water supply demands, all GCMs show a clear decrease in probability of surplus releases (Figure 6a). This is natural to expect since 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 months out of 240 months) in which the model-suggested releases exceed the required release. Further, from Figure 6a, BCCR is the only GCM that stands 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 (Figure 6b).

As expected, all GCMs suggest increase in drought risk on both attributes – the probability of deficit in meeting the target releases (Figure 7a) and the probability of zero release under increased water supply demand (Figure 7b) – as the water supply demand increases. For comparison, we also provide the estimated drought risk under current inflow conditions which do not consider projected climate change. Since 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, since 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, we evaluate whether we can offset the increased drought risk due to climate change and projected population growth by altering operational strategies.

4.4 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 216 ft-MSL. One way of reducing the
drought risk is to increase the conservation storage in the reservoir so that the resulting risk remains the same as that of current risk for the desired yield of 625 CFS. However, this increased water supply allocation should not result in any increased downstream extreme flood risk (i.e., probability of release = 5000 CFS). Similarly, increasing the water supply allocation alone is bound to increase the probability of shortfalls on water quality releases (600 CFS) for a given set of net-inflows if the operating rule curve is fixed. Hence, we ensure that both the probability of extreme flood risk (5000 CFS) and the probability of shortfalls on water supply and water quality releases (600 CFS) remain as that of current risk reported in Table 2 for a given set of inflows. Since changing the rule curve from 216 ft-MSL to 220 ft-MSL did not change the probability of no release under observed flows as well as under GCM projected net-inflows, we dropped that criterion 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, since 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 3) 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 2) for a given set of net-inflows.

Table 3 provides the permissible water supply releases under different operating levels (ranging from 216 ft-MSL to 220 ft-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 observed inflow pattern which assumes no climate change impacts, the existing operating rule curve at 216 ft-MSL has to be increased for potential water supply allocation due to future population growth demands 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 2. Information in Table 3 could also be employed for adaptive planning depending on the level of population growth in the area. Thus, as the population grows in the Triangle area, water managers could potentially change the rule curve that ensures the current level of probability of shortfalls and flood risk. Based on this, we infer that by increasing the rule curve to 220 ft-MSL, a total of 190 CFS 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. We have capped the maximum allocation that would be required for water supply release at 205 CFS due to population growth. With the exception of GCM BCCR which shows increased net-inflows (Figure 5), the rest of the GCMs show consistent allocation patterns for water supply release under different operational rule curves. By increasing the rule curve to 220 ft above MSL, an increased allocation up to 205 CFS 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 stationarity in net-inflows assumption (i.e., observed inflows). Results in Table 3 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.
5. Discussion

The main objective of this study is to quantify the impacts of near-term climate change and increased water demand on a within-year reservoir system, Jordan Lake, which supplies water to the Triangle Area in NC. By forcing the SWAT model with downscaled inputs from four selected GCMs under the A1B climate change scenario (Maurer et al. 2007), we obtained the change in the mean monthly inflows and standard deviation of the monthly inflows between the baseline period (1981-2010) and the planning period (2012-2041). These differences in the mean monthly net-inflows and the standard deviation in the net-inflows were then added to the USACE’s observed net-inflows for the period 1981-2010 to obtain the projected net-inflows for the period 2012-2041. These projected mean monthly net-inflows and variances of the monthly net-inflows for each GCM were combined by preserving month-to-month correlations to generate 50 sets/realizations of monthly inflows over the period 2012-2041 for further analyses in understanding the impact of climate change and urbanization on the Lake Jordan within-year reservoir system.

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. On the other hand, if we were to use the bias-corrected net-inflows obtained from SWAT model, then we would have had just only one realization of monthly inflows for the period 2012-2041. Since these climate models were initialized with initial atmosphere and ocean conditions based on 20th century control simulations, the primary information from these GCMs lies in their ability in predicting mean monthly values and variances of the monthly values rather than in predicting monthly time series of precipitation and temperature obtained from these GCMs. Hence, we combined the changes in the mean monthly net-inflows and variances in the monthly net-inflows with a parametric streamflow generation model for obtaining multiple realizations of net-inflows for the reservoir analyses.

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) US due to the smaller (larger) interannual variability in streamflows. For this purpose, we consider the resilience index, $m$, of a reservoir system (Vogel and Stedinger (1987) and Vogel and Bolognese (1995)):

$$m = \left(1 - \alpha \right) / C_v$$  \hspace{1cm} (12)

where $\alpha$ denotes the ratio of the yield from the reservoir to the mean annual inflow into the reservoir and $C_v$ is the coefficient of variation of annual inflows. 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. We computed $m$ for both observed inflows and for the four GCM-projected inflows for a water quality release of 600 CFS and for thirteen different values of water supply releases from 25 CFS to 205 CFS with an increment of 15 CFS. 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 25 to 205 CFS. Thus, using the mean annual inflows given in Section 3.4 for both observed and GCM-projected inflows, we computed thirteen different values of $m$ for a given inflow scenario. For each of the thirteen different yields, we also obtained the failure probability of total yield (i.e., probability of total yield < (600 CFS + water supply release in CFS)) for each set of inflow scenario (Figure 8).
Figure 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 216 ft (8a) and 220 ft above MSL (8b). For a given set of inflows, as the water supply demand increases from 25 CFS to 205 CFS, 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 25 CFS to 205 CFS. Since 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 Figure 8 is the variability in the system resilience ($m$). 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. Relatively smaller change in the failure probability across 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 US. 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, due to climate change, reservoir systems will take more time to recover as both the coefficient of variation of projected inflows and the fractional yield, $\alpha$, increase. The observed coefficient of variation (CV) of annual streamflows ranges between 0.2-0.4 for the eastern US 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 US has suggested increase in the coefficient of variation of runoff over the southeastern US by 1.5 to 2 times (Milly et al. 2005; Hayhoe et al. 2006; Lettenmaier et al. 2008) though considerable differences lie across the models. Our 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. Our future effort will focus on quantifying the changes in the coefficient of variation of annual flows based on the recent generation AR5 climate model runs.

6. **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, we evaluated the impact of climate change on a within-year reservoir system, Lake Jordan in NC, under climate change serving a rapidly growing urban population. For this purpose, we forced the downscaled GCM projections with SWAT model to obtain the changes in mean monthly streamflows over the period 2012-2041 for the reservoir system. Our findings are similar to other findings (Milly et al. 2005) indicating a 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, we forced the reservoir model 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 (> 625 CFS) by the four GCM’s considered in this study while there is a decrease in shortfall releases (< 625 CFS) 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 < 600 CFS + water supply demand and probability of zero releases) increases while there is a decrease in risk associated with surplus releases (> 600 CFS + water supply demand). This is expected since increase in water demands will stress the conservation storage. In particular, there is no significant decrease in maximum flood release of greater than 5000 CFS. Under near-term climate change, increase in water supply demands from 25 CFS up to 205 CFS can be offset by increasing the rule curve from 216 ft-MSL to 220 ft-MSL without changing the observed flood and drought risks under existing operations.

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 won’t change, the study investigated allowable releases for urban demand by increasing the current operating level of 216 ft-MSL to 220 ft-MSL. Based on the analyses, we 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 storages 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 time for the reservoir to reach its operating level, which could result in 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 inter-comparison project (CMIP5) supports 30-year hindcasts and every five-year updated hindcasts for 10 years, one could utilize them in developing relevant drought management plan with stakeholder participation. Our future studies will rigorously evaluate the proposed intervention measures for within-year reservoir systems using AR5 hindcasts available from CMIP5.
7. References


Table 1: Performance of SWAT model in simulating the flows at Haw River near Bynum using observed (1/8 degree) and projected climate forcings from four different GCMs during 1981-2010.

<table>
<thead>
<tr>
<th>Streamflow Statistics</th>
<th>Observed</th>
<th>BCCR</th>
<th>CCCMA</th>
<th>CNRM</th>
<th>CSIRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Percentage Bias</td>
<td>27.7</td>
<td>70.3</td>
<td>70.4</td>
<td>72.2</td>
<td>70.2</td>
</tr>
<tr>
<td>Simulated Mean (CFS)</td>
<td>1410</td>
<td>1204</td>
<td>1204</td>
<td>1204</td>
<td>1204</td>
</tr>
<tr>
<td>Coefficient of variation simulated</td>
<td>0.78</td>
<td>0.67</td>
<td>0.72</td>
<td>0.76</td>
<td>0.74</td>
</tr>
<tr>
<td>Root Mean Square Error</td>
<td>36.3</td>
<td>96.2</td>
<td>97.3</td>
<td>100.6</td>
<td>98.8</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>0.94</td>
<td>0.32</td>
<td>0.33</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>USACE’s Observed Mean (CFS)</td>
<td>1204</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of variation USACE’s observed flow</td>
<td>0.94</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</table>
Table 2: Baseline flood/surplus and drought risks for Jordan Lake based on observed net-inflows and inflows generated based on the projected precipitation from different GCMs in meeting water quality (600 CFS) and water supply (25 CFS) demands. The probability of flood risk is assessed based on monthly releases above 5000 CFS. Entries in the last three rows of the table have units of CFS, and represent increments below (second to last row) or above (last and third to last rows) 625 or 5000 CFS, e.g., for months with releases >5000 CFS, the BCCR model gave an average monthly release of 1324 CFS in excess of 5000 CFS (i.e., an average monthly release of 5000 + 1324 = 6324 CFS).

<table>
<thead>
<tr>
<th>Flood and Drought Attributes</th>
<th>Observed</th>
<th>BCCR</th>
<th>CCCMA</th>
<th>CNRM</th>
<th>CSIRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of months with release &gt;625 CFS</td>
<td>0.658</td>
<td>0.745</td>
<td>0.669</td>
<td>0.648</td>
<td>0.648</td>
</tr>
<tr>
<td>Fraction of months with release &lt; 625 CFS</td>
<td>0.02</td>
<td>0.008</td>
<td>0.017</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Fraction of months with no release</td>
<td>0.005</td>
<td>0.002</td>
<td>0.005</td>
<td>0.003</td>
<td>0.004</td>
</tr>
<tr>
<td>Fraction of months with release &gt; 5000 CFS</td>
<td>0.047</td>
<td>0.063</td>
<td>0.063</td>
<td>0.035</td>
<td>0.06</td>
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<tr>
<td>Average monthly release (CFS) in excess of 625 CFS</td>
<td>2324</td>
<td>2565</td>
<td>2405</td>
<td>2247</td>
<td>2440</td>
</tr>
<tr>
<td>Average monthly release (CFS) in shortfall of 625 CFS</td>
<td>264</td>
<td>294</td>
<td>295</td>
<td>327</td>
<td>326</td>
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<tr>
<td>Average monthly release (CFS) in excess of 5000 CFS</td>
<td>1247</td>
<td>1324</td>
<td>1669</td>
<td>1192</td>
<td>1509</td>
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</table>
Table 3: Increased water supply releases (in cfs) under different operating levels for observed flows and GCM-projected net-inflows over the planning period 2012-2041.

<table>
<thead>
<tr>
<th>Elevation (ft)</th>
<th>Observed (cfs)</th>
<th>BCCR (cfs)</th>
<th>CCCMA (cfs)</th>
<th>CNRM (cfs)</th>
<th>CSIRO (cfs)</th>
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<tbody>
<tr>
<td>216</td>
<td>25</td>
<td>165</td>
<td>55</td>
<td>55</td>
<td>75</td>
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<td>217</td>
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<td>205</td>
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<td>190</td>
<td>205</td>
<td>205</td>
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</table>
Figure 1: Location of Jordan Lake Reservoir in the Upper Cape Fear River Basin. The shaded areas indicate the four counties (Wake, Orange, Durham and Chatham) that are experiencing tremendous growth in population.
Figure 2: Schematic diagram for evaluating the impacts of near-term climate change and increased water supply demand on the Jordan Lake Reservoir
Figure 3: Pertinent data relevant to Jordan Lake Reservoir
Figure 4: (a) Mean monthly streamflow and (b) standard deviation of monthly streamflows for the observed period 1981-2010 and the future period 2012-2041 based on four different GCMs.
Figure 5: Number of months with water supply and water quality releases (a) greater than the target releases and b) less than the target releases over the observed period (1981-2010) and the projected period 2012-2041 (four GCMs). Water quality releases and water supply releases are assumed as 600 CFS and 25 CFS based on the current operational rule curve of 216 MSL level.
Figure 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 and (b) probability of occurrence of maximum allowed flood release.
Figure 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 and (b) probability of occurrence of no releases for both water supply and water quality uses.
Figure 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) 216 ft-MSL and (b) 220 ft-MSL.