Bridging Hydrology, Ecology, and Reservoir Management to Address Environmental Flow Specifications from Dams in a Changing Climate

by

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EXECUTIVE SUMMARY

Water resource management has altered the natural flow regime of rivers around the globe. Buffers to environmental risk and uncertainty, dams balance competing demands for water storage and release for human needs. While dams have served as a cornerstone for human development, they have historically been tied to river exploitation, jeopardizing ecological health and species richness of streams and rivers. This project seeks to assess the impacts of current reservoir management practices on downstream ecological integrity in a changing climate with a focus on rainfall distribution shifts. We assess these impacts in a ‘model-world’ that captures some of the complexities existing in natural systems while enabling various dam management scenarios to operate under controlled conditions. For this reason, a lumped three-part mathematical model was developed to represent the impacts of precipitation and dam management on the stability of a simplified food web operating downstream from the dam. First, a watershed routing model was derived to link precipitation statistics and watershed land cover properties using a prescribed unit hydrograph. Second, a nonlinear reservoir model linking inflow, outflow and storage behind the dam was used to generate distinct patterns of streamflow variability downstream of the dam. Last, the dynamics of a three species food web were coupled to the aforementioned flow downstream from the dam so as to determine whether reservoir operations can sustain the downstream food web stability. This three-part lumped model was operated under five reservoir management scenarios: Natural flow variability, run of river, minimum flow management, drought management, and flood management. Using predictions from the IPCC AR5 Report (2013), changes in precipitation frequency and depth due to long term shifts in the climate were evaluated assuming long-term annual precipitation is not altered. By simulating multiple reservoir management scenarios, it is envisaged that reservoir operators can accommodate ecological integrity explicitly. As expected, flow variability was found to decrease substantially in each of the four dammed scenarios when compared to an unregulated flow regime, with the range of flows shifting from $10^2$-$10^8$ to $4$-$5$ $10^5$ m$^3$/day. With less frequent and more intense storms, the outflow from the reservoir shifted towards less frequent, higher magnitude flow rates in each scenario. None of the scenarios tested maintain populations in all trophic levels for the duration of the modeling period when faced with high variability in rainfall inter-arrival times. Presently, reservoir managers operating their dams under run of river or flood management will achieve the greatest
downstream ecological integrity. However, as precipitation patterns shift from more frequent and less intense to less frequent and more intense storms, these reservoir types are most at risk to ecological degradation. The downstream food web appeared to be resilient to a changing precipitation pattern in a minimum flow management scenario, indicating that current management practices that preserve “ecological integrity” may be advantageous in an uncertain climate future. While the study’s findings support that minimum flow regulation may be one of the best management approaches in a changing climate, the top trophic level is only maintained during 33.6% of the modeling time period for said management scenario. Continued efforts should be made to optimize reservoir management practices so as to improve ecological integrity in an uncertain future. Serving as a first attempt at linking shifts in precipitation statistics, hydrology, reservoir management, and ecology, this study provides new insight into the effects of dam management on downstream food web dynamics, allowing reservoir managers to assess the impacts of their management decisions to preserve ecological integrity.
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Introduction

Water resources management has altered the natural flow regime of rivers around the globe. In the US alone, there are an estimated 84,000 dams artificially controlling more than 85% of inland waterways (Poff et al, 1997). Buffers to environmental risk and uncertainty, dams balance competing demands for water storage and release for human needs. While adequate and sustained water supply, as well as flood control, have been a cornerstone of human development, dam operations have historically been tied to river exploitation jeopardizing ecological health and species richness of streams and rivers. The immeasurable benefits society derives from healthy river systems are under imminent threat as rivers deteriorate.

Conventionally, ecological protection has focused on water quality and minimum flow regulation from dams. The management strategies applied to control river flow range from the minimalistic minimum flow (Montana/Tennant method) to comprehensive, modified flow regimes driven by different monthly and event-based allocations (Range of Variability Approach) (Richter et al., 1997). Minimum flow requirements fail to recognize that water systems depend on their natural dynamic character driven by 1. the magnitude of monthly water condition, 2. the magnitude and duration of annual extreme water conditions, 3. timing of annual extreme water conditions, 4. frequency and duration of high/low pulses, and 5. rate/frequency of water condition changes (Poff et al, 1997). Aquatic ecosystems are conjectured to follow the intermediate disturbance hypothesis stating that ecosystems are healthier under disturbances that are neither too small nor too large. Whether based on single or historic flow parameters, conventional hydrological flow assessments hold poor or untested ecological capability of their model output (Tharme, 2003). There is little evidence that these hydrological flow indices truly protect the ecological attributes of streams.

Because of a knowledge gap in bridging water input to reservoirs and output needed for maintaining ecological integrity, management efforts do not accommodate the natural dynamic character of stream flow quantity and timing. The central question of this project is to find an alternative to minimum flow requirement: Can we do ‘better’ by incorporating ecological integrity of rivers and their dependence on the natural dynamic flow character? This project will use a simplified food web model as a proxy of ecological integrity.
In the introduction to this project, the idea of ‘natural’ river systems has been highlighted as some condition that can serve as a control in comparison to systems that are ‘disturbed’ or ‘modified’ by dams. What can be understood as the natural state of a river both in terms of flow regime and ecology? Lotic (flowing water) ecology is a young science, the conceptual foundations of which were forged in Europe and North America, when most rivers had already been heavily regulated for many decades (Ward et al., 2001). Principles of river management have therefore largely been based on findings from regulated systems often lacking the fundamental knowledge of the functions and structures that govern healthy dynamic rivers.

Poff et al. (1997) argue that dynamic flow regimes are prerequisites for healthy lotic ecosystems. The authors define five critical components that regulate ecological processes in the river: 1. Magnitude of discharge described as the volume of water moving past a location per unit time, 2. Frequency of occurrence referring to the number of times a given magnitude recurs in a fixed time interval, 3. Duration of a given flow event, 4. Timing predicting at what regularity a particular flow occurs, and 5. Rate of change describing how long it takes for flow to undergo a change in magnitude. These critical flow components affect the primary regulators of river integrity: water quality, energy sources, physical habitat, and biotic interactions. The success of the growing literature on river dynamism (Suen and Eheart, 2009; Richter et al., 2003; Poff et al., 1997; etc.) has not been to redirect or limit focus to studies of water quantity and water availability in river systems but to trigger process-based approaches to riverine integrity forcing hydrologists and ecologists to examine rivers in light of their complex structural functioning. Continued efforts away from stand-alone assessors of river health have the potential to promulgate a more integrative assessment of natural river processes informing effective and sustainable river management.

Any discussion of lotic systems should be directly relatable to an understanding of their structure and function as entire ecosystems. Accordingly, this project sets out to explore ecological integrity at the interface of the food web, where hydrological and ecological properties confluence. According to Moss (2007), ecological integrity “can be characterized by the parsimony of available nutrients, characteristic physical and biological structure, strong connectivity among
systems and mechanisms of resilience to cope with normal, ‘natural’ change”. It follows that neither unique lists of species or single formulae can adequately define high-quality systems at a particular spot. While retaining their fundamental functional characteristics, rivers hold substantial inherent variability, biotic as well as abiotic.

A dominant paradigm in river management and ecological restoration is that increasing habitat heterogeneity (HH) promotes biodiversity rehabilitation (Tews et al., 2004). Palmer et al. (2010), however, argue that there is no evidence that physical heterogeneity is the primary factor determining stream biodiversity. When degraded waterways are repaired, restoration techniques should go beyond mere channel reconfigurations and enhancements of structural complexity (with boulders, wood, meanders, etc.). Rivers are sensitive to a multitude of stressors, which among others can include poor water quality, biologically unsuitable flow regimes, altered inputs of nutrient, sediment or sunlight, dispersal barriers, and degraded physical habitats. Rivers should be restored in acknowledgment of these stressors, individually or collectively. The complexity of stressors should not be a deterrent for stream restoration projects but should encourage a more integrated approach to stream restoration beyond HH techniques and establish structural links between systems and stressors.

**Dammed Rivers**

Altering the flow of water, sediment, energy, nutrients, and biota, dams pose a threat to habitat dynamics. Even subtle human adjustments upstream can profoundly affect ecological relations downstream from dams. For example, dams may disturb established relations between water and sediment movement and consequently impact the geomorphology of rivers (Ligon et al., 1995). Reduced peak flows often forge low-sinuosity, single-thread rivers that exhibit armoring and channel incision. These geomorphologic conditions are problematic since they threaten spawning grounds for the local biota. Altered timing, frequency or duration of high flows can further displace resource reserves e.g. phytoplankton (Richter et al., 1997). In addition, the physical obstruction of the dam hampers fish migration. From a geochemical perspective, migrating fish carry nutrients, the decline of which can trigger significant loss of nitrogen (Helfield and Naiman, 2001) and phosphorus (Larkin et al., 1997). Further, reservoirs themselves can act as nutrient sinks reducing
the amount of nutrients transported and made available downstream (Friedl and Wüst, 2002). Potentially positive for polluted eutrophic rivers, this process can have dramatic effects for oligotrophic rivers. Beyond these effects, dams are responsible for a loss of connectivity between freshwater bodies (i.e. rivers and their floodplains, lakes, and ponds) (Sayer, 2014) and thereby pose a significant threat to global biodiversity (Poff et al., 2007).

It is suggested that in assessing the health of regulated dammed rivers, it is necessary to expand on the empirical evidence suggesting a small group of biological indicators can measure river condition (Norris and Thoms, 1999). Rather, it is encouraged, to study the linkage between indicators and the physical and chemical features that influence them. In the words of Ligon et al. (1995, 183): “If the stream's physical foundation is pulled out from under the biota, even the most insightful biological research program will fail to preserve ecosystem integrity” (p. 183). Therefore, in an attempt to assess both the structure and function of dammed rivers and their ecosystem, this project uses a process-based approach to assess riverine integrity.

Dam management practices can pose a serious threat to healthy rivers and their associated benefits. Natural flow regimes are largely rendered impