

# Multi-reservoir system response to alternative stochastically simulated stationary hydrologic scenarios: An evaluation for the Apalachicola-Chattahoochee-Flint (ACF) Basin

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## ABSTRACT

*Study region:* Apalachicola-Chattahoochee-Flint (ACF) Basin in the Southeast US

*Study focus:* Operational rules of managed river systems are typically developed based on historical hydrology. This approach fails to consider alternative plausible hydrologic conditions that may occur outside the observational period-of-record. Here, we evaluated operational rules of a transboundary managed river system—the ACF Basin—with multiple reservoirs under historical observations and 100 stochastic streamflow realizations representing the current streamflow conditions of the basin. These scenarios, which had comparable averages as the historical records but greater extremes, were simulated by coupling a stochastic streamflow model with a basin-wide river system model. We used these scenarios to evaluate the response of the ACF Basin against metrics for urban water supply, required freshwater inflows, floodplain forest ecosystem water needs and hydropower generation. The evaluation was done based on the magnitude, frequency, duration and seasonality of these metrics.

*New hydrological insight of the region:* The unique aspect of this paper is using a stochastic streamflow model coupled with a river basin model to evaluate the response of the ACF Basin's current operational rules under several hypothetical plausible stationary hydrologic scenarios. We found that, overall, the basin response in terms of all the metrics used here was less favorable under the alternative stationary hydrologic scenarios than the historical hydrology. Our evaluations suggested that the reservoir operational rules should be revisited to consider a broader range of plausible hydrologic conditions.

## 1. Introduction

Regulated river systems are managed by a series of hydraulic infrastructures such as dams and/or gated spillways. Operational rules

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for these river systems are typically defined by modeling how well a system operates under prescribed management options using historically observed streamflows (Şen, 2020; Wu et al., 2023). This approach fails to consider alternative plausible hydrologic conditions that may have occurred historically outside the observational period-of-record (Bertoni et al., 2019) or that may occur in the future and differ from the historically recorded streamflows in terms of magnitude, frequency, duration and/or timing of extreme events (Taner et al., 2017; Ray et al., 2018). This approach fails to consider whether tuning a reservoir system to operate well under a singular historical hydrologic regime, which occurred under the observed historical period-of-record, translates into a system operating well under a broader range of plausible alternative hydrologic regimes in the future. Researchers have suggested that historical climate trends will not necessarily be repeated in the future (e.g., Milly et al., 2008, 2015). Therefore, revisiting the operational rules for reservoir systems may be prudent when considering that these rules may be subject to different flow regimes in the future (Giuliani et al., 2021; Wu et al., 2023). We should be concerned about strategic infrastructure that may fail to function as originally designed or that reservoir operational rules may not perform as originally intended, which can result in unacceptable conditions (Ansar et al., 2014).

A majority of past research has focused on the impacts of nonstationary climate scenarios on critical hydraulic infrastructure such as dams and levees (e.g., Lettenmaier et al., 1999; Mallakpour et al., 2019, 2020; Boulange et al., 2021) or the performance of such infrastructures under historical conditions (e.g., Ahmadisharaf and Kalyanapu, 2015), with limited attention to the impacts of alternative stationary realizations of the climate or hydrology on these infrastructures. An important consideration in anticipating future changes in global climate is the expectation of increased weather variability inducing more intense and frequent hydrologic extreme events like droughts and floods. The magnitude, duration, timing and frequency of these events will be different than what we have experienced in the past (Gavahi et al., 2020; Intergovernmental Panel on Climate Change [IPCC], 2022). Alternative stationary climate scenarios refer to climate conditions with comparable mean values but different extremes than observations, including potentially more extreme events or longer periods of low and high flows. Because of various uncertainty sources involved in nonstationary simulations ranging from uncertainties of climate models to those in statistical model structure, we here use stationary simulations to better depict the current internal variability of the system. Such scenarios can be generated based on stochastic analyses of historical records. Examples of past studies stochastically simulating streamflow time series include Stedinger et al. (2014), Stedinger et al. (2015), Brunner et al., (2019, 2020, 2021) and Brunner and Gilleland (2020). These analyses rely on fitting a suitable probability distribution on historical streamflow records and then using a stochastic technique such as a Monte Carlo method to generate alternative hydrologic scenarios.

Stochastic models are used to increase the size of the sample at hand to get an idea of the full variability of a phenomenon, e.g., by producing large ensembles of time series or large event sets. In hydrology, stochastic models are used for different purposes, including developing management plans for extreme events, refining water management plans, or predicting plausible ranges of reservoir inflows. There exist various modeling approaches and one can distinguish between direct modeling approaches that simulate streamflow using a stochastic model and indirect approaches that use a hydrologic model to transform stochastically generated meteorological time series to streamflow (Stedinger and Taylor, 1982; Yevjevich, 1987; Vogel, 2017). The direct approaches most commonly applied are parametric and nonparametric models. Parametric approaches include autoregressive moving average models (Stedinger and Taylor, 1982; Papalexioiu, 2018), fractional Gaussian noise models (Mandelbrot, 1965), broken line models (Mejia, 1972) and fractional autoregressive integrated moving average models (Hosking, 1984). Nonparametric models comprise various bootstrap techniques like simple bootstrap, moving block-bootstrap, nearest-neighbor bootstrap (Salas and Lee, 2010; Herman et al., 2016), matched-block bootstrap (Srinivas and Srinivasan, 2006), maximum-entropy bootstrap (Srivastav and Simonovic, 2014) and kernel density estimation (Lall and Sharma, 1996; Sharma et al., 1997). Such alternative hydrologic scenarios are crucial for testing the robustness of the management rules of reservoir systems. Despite their potential benefit for stress-testing reservoir systems, the use of such scenarios for evaluating the functionality of reservoir operation systems is currently not widely practiced. Stochastic simulations can be used to increase the sample size of historical observations in order to enable studying extreme but plausible streamflow scenarios that are missing in the historical period-of-record.

To test how well a reservoir management approach designed from the historically observed flows performs under more variable streamflow conditions, we evaluated the case study of Apalachicola-Chattahoochee-Flint (ACF) Basin in the Southeastern US using stochastic evaluations. The hydroclimatology of the Southeastern US can be generally characterized as having large amounts of annual precipitation, limited seasonality and a high degree of interannual variability (Labosier and Quiring, 2013). Although precipitation is relatively abundant (>1000 mm/year) in most years, increasing water demands, temperatures and changing precipitation patterns can put stress on regional water resources (Qi et al., 2020). For instance, increased water use throughout the Flint Subbasin has resulted in streamflow declines during extended droughts (Emanuel and Rogers, 2013; Rugel et al., 2012). From 2000–2014, minimum flows observed in the Lower Flint River and its tributaries have been substantially lower than those observed during previous historical droughts (Golladay and Hicks, 2015). Streamflow rates have decreased by ~20% after the introduction of irrigation in the Lower Flint Basin. Such decreases mainly occur during La Niña phases, which is exacerbated (decreased by ~50%) during growing season by irrigation (Singh et al., 2016). Indeed, droughts of extended duration occurred more frequently between 1696 and 1820 than in the period in which local and state water supply decisions were developed (mid-1990 s to the present). According to tree-ring analyses by Pederson et al. (2012), the period of historically observed flows upon which the modeling for developing water management guidelines for the most recent Water Control Manual (WCM) for the basin was developed (1939–2012), was amongst the wettest since at least 1665.

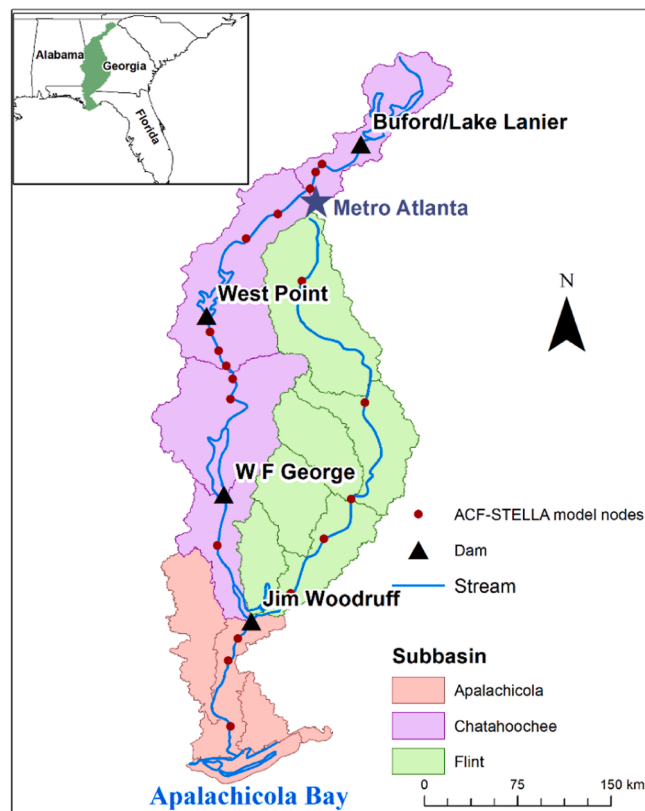
Our objective is to evaluate the suitability of the current reservoir management system operational rules under alternative hydrologic regimes that were not observed in the past, but may occur in the future. The research question is: do operational rules for a managed river system under past hydrologic conditions perform satisfactorily under different alternative hydrologic conditions

(hereafter called “stochastically simulated stationary hydrologic scenarios”) with an altered range of variability in terms of the magnitude, duration, frequency and timing of flood and drought events? This question is addressed by developing a modeling framework for the ACF Basin, a transboundary basin in the southeastern US with multiple large dams operated to meet various management purposes (e.g., urban water supply, fish and wildlife resources, commercial navigation, flood control and hydropower generation). The framework includes a stochastic streamflow model, for producing alternative stationary hydrologic scenarios, coupled with a basin-wide river system model. We then measure the reservoir system response through the river system model’s output using a set of management metrics. The unique aspect of this paper is using a stochastic streamflow model coupled with a river basin model to evaluate the response of the ACF Basin’s current operational rules under several stationary hydrologic scenarios, a unique contribution to the basin hydrology and management of the major reservoirs. Our analyses contribute to the future management of the ACF Basin and similar basins since multi-objective operation of multi-reservoir river systems in the future is expected to be subject to hydrologic regimes that will most likely differ from the past in terms of magnitude, timing, frequency and duration of extreme hydrologic events.

## 2. Study area

The ~53,000 km<sup>2</sup> ACF Basin (Hydrologic Unit Code [HUC] 0313) has a semi-humid climate and is located in the Southeastern US lying in the States of Alabama, Florida and Georgia (Fig. 1). The basin’s estuary is a valuable ecosystem with species like oysters, finfish and shrimp that are important to the regional economy (Pine et al., 2015; Leitman et al., 2016, US Fish and Wildlife Service [USFWS], 2016). In addition, the river hosts several federally listed species, including the Gulf sturgeon and several species of mussels (USFWS, 2016). Over the past decades, the basin has been ensnared in lawsuits, including a US Supreme Court lawsuit between Florida and Georgia, based on a contention by Florida that actions by Georgia had harmed the Apalachicola Bay (US Supreme Court, 2018, 2021, US Army Corps of Engineers [USACE], 2016). This lawsuit was resolved in 2021 with the Supreme Court stating that although harm had occurred, Florida did not prove harm was caused by Georgia (US Supreme Court, 2021). A WCM defining system-wide reservoir management for the ACF Basin was adopted by USACE (2016). We followed the reservoir operation rules for the preferred alternative in the WCM to model the hydrologic scenarios.

The ACF Basin can be delineated into three major subbasins: Apalachicola, Chattahoochee and Flint subbasins. Fig. 1 shows that the majority of the basin is in the Flint and Chattahoochee subbasins. Consequently, ~90% of the basin inflow to Apalachicola River



**Fig. 1.** The Apalachicola-Chattahoochee-Flint (ACF) Basin stream network, major reservoirs/dams and locations for which the basin-wide river system model output is generated.

originates above the Florida border. Florida, therefore, cannot manage the inflow to this river without working with the upstream States of Alabama and Georgia and the federal government since all of the basin's reservoir storage capacity is in federally operated reservoirs. The 22,553 km<sup>2</sup> Chattahoochee Subbasin has three major federally managed reservoirs—Lake Lanier, West Point Lake and W.F. George (hereafter called 'major reservoirs')—with a combined storage of 1.97 billion m<sup>3</sup> in the conservation pools of the major reservoirs (USACE, 2016). This subbasin receives far less groundwater inflow than the Flint and its predominant water extractions are for municipal and industrial uses (Rugel et al., 2015; USACE, 2016; Karki et al., 2021). The 21,900 km<sup>2</sup> Flint Subbasin contains no reservoirs with substantive storage volume. The Flint River receives a significant inflow contribution from groundwater resources in the Dougherty Plain and groundwater withdrawals for agricultural irrigation reduce flows in the river (Torak and Painter, 2006; Rugel et al., 2015; Mitra et al., 2014). The majority of the irrigation water use in the Flint Subbasin, however, comes from groundwater sources not directly from the Flint River (Leitman et al., 2017).

There is an additional Federally managed reservoir with minimal storage capacity at the confluence of the Flint and Chattahoochee subbasins, Lake Seminole/Jim Woodruff Dam, which has less than 2% of the basin storage capacity at full conservation pool (USACE, 2016). Because of the relatively flat topography and river-bed degradation, which has occurred below this dam, the reservoir has no storage capacity at extremely low flows and meeting release rules called for under the WCM requires the three upstream reservoirs to support the releases. Historical records (1939–2012) show that streamflow in the Apalachicola River tends to be greatest from January through April and declines until about November. The ACF Basin has experienced severe droughts in the past, including a severe one in 2011–2012 (Gordon et al., 2012).

Lake Lanier has ~65% of the entire basin storage capacity (USACE, 2016), but only impounds ~11.9% of the Chattahoochee Subbasin and 6.0% of the combined Flint and Chattahoochee Subbasins at full conservation pool. Lake Lanier has issues with refilling when its pool is drawn down because of its location and this requires the storage pool to be managed conservatively. The West Point and W.F. George reservoirs have ~33% of the ACF Basin storage capacity at full conservation pool and because they impound a greater area of the Chattahoochee watershed than Lake Lanier, they are less subject to refill issues experienced at Lake Lanier. Releases are made from W.F. George Reservoir to support Woodruff releases and then releases are made from West Point to balance its pool with W. F. George and ultimately releases are made from Lanier to balance its pool with W.F. George and West Point based on guidelines in the WCM. The WCM calls for the storage in the pools to be balanced, so that whenever possible support of Jim Woodruff releases is equitably shared among the three major storage pools.

Table 1 shows that the water released through Jim Woodruff Dam under the WCM is based on the time of year, the basin inflow to the Chattahoochee and Flint subbasins and the composite storage in the major reservoirs (i.e., the summation of storage in Lake Lanier, West Point and W.F. George reservoirs). Release rules are determined by a zone scheme within the reservoirs where the greater the composite volume the greater the minimum release from Jim Woodruff Dam which dictates reservoir release support for the flow in the Apalachicola River. The conservation pool of the three major reservoirs is divided into four Action Zones. The purpose of these action zones is to define the volume of water to be released for certain management actions. If a reservoir pool is in Action Zone 1, the maximum desired release is made and if a pool is in Action Zone 4, no release is made for that purpose or in the case of releases for Jim Woodruff Dam outflow, only the minimum release is supported. Action Zones 2 and 3 are transitions from making no or minimum releases to the maximum desired release. The action zones are used to define releases both for the individual reservoirs as well as for defining the volume of support from the reservoir system for releases from Jim Woodruff Dam. For example, the action zones are used to define the number of peaking hours for hydropower from the individual reservoirs as well as for releases from Jim Woodruff Dam under the WCM.

Of the parameters used in the WCM to define releases from Jim Woodruff Reservoir, only the composite storage can be directly controlled by management actions. Although the WCM only defines releases from Jim Woodruff Dam, meeting the release rules for this

**Table 1**

Apalachicola-Chattahoochee-Flint (ACF) Water Control Manual release rules for Jim Woodruff Dam (m<sup>3</sup>/s) (US Army Corps of Engineers [USACE], 2016).

Months	ACF Basin Composite storage	ACF Basin inflow (m <sup>3</sup> /s)	Minimum releases from Jim Woodruff Dam (m <sup>3</sup> /s)	ACF Basin inflow available for storage
March- May	Zones 1 and 2	≥ 962.9 ≥ 453.1 and < 962.9 ≥ 141.6 and < 453.1 < 141.6	708.0 453.1 Basin inflow 141.6	Up to 100% > 708.0 453.1 + 50% Basin inflow > 453.1
	Zone 3	≥ 1104.5 ≥ 311.5 and < 1104.5 141.6–311.5 < 141.6	708.0 311.5 + 50% > 1104.5 Basin inflow 141.6	Up to 100% > 708 Up to 50% > 311.5
June–November	Zones 1, 2 and 3	≥ 623.0 ≥ 283.2 and < 623.0 < 141.6	453.1 283.2 + 50% > 283.2 141.6	Up to 100% > 453.1 Up to 50% > 283.2
December–February	Zones 1, 2 and 3	≥ 141.6 < 141.6	141.6 141.6	Up to 100% > 141.6
If drought triggered	Zone 3	N/A	141.6	Up to 100% > 141.6
Anytime	Zone 4	N/A	141.6	Up to 100% > 141.6
Anytime	Zone 5 (Drought zone)	N/A	127.4	Up to 100% > 127.4

dam in Table 1 requires all major reservoirs to make releases because of Lake Seminole's limited storage capacity.

An important aspect in the WCM release rules is the implementation of drought and emergency drought operations. Drought operations under the WCM are initiated when the composite storage enters Zone 3, while emergency drought operations are initiated when the composite storage enters Zone 5 (a subsection of Zone 4). Under the WCM, these operations are not terminated until the composite storage returns to Zone 1. It is important to understand that the WCM defines the volume of support for the Jim Woodruff release from the reservoir system to meet a specified release, not necessarily the actual volume of the release from Jim Woodruff Dam.

Since over half of the ACF Basin upstream of the Jim Woodruff Dam has no storage facilities (e.g., the Flint and Lower Chattahoochee Subbasins) and a major portion of the storage capacity in the Chattahoochee Subbasin is in the upper part of the basin, inflows from the Flint Subbasin and/or from the Chattahoochee Subbasin below Lake Lanier routinely determine the outflow from Jim Woodruff. This sometimes allows for minimum releases to be greater than those supported under the WCM in drought operation. Because the majority of the storage capacity of the Chattahoochee is at Lake Lanier, the reservoir has a large influence of when, how often and for how long the volume of water is composite in zone 3, 4 or 5 and therefore when drought and emergency drought operations are in effect.

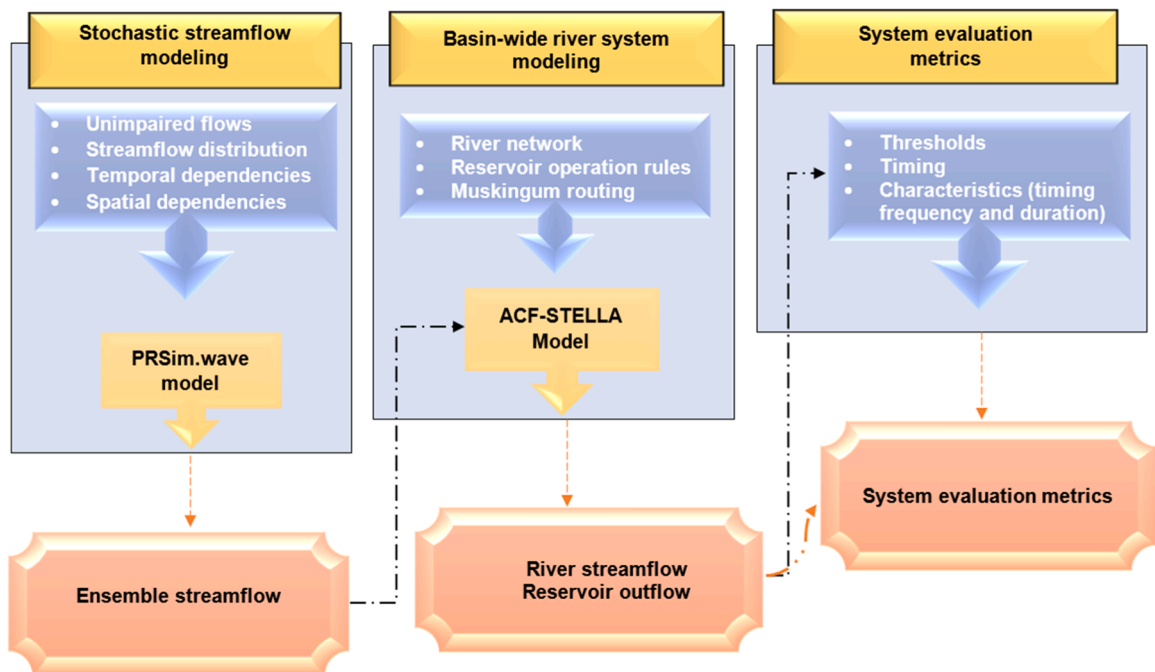
### 3. Methodology

We coupled a stochastic streamflow generator model, Phase Randomization Simulation using wavelets (PRSim.wave; Brunner and Gilleland, 2020), with a basin-wide river system model, ACF-STELLA (Leitman and Kiker, 2015), to evaluate the effectiveness of the reservoir operations at the basin scale. PRSim.wave used an unimpaired flow (UIF) dataset, which is a synthesized dataset that represents the historically observed flow without the influence of reservoirs or consumption (USACE, 1997). The UIF dataset was originally developed during the ACF Comprehensive Study and has been periodically updated by the USACE with the states of Alabama, Florida and Georgia since then to extend from 1939–2012.

In PRSim.wave, the UIF dataset was used to generate individualized hydrologic scenarios at selected locations throughout the ACF system. This ensemble of realizations was then used as basin inflow by ACF-STELLA to generate reservoir releases and river streamflow across the entire river network. We then compared the output from the model with: (1) the UIF as historical streamflows; and (2) the 100 distinct hydrologic scenarios, with a set of performance metrics discussed in the forthcoming subsection to determine whether reservoir operational rules resulted in acceptable conditions with regard to the performance metrics discussed below. The general methodological framework is presented in Fig. 2.

#### 3.1. Stochastic streamflow model

The 100 hydrologic scenarios were generated using PRSim.wave (Brunner and Gilleland, 2020). Fig. 3 provides a general overview



**Fig. 2.** A schematic of the framework for evaluating multi-reservoir river systems under stochastically simulated stationary hydrologic conditions: (1) stochastic streamflow model; (2) basin-wide river system model (ACF-STELLA); and (3) system evaluation metrics. PRSim.wave: Phase Randomization Simulation using wavelets; ACF: Apalachicola-Chattahoochee-Flint.

of the PRSim.wave conceptual framework.

PRSim.wave uses daily streamflow records from the UIF dataset for the period 1939–2012 at the nodes shown in Fig. 1 for model fitting. This model allows for jointly simulating continuous streamflow time series at multiple locations. It couples an empirical spatiotemporal model based on the wavelet transform and phase randomization with the flexible four-parameter kappa distribution. An underlying assumption of PRSim.wave is that the mean of these generated scenarios is comparable to the mean of historical observations, yet the model generates more extreme low and high flows by using the kappa distribution, which allows for extrapolating beyond the observed. This is consistent with the definition of a ‘storyline’ suggested by Shepherd et al. (2018), that is “physically self-consistent unfolding of past events, or of plausible future events or pathways”.

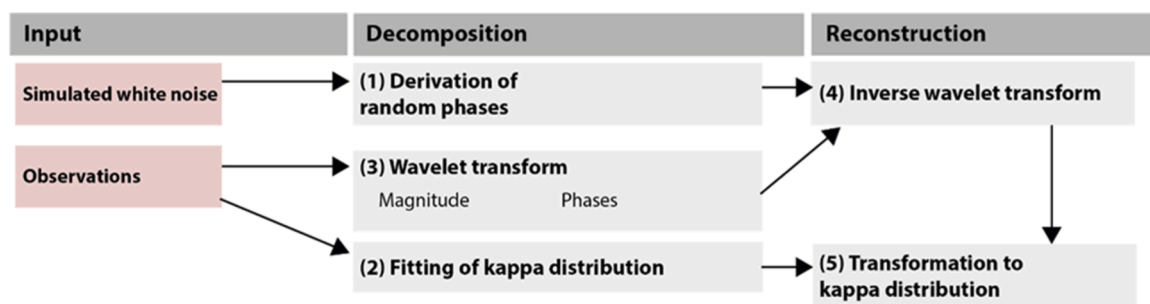
The stochastic approach contains the following steps: (1) deriving random phases; (2) fitting the distribution; (3) wavelet transformation; (4) inverse wavelet transformation; and (5) transforming to kappa distribution. For further details, the reader is referred to Brunner and Gilleland (2020). This model uses daily streamflow records from the UIF dataset for the period 1939–2012 at the nodes shown in Fig. 1 for model fitting. The stochastic simulations by PRSim.wave reproduce the distributional and temporal auto-correlation characteristics of streamflow in individual subbasins of the ACF Basin and the spatial dependencies of flows among them. Average annual flow for the 100 realizations and historical flows differ by less than 0.5% for the entire simulation period, which aligns with the PRSim.wave assumption of comparable average conditions for observations and simulations. Table 2 compares the average monthly flows at the lowest control point in the ACF basin (Jim Woodruff Dam) for the UIF dataset with that of a composite of the 100 stochastically simulated stationary hydrologic scenarios.

### 3.2. Basin-wide river system model

Modeling the hydrologic scenarios was done using ACF-STELLA (Leitman and Kiker, 2015). This river system model is an object-oriented model developed in STELLA®. The primary input data for the ACF-STELLA model include: (1) basin inflow data (UIF); (2) consumptive demand data; (3) evaporation data; and (4) reservoir data including data related to conservation pool characteristics (rule curve elevations, Action Zone elevations etc.) and release rules. The consumptive demand data are the same as the data used in the Hydrologic Engineering Center’s Reservoir System Simulation (HEC-ResSim; Klipsch et al., 2021) model developed for the ACF Basin. The evaporation data is based on a formula developed by USACE (1997) and the three States and is based on the surface area of the reservoirs on a given day. All of the operational data were taken from USACE (2016) and verified by the Corps in the process of calibrating the ACF-STELLA model with the Corps HEC-ResSim model. The model takes the UIF dataset as basin inflow and simulates reservoir operations, consumptive withdrawals and evapotranspiration over the basin at a daily timestep based on reservoir system operation rules in the WCM. Operational rules and consumptive demands are held constant throughout the 74 years the model is run, so the model essentially runs these operational rules under 74 different annual hydrologic conditions. Each of the 100 realizations generated under PRSim was used as basin inflow into the ACF-STELLA model in place of the UIF dataset to generate a series of distinct hydrologic scenarios. The model was recently used by the USFWS (2016) to develop a Biological Opinion for the WCM update and has been shown to produce comparable results with the current WCM’s reservoir system modeling approach in the ACF Basin (Hathorn, 2020), which was done using the HEC-ResSim model. In our analyses, the consumptive demands used in ACF-STELLA were the same as those used in the HEC-ResSim for the preferred alternative (Alt. 7 K; USACE, 2016). The ACF-STELLA model uses the Muskingum method (USACE, 1936) for flow routing across the river network.

### 3.3. System evaluation metrics

Reservoir system operation decisions in the ACF Basin are based on meeting Congressionally authorized project purposes. In the ACF, these include the management of hydrologic extremes (floods and droughts), water supply, fish and wildlife, navigation, reservoir-based recreation and hydropower generation (USACE, 2016). We evaluated the basin response to our stochastically



**Fig. 3.** Illustration of the stochastic simulation approach by Phase Randomization Simulation using wavelets (PRSim.wave) model. PRSim.wave has five main steps: (1) derivation of random phases using a white noise time series; (2) fitting of the kappa distribution to the observed streamflow time series; (3) wavelet transform to derive the amplitudes and phases of the time series; (4) inverse wavelet transform reconstructing a streamflow time series using the random phases from Step 1 and the amplitudes from Step 3; and (5) transformation to the kappa distribution using the parameters estimated in Step 2. Steps 1–5 are repeated  $n$  times to generate  $n$  realizations of different time series.

**Table 2**Release rules for Jim Woodruff Dam ( $\text{m}^3/\text{s}$ ) for historical and simulated conditions (composite).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Historical	749	902	1079	926	567	404	438	371	316	341	411	563
Stochastically simulated stationary hydrologic scenarios	751	902	1.069	927	580	424	436	381	334	345	411	577
Difference (%)	-0.19	-0.01	+0.93	-0.05	-2.30	-4.84	+0.48	-2.73	-5.74	-1.23	+0.15	-2.44

simulated stationary hydrologic scenarios using a set of metrics to reflect a variety of management purposes. These included (Table 3): 1) urban water supply; 2) composite storage of major reservoirs; 3) inflows to the Apalachicola River floodplain and estuary; and 4) hydropower generation. The composite storage metric considers the volume of support provided from the ACF reservoir system to Jim Woodruff Dam releases and the resultant release which is the inflow to the Apalachicola River. As noted earlier, these are not necessarily the same.

If the purpose of an evaluation is to select the best approach to managing a basin such as what was done in developing the WCM, then a broader range of metrics which includes all project purposes as well as other major stakeholder concerns should be taken into consideration. In this case, however, we are only concerned with whether the management approach used in the WCM is acceptable under alternative hydrologic conditions and a more limited set of metrics suffices. The selected metrics are dependent on the magnitude, duration, frequency, timing and location of flows or of storages.

For each metric, we analyzed how often pertinent thresholds defined by the metrics were exceeded for both the UIF and the stochastically simulated stationary hydrologic scenarios as basin inflow. We compared the historical and hydrologic scenarios based on these metrics using the average values and percentiles. The empirical cumulative distributions of metrics were also compared using the two-sample Kolmogorov-Smirnov (K-S) tests (Massey, 1951).

### 3.3.1. Urban water supply

This metric is evaluated based on the storage pool elevation at Lake Lanier, which serves as a key contributor to the source of drinking water for Metro Atlanta, Georgia. The relevant elevations considered for this metric are the elevations of water intakes in the reservoir and the bottom of Lake Lanier storage pool (315.0 m). Multiple local governments—counties and cities—withdraw water from Lake Lanier (USACE, 2016). Concerns over water suppliers having access to drinking water are significant at an elevation of 324.0 m and only become greater as the elevation declines. The City of Buford's intakes are at elevations 323.70, 320.65, 317.60 and 314.55 m. The City of Gainesville has three intake structures, each with intake ports ranging from an elevation of 324.0 m down to 312.4 m (USACE, 2016). Failure to keep the pool elevation above a water supply intake would require pumping and treating the drinking water at considerable expense. If the water level drops below the bottom of the conservation pool, even more draconian measures would be necessary to secure the water supply for Metro Atlanta. This metric is evaluated in terms of the percent of time and the maximum number of consecutive days the elevation at Lake Lanier is below 324.0, 320.0, 317.0 and 315.0 m.

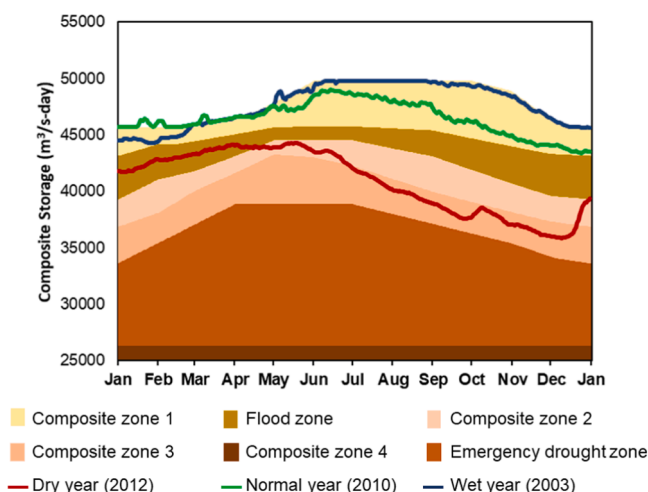
### 3.3.2. Composite storage of major reservoirs

The composite storage is one of the factors that defines the minimum rate of support from the federal storage reservoirs for the release from the Jim Woodruff Dam under the WCM (Table 1). Composite storage is the only variable in the WCM's reservoir management rules that can be controlled to influence management of the basin. Time of the year and basin inflow cannot be managed. Fig. 4 shows the elevations for defining composite storage over the year and the resultant modeled composite storage for three years representing a wet year, normal year and dry year using the UIF set as the basin inflow. In addition to comparing the volume of composite storage, an evaluation was made on the percentage of time the composite storage was in the various composite zones and the frequency of time that drought and emergency drought operations were in effect since these operations are triggered by the composite storage.

**Table 3**

Quantitative metrics used to measure the basin response.

Metric	Indicator	Relevant period	Characteristics
Urban water supply	Reservoir elevations at Lake Lanier below the elevation of the bottom of the conservation pool and water intakes in the reservoir < 315, 317, 320 and 324 m	Throughout the year	Magnitude, frequency and duration
Inflow to river floodplain and estuary	Jim Woodruff Reservoir releases of $127.4 \text{ m}^3/\text{s}$ (emergency drought), $141.6 \text{ m}^3/\text{s}$ (drought) and $169.9 \text{ m}^3/\text{s}$ for low flow Jim Woodruff Reservoir releases > $400 \text{ m}^3/\text{s}$ for inundation of forest floodplain	For low flows throughout the year For floodplain release focus on growing season and fish spawning season	Magnitude, frequency, timing and duration
Composite storage zone	Total storage in the major reservoirs	Throughout the year	Magnitude, frequency and duration
Hydropower generation	Amount of time in each Action Zone (1, 2, 3 or 4) at each major reservoir	Throughout the year	Frequency of time in action zone



**Fig. 4.** Composite storage zones in the Apalachicola-Chattahoochee-Flint (ACF) Basin in wet, normal and dry years with the unimpaired flow (UIF) as the basin inflow.

### 3.3.3. Inflow to the river floodplains and estuary

Apalachicola River is a major source of freshwater inflow and nutrients to the West Florida Shelf in the northeast Gulf of Mexico (Morey et al., 2009) and for Apalachicola Bay proper. Prolonged extreme low flow events in this river were associated with the collapse of the oyster industry (Pine et al., 2015). Thus, the occurrence of extreme low flows is an important consideration with regard to the Apalachicola River and estuary.

The concerns with flow in the Apalachicola River and Estuary are associated with the flow necessary to inundate the river floodplain and the frequency, timing and duration of extreme low flow events in the river and into the estuary. Many of the natural levees along the Apalachicola River begin to be overtopped at a flowrate of about  $400 \text{ m}^3/\text{s}$  (Light and Darst, 1998) and the inundation area of the floodplain relative to the river flow increases more rapidly once the levees are overtopped. The seasonal flooding of the Apalachicola River floodplain is important to the ecological integrity of the riverine and estuarine ecosystems for fish spawning and nutrient delivery (Burgess et al., 2012). Many of the fishes in the Apalachicola River spend a portion of their lifecycle in the floodplain and may be considered floodplain dependent. In the summer months, long periods (greater than 60 days) of low flows have changed the vegetative components of the swamp and the salinity structure of the estuary. We evaluated this metric based on the volume of flow into the Apalachicola River through the Jim Woodruff Dam. Our metric is based on the volume of flow under the drought and emergency drought thresholds in the WCM and on the inundation of the river floodplain.

The minimum release to the Apalachicola River under the WCM is  $141.6 \text{ m}^3/\text{s}$  during normal and drought periods. During extreme drought periods, this release is reduced to  $127.4 \text{ m}^3/\text{s}$ . A sustained period of extreme low flows precipitated the US Supreme Court lawsuit based on the argument that Georgia withdrawals resulted in ecological damages to the Apalachicola River's floodplain and estuary (US Supreme Court, 2017). In their filing with the Supreme Court, Florida argued that the number of days Woodruff's release was below  $169.9 \text{ m}^3/\text{s}$  proved that agricultural withdrawals from the Flint had reduced releases to the Apalachicola River over time. Therefore, the release volume was also included in our analyses. Under this metric, we considered the frequency, timing and duration of low flows. The seasonality of low flows was also evaluated as it affects the population of some marine species like oyster juveniles. With regard to floodplain inundation, the concerns would also include timing of floodplain inundation both with regards to fish spawning activities and the growing season for floodplain trees.

### 3.3.4. Hydropower generation

This metric was based on Action Zones at the individual major reservoirs. If sufficient conservation storage is available, the storage facilities (Buford, West Point and Walter F. George) typically provide a minimum of two hours of peaking generation per day, five days per week at powerhouse capacity throughout the year. The amount of daily generation is governed by a preset guide curve and Action Zone elevations for each reservoir, with diminishing energy generation with declining storage (USACE, 2016). By evaluating how often each of the reservoirs is in the various Action Zones, it can be determined how well a specific hydrologic scenario performs relative to supplying peaking power. Our focus in this metric was the amount of time each of the reservoirs falls in Action Zone 1 when the most peaking power is produced and in Zone 4 when no peaking power is produced. In the other Action Zones—2 and 3—two hours of peaking power are provided.

## 4. Results

### 4.1. Basin-wide river system modeling

Fig. 5 shows the 5th, 50th (median) and 95th percentile time series of water elevations at Lake Lanier, composite storage in the study basin and Jim Woodruff outflow, for the historical flows and stochastically simulated stationary scenarios. This figure shows that the extremes are generally greater (i.e., smaller low flows and greater high flows) in the stochastically simulated stationary scenarios than the UIF. For Lake Lanier elevations and the composite storage, the differences are more extreme for lower elevations since the elevation of Lake Lanier and the upper elevation of water in the conservation pools are limited by the design of a reservoir. In the ACF-STELLA model, water is not stored in the flood pool of a reservoir. Therefore, contrary to Jim Woodruff outflow, their upper values are constrained and do not reflect more extreme events as this outflow does. Lake Lanier is managed conservatively to prevent the reservoir from dropping below the elevation of the water intakes. Once the top of the individual conservation pools or of the composite storage is reached, water is spilled to keep storage within the boundaries of the conservation pool. For Jim Woodruff outflow, this disparity is not evident because PRSim.wave was designed to produce comparable outflow from Jim Woodruff Dam over the entire study period (1939–2012).

### 4.2. Assessment of system evaluation metrics

#### 4.2.1. Urban water supply metric

Fig. 6 shows the monthly water elevation at Lake Lanier for the historical inflows and the stochastically simulated stationary scenarios alongside the elevations of Lake Lanier's water intake thresholds in the reservoir and the bottom of the conservation pool. Overall, the elevation at Lake Lanier was more extreme (both for less and greater) in the output for the stochastically simulated stationary scenarios than in the historical output. Every month, the extreme low elevations were at levels that were unacceptable (i.e., at or near the bottom elevation of the conservation pool). For the 324.0 m threshold of the urban water supply metric, the elevation at Lake Lanier for both the UIF and stochastically simulated stationary scenarios falls below the threshold with some regularity. For the stochastically simulated stationary scenarios, the elevation is below the 75th percentile during the fall and winter. Furthermore, for the scenarios the elevation falls below the 317.0 m threshold in every month. For the UIF, the elevation is above the 320.0 m threshold in most of the months and never below the 317.0 m threshold.

We also found that the greatest annual frequency of water supply threat and the longest duration of drought in the basin were both greater for the stochastically simulated stationary hydrologic scenarios than the UIF (Fig. 7). Upper tails of the distributions of frequency and longest duration were also much greater under the stochastically simulated hydrologic scenarios; i.e., more extreme and

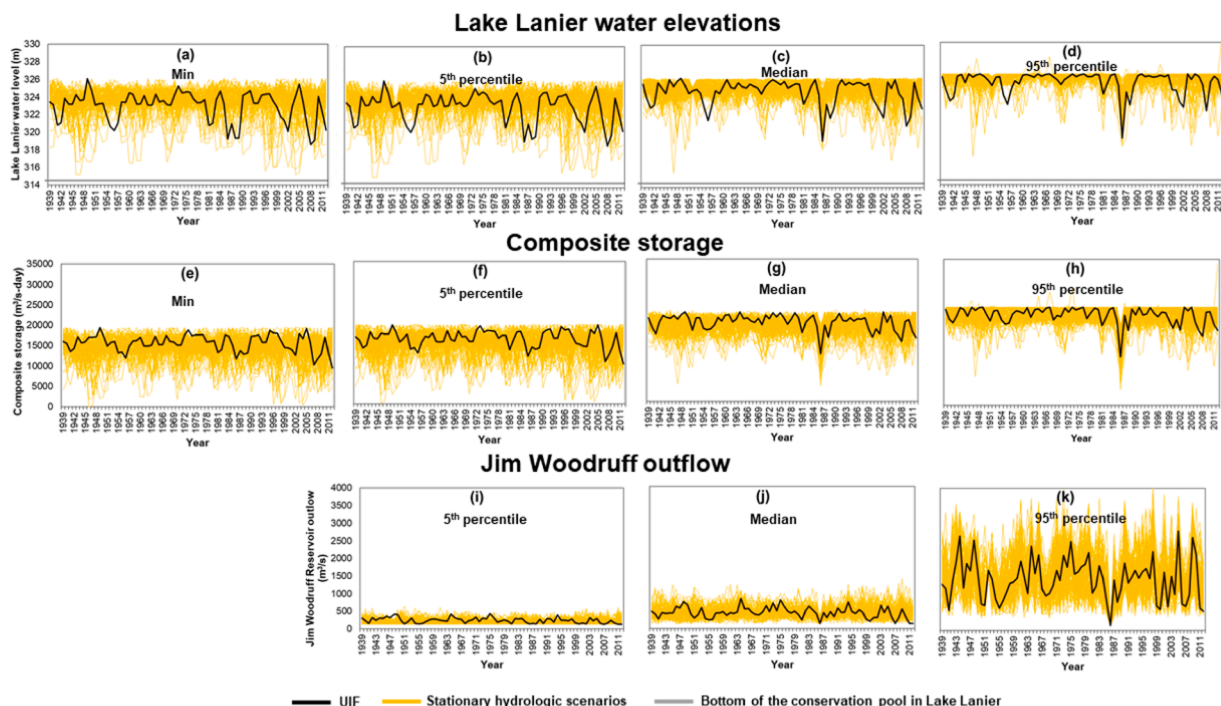


Fig. 5. Minimum, 5th, 50th and 95th percentile time series of: (a-d) water elevations at Lake Lanier; (e-h) composite storage; and (i-k) Jim Woodruff outflow in the unimpaired flow (UIF) and stochastically simulated stationary hydrologic scenarios. Minimum time series are not presented for Jim Woodruff outflow since it is constantly  $141.6 \text{ m}^3/\text{s}$ .

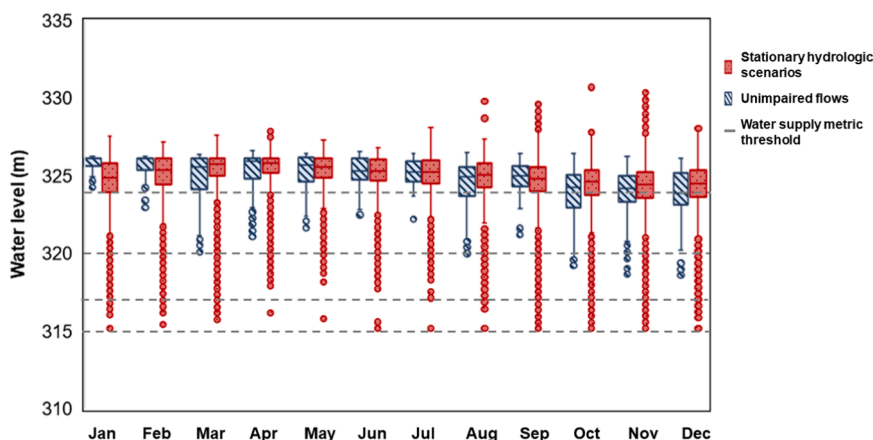


Fig. 6. Box-and-whisker plots of the monthly water elevations at Lake Lanier Reservoir for the unimpaired flows and an ensemble of the 100 stochastically simulated hydrologic stationary scenarios. The dashed lines represent the elevations of the bottom of the conservation pool and of water intakes from the cities of Gainesville and Buford, Georgia.

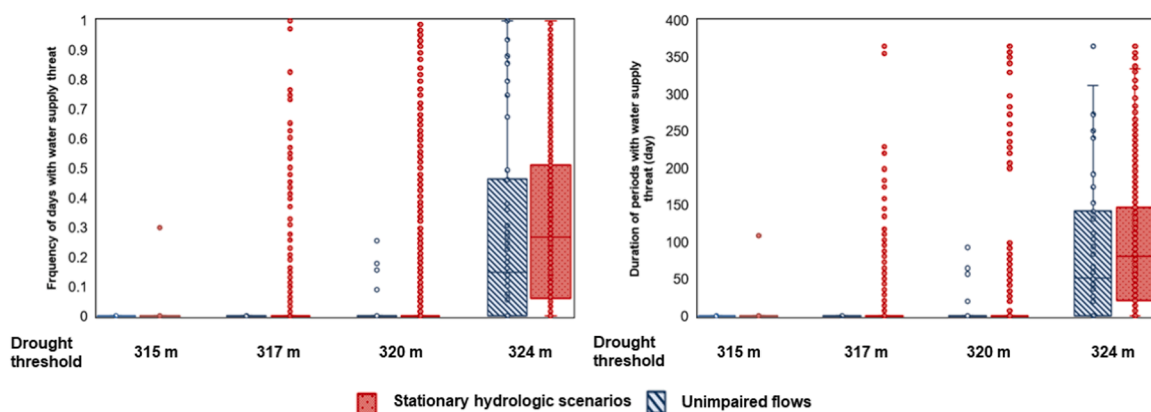


Fig. 7. Box-and-whisker plots of the urban water supply metric for the annual: frequency; and longest duration of days when the drought thresholds (315, 317, 320 and 324 m) are exceeded under the unimpaired flows and 100 stochastically simulated stationary hydrologic scenarios.

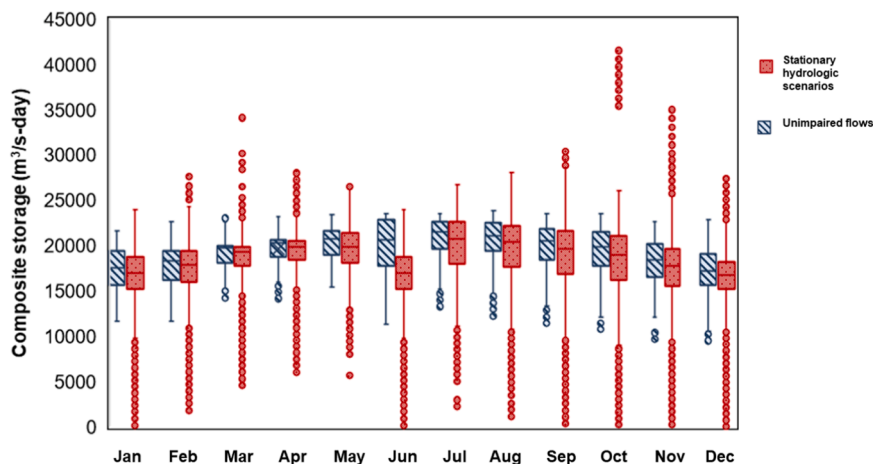


Fig. 8. Modeled composite storage for ACF Basin for the unimpaired flows and an ensemble of the 100 stochastically simulated stationary hydrologic scenarios.

elongated water supply threats are possible than the ones historically experienced. However, the K-S test results showed that the distribution of both these characteristics under the stochastically simulated scenarios remains statistically identical to the historical distribution (significance level of 5%). Our seasonality analyses showed that there is a greater threat of Lake Lanier elevation falling below the elevation of the lowest water intake during the summer. Fig. 7 also shows that, in the stochastically simulated scenarios, the occurrences of being below the four urban water supply thresholds were infrequent, except for the 324.0 m threshold. The duration for the Lake Lanier elevation < 324.0 m threshold was significant though.

#### 4.2.2. Composite storage of major reservoirs

Fig. 8 shows the monthly composite storage for the historical and the 100 stochastically simulated stationary hydrologic scenarios. The composite storage was lowered under the stochastically simulated scenarios for the median, 75th percentile and low values (i.e., smaller than the lower quartile). Composite storage was also greater every month at high values (i.e., greater than the upper quartile). In half of the months, the composite storage neared zero, meaning the reservoirs had no available water for any use and in every month the extreme low values were below 5000 m<sup>3</sup>/s-day.

We next evaluated the percentage of time that drought and emergency drought operations were in effect. Since the Flint Subbasin is unregulated and Lake Seminole has very limited storage during the drought conditions, it is possible for the system to be in drought or emergency drought operations and the volume of outflow from Jim Woodruff Reservoir to exceed the prescribed minimum release thresholds. Fig. 9 shows the average number of days/month that Jim Woodruff Reservoir outflow was less than 141.6 m<sup>3</sup>/s and 169.9 m<sup>3</sup>/s for both the UIF flows and the stochastically simulated stationary hydrologic scenarios. Drought and emergency drought operations occurred more often under the hydrologic scenarios than under the UIF. Under the UIF, the drought operation was triggered during 17.4% of the year, while under the individual stochastically simulated stationary hydrologic scenarios, drought operations were in effect between 23.3% and 31.8% of the time in the individual runs with an ensemble average of 27.8%. When evaluating the difference for the emergency drought operation, we found that this operation was not triggered under the UIF flows but had an annual range of 0.0%–5.1% under the individual stochastically simulated stationary hydrologic scenarios with an ensemble average of 1.3%. An increase in the average number of days/month outflow was at or less than 141.6 m<sup>3</sup>/s (emergency drought release) and 169.9 m<sup>3</sup>/s (drought release) was found for the stochastically simulated stationary hydrologic scenarios. For releases at or less than 141.6 m<sup>3</sup>/s, the differences are greatest in June, July and August, while for releases at or less than 169.9 m<sup>3</sup>/s, the differences are greatest in June through December. However, for every month of the year, there are more days during which outflow is less than 169.9 m<sup>3</sup>/s. This increase in the number of days with extreme low flows is driven by both the increases in the number of days that drought and extreme drought operations are triggered under the 100 realizations and that Zone 5 was in effect far more often under the 100 realizations.

Table 4 shows how often the composite storage was in each of the zones for the UIF and the stochastically simulated stationary simulated scenarios. Under the UIF flow scenario, the composite storage fell in Zones 1 and 4 more frequently, while under the stationary hydrologic scenarios, the composite storage fell in Zones 2, 3 and 5 (extreme drought) more frequently. Overall, the time in which the composite storage is in various composite zones is more favorable under the UIF dataset. Under the stochastically simulated stationary hydrologic scenarios, volume of composite storage was more extreme for both low and high volumes. For these scenarios, the minimum volume was comparable to the 98th percentile of the UIF, suggesting that the minimum composite storage volume was less than that of the UIF for a significant amount of time. In several months, the minimum value was at or close to having no storage in all major reservoirs of the basin.

#### 4.2.3. Inflow to the river floodplains and estuary

Fig. 9 shows the average number of days/month flow was less than 141.6 m<sup>3</sup>/s and 169.9 m<sup>3</sup>/s for the UIF and the hydrologic scenarios and Table 5 how frequently the drought and the emergency drought triggers were in effect. How often and when drought and emergency drought operations are in effect is important to the floodplain and estuary because the majority of the ACF watershed is above Jim Woodruff Dam. This, therefore, defines how often and when low and extreme low flows will occur.

Fig. 9 and Table 5 show that the drought and emergency drought triggers were set off more frequently in the stochastically

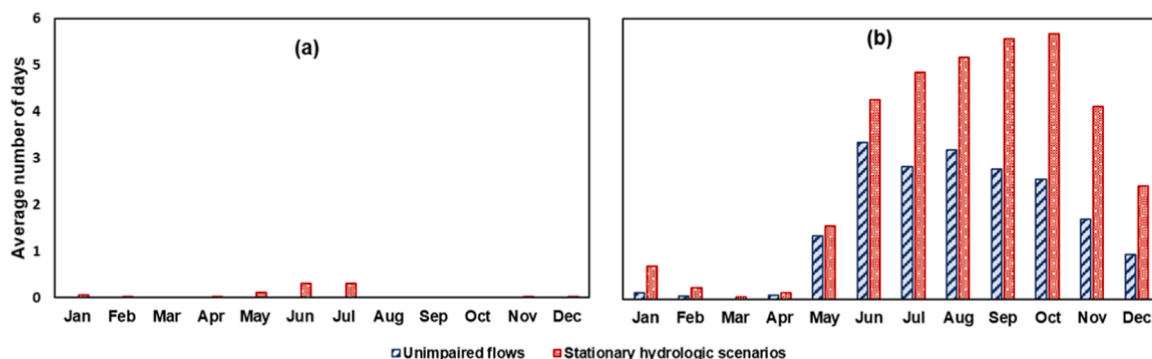


Fig. 9. Average number of days/month that Jim Woodruff outflows were at or below the: (a) emergency drought threshold (141.6 m<sup>3</sup>/s); and (b) drought threshold (169.9 m<sup>3</sup>/s).

**Table 4**

Frequency of time a composite storage zone was in zone elevations for the unimpaired flows (UIF) and stochastically simulated stationary hydrologic scenarios (100 realizations of the UIF).

Hydrologic scenario	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
UIF	56.36%	22.23%	11.92%	8.78%	0.70%
Average of 100 stochastically simulated stationary hydrologic scenarios	47.03%	27.05%	14.36%	7.37%	3.20%

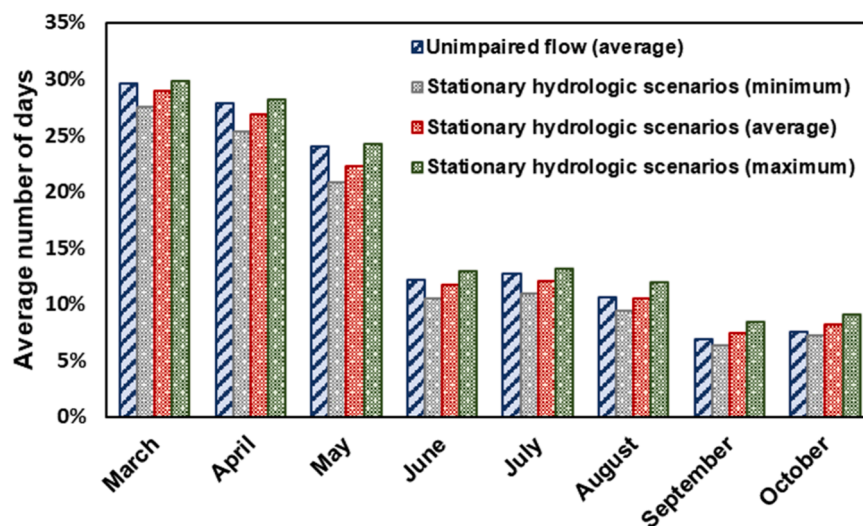
**Table 5**

Frequency of time which the drought trigger and emergency triggers were in effect under the unimpaired flow (UIF) set and stochastically simulated stationary hydrologic scenarios (100 realizations of the unimpaired flow).

Drought trigger	UIF	Stochastically simulated stationary hydrologic scenarios
Maximum	—	31.84%
Average	17.44%	27.83%
Minimum	—	23.29%
Extreme drought trigger	UIF	Stochastically simulated stationary hydrologic scenarios
Maximum	—	5.07%
Average	0.00%	1.30%
Minimum	—	0.00%

simulated scenarios than in the UIF. When these triggers are in effect, support from the ACF storage reservoirs is at its minimum threshold coinciding with an increase in the number of days extreme low flows can occur. It should be recognized that even when drought and emergency drought operations are in effect, it is possible for releases from Jim Woodruff Dam to be greater than the minimum levels provided by the reservoir system support. This apparent disparity is caused by the fact that Lake Lanier is slow to recover from being drawn down during drought events because the reservoir impounds such a limited part of the ACF Basin, yet, it has about two-thirds of basin's storage capacity. Therefore, Lake Lanier has an oversized impact on defining when drought relief is in effect. It is not uncommon for drought relief to be in effect and the storage pools at the West Point and W.F. George Reservoirs to be in Zone 1 near the top of their conservation pools, suggesting that the 90% of the basin above the Jim Woodruff Reservoir is providing basin inflow to this reservoir and causing this apparent disparity.

The river floodplain is integral to the productivity of the riverine ecosystem (Burgess et al., 2012). Fig. 10 shows the number of days/month from March through October during which Jim Woodruff outflow exceeded  $400 \text{ m}^3/\text{s}$ . The flow threshold needed to top the river's levees for inundation of forest floodplain, for the UIF and the hydrologic scenarios. This figure compares the frequency of time that flow exceeded the volume necessary to top the natural levees along the Apalachicola River from March through October. The number of consecutive days during which Jim Woodruff outflow was below the threshold of  $400 \text{ m}^3/\text{s}$  for increased floodplain inundation was greater in 60% of the stochastically simulated stationary hydrologic scenarios than under the UIF. The maximum number of consecutive days that the outflow was below this threshold was over twice as large in the stochastically simulated stationary hydrologic scenarios. The mean outflow of Jim Woodruff Reservoir when the drought trigger was in effect was  $406.3 \text{ m}^3/\text{s}$  under the UIF flows and  $444.4 \text{ m}^3/\text{s}$  for the stochastically simulated stationary hydrologic scenarios.



**Fig. 10.** Number of days per month during which Jim Woodruff outflow exceeded  $400 \text{ m}^3/\text{s}$  (the flow threshold for inundation of forest floodplain) under the unimpaired flow (UIF) set and stochastically simulated stationary hydrologic scenarios (100 realizations of the unimpaired flow).

#### 4.2.4. Hydropower generation

According to Fig. 11, the frequency of time and the maximum duration of time during which all three of these reservoirs were in Action Zone 1 was reduced for the hydrologic scenarios and the frequency of time and maximum duration of time these reservoirs were in Zone 4 increases for the hydrologic scenarios for West Point and WF George.

### 5. Discussion

Our analyses showed that reservoir system management approaches developed considering only historical hydrology proved to be unacceptable when a broader range of stationary hydrologic scenarios is considered. One of the concerning effects of our analyses was the lowering of Lake Lanier to near the bottom of its conservation pool. Lake Lanier plays an integral role in meeting Metropolitan Atlanta's water supply and, as a headwater reservoir, refill at this reservoir is difficult due to the small contributing watershed. If water elevations at this reservoir drop close to the bottom of the pool or even the elevation of the lower water intakes, it could take a long time to refill the reservoir meaning it is possible for a prolonged water shortage.

Water elevations at Lake Lanier were far lower in the stochastically simulated stationary scenarios than in the UIF flows. Factors causing water elevations at Lake Lanier to be lowered can be categorized into those at and above this reservoir and those that define the water release from the reservoir to the basin downstream of the Lake Lanier Reservoir (Fig. 1). Causal factors for lowering Lake Lanier storage that relate to inflows into Lake Lanier or consumptions from the reservoir include a relative deficit in inflows to the reservoir from the contributing streams, changes in withdrawals or returns for the Metro Atlanta region directly from or into this reservoir and evaporative losses from the reservoir. Of these, only the local inflow differences can cause the magnitude of changes noted in Fig. 6. Consumptive extractions and evaporation were not changed in modeling the stochastically simulated stationary hydrologic scenarios.

Causal factors related to water releases from Lake Lanier to the downstream areas include: 1) meeting minimum flow requirements for water quality control at Peachtree Creek; 2) balancing pool elevations in the reservoir with the two other major reservoirs; 3) providing support to the Apalachicola River to meet minimum flow requirements of the WCM; 4) contributions to meeting the minimum required release from the Jim Woodruff reservoir; and 5) providing hydropower generation. Among these, the first, second and fourth factors can cause the magnitude of the changes. If the WCM is to be revised to address the lowering of water level at Lake Lanier under the stochastically simulated stationary hydrologic scenarios, an exhaustive evaluation of the causal factors for lowering the reservoir water level is required.

Our analyses showed that under the stochastically simulated stationary hydrologic scenarios, the current operational rules for the ACF basin result in the composite storage being exhausted. This, in turn, would curtail the capacity of the reservoir system to buffer the occurrence of extreme low flows in the Apalachicola River and Estuary. Peaking power produced by Buford, West Point and W.F. George Dams would also be lessened under the hydrologic scenarios.

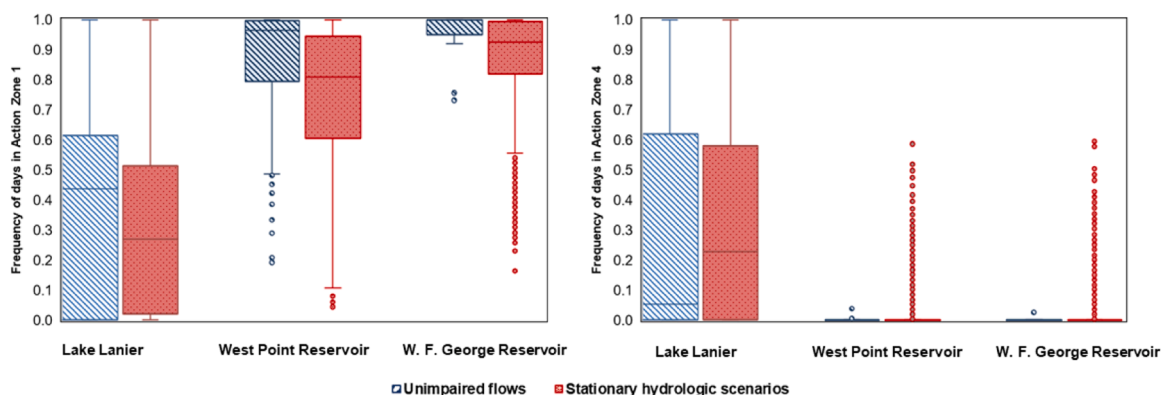
Similar to Schlef et al. (2018), who showed the substantial impact of natural climate variability on water supply in the ACF Basin, our results showed that urban water supply is threatened under alternative hydrologic scenarios. Our results also agreed with global climate model (GCM)-based assessments of Tasker (1993) on shorter periods of low flow days in the basin. Georgakakos and Yao (2000, 2003), Georgakakos et al. (2010) and Sun (2013) used future climate projections by GCMs and predicted that under prolonged droughts, the ACF Basin would frequently fail to meet the need for water supply, power demands and ecosystem protection. The authors further suggested the need to revisit the current operational rules of the federally managed reservoirs to cope with the future climate conditions. This suggestion was similar to ours based on stochastically simulated stationary hydrologic analyses. Similar to our findings on the water supply metric under stationary hydrologic scenarios, Yao and Georgakakos (2011) and Jiang (2013) evaluated that the ACF Basin is anticipated to experience water supply deficits under climate change scenarios. Viger et al. (2011) and Walker et al. (2011) showed that, under future climate change scenarios, Flint Subbasin experiences a slight decrease in streamflow. The study of Liu et al. (2013) on the entire Southeast US also projected more severe and prolonged droughts. Most of the previous studies focused on water supply and drought risk but a range of relevant metrics, which were studied here, have been rarely considered in climate variability/change assessments.

#### 5.1. Application of the presented framework to other regulated basins

While our framework was demonstrated through a case study on the ACF Basin, this framework can be applied to evaluate the effectiveness of reservoir operations in other basins. To apply this framework to other basins, historical daily streamflow observations must exist for an adequately long period and be converted to flow sets similar to the UIF dataset, so that flows occurring from the first year to the last year of the dataset are comparable (e.g., impacts of variable consumption and/or variable regulation are removed from the dataset). The stochastic streamflow model (PRSim.wave) can then be coupled with a basin-wide river system model and the stochastic streamflow model can be used to extend the number of years evaluated. This river system model can be deterministic but should be applied within a probabilistic framework; e.g., by coupling it with a Monte Carlo method. The system evaluation metrics should be specified based on the reservoir management purposes of the given basin. These metrics can be prioritized based on the specific basin needs and management priorities. It is also recommended that evaluation metrics be weighted to reflect the importance of individual metrics.

#### 5.2. Limitations and future research

Our analyses should be expanded to consider nonstationary climate effects on managing the watershed using climate change



**Fig. 11.** Box-and-whisker plots of the hydropower generation metric for the ratio of days (annual frequency) in: (a) Action Zone 1; and (b) Action Zone 4 in the major reservoirs 4 under the historical and stochastically simulated stationary hydrologic scenarios.

scenarios (IPCC, 2022). An adaptive management plan should be developed to implement this research and permit a management approach that evolves over time and is reversible (Feldman, 2008). Limitations exist in our study and we recommend that they are investigated in the future. A series of workshops and surveys for a broad range of stakeholders, are recommended to derive ranges and thresholds for the metrics. Selection of the metrics in other basins would depend on the purposes of the reservoir operations, types of aquatic habitats, among others. Researchers also need to transparently communicate stochastic analyses, similar to the present study, to the stakeholders and inform them about these alternative stochastically simulated stationary hydrologic scenarios and their expected consequences. Other metrics such as risk of dam failure (when operated at high pool elevations) can be also added to our set of metrics for the study area to obtain a fuller picture of the system response. If efforts are spent developing a new set of management guidelines, a complete set of metrics, including those related to flood control and other public uses of river systems should be developed and included in the development of these guidelines. Alternative indicators can be also proposed for the system metrics. For instance, the marine ecosystem health is linked with salinity and is not fully explained by freshwater inflows, our proxy variable, while water supply can be represented by more sophisticated drought indicators (e.g., Steinemann, 2003). Further, we focused only on the streamflow variability; the variability of other factors like soil water content that can trigger drought events (Sohrabi et al., 2015) and their relationships with streamflows were not explored. These should be explored along to provide a fuller picture of alternative hydrologic scenarios and the reservoir response. Increased water uses and withdrawals due to population growth, particularly in the basin upstream where mostly urbanized areas (metro Atlanta) are located, can also affect the hydrologic dynamic and the system metrics (Karki et al., 2021). A similar stochastic approach to this study (PRSim.wave) can be further developed to generate multi-variate stochastic scenarios of the future.

## 6. Summary and conclusions

In this paper, we evaluated how well the response of operational rules of a managed river system—the ACF Basin in the Southeast US—would perform well under a set of alternative stationary hydrologic conditions. The basin response was evaluated under historical observations and 100 stochastic streamflow realizations of the stationary hydrology, which represent plausible hydrologic conditions that may occur in the future or occurred outside the observational period-of-record in terms of magnitude, frequency, timing and duration of these events. These stationary scenarios were simulated by coupling a stochastic streamflow model—PRSim.wave—with a basin-wide river system model—ACF-STELLA. The 100 scenarios were used to evaluate the multi-reservoir system response against four pertinent metrics—urban water supply, required freshwater inflows, floodplain forest ecosystem water needs and hydropower generation—that were dependent on the elevation and storage of the major reservoirs in the study basin. We evaluated these metrics based on magnitude, frequency, duration and seasonality. Overall, we found that the ACF Basin response in terms of all the metrics was less favorable under the stationary hydrologic conditions than the historical condition. This showed that the current operation rules (defined by the WCM) did not perform satisfactorily in all cases under these alternative flow conditions. This finding is significant because it demonstrates that in an era of changing climate (and subsequently hydrologic processes), it is not prudent to have operational rules fixed for multiple decades. Instead, managers need to select metrics to define what operational results are acceptable and have more flexible operational rules to allow meeting these metrics. There needs to be a better link between current scientific and engineering understanding of the basin and present-day management.

The presented framework in this paper provides a foundation for analyzing current reservoir operational rules and proposes alternative operation strategies that are efficient under otherwise plausible hydrologic conditions considering various management metrics. These strategies can be developed by coupling multi-objective optimization algorithms with our modeling framework. The revisit should define further research that helps us better understand relationships between the basin management and the system evaluation metrics developed to define acceptable conditions. On a broader scale, the ongoing problems being experienced in the Colorado, Mississippi and Columbia basins (Payne et al., 2004; Hoerling et al., 2019) suggest that consideration of a broader range of hydrologic scenarios is necessary to avoid bad surprises. To define an effective management of a reservoir system for the future,

hydrologic conditions beyond those observed in the past need to be considered.

### CRediT authorship contribution statement

**Steve Leitman:** Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Ebrahim Ahmadisharaf:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Manuela I. Brunner:** Conceptualization, Methodology, Software, Writing - review & editing, Visualization.

### Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Steve Leitman reports financial support was provided by Florida State University.

### Data Availability

Datasets for this research—UIF and stochastically simulated stationary streamflows—are available at [Ahmadisharaf et al. \(2023\)](#).

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### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2023.101608](https://doi.org/10.1016/j.ejrh.2023.101608).

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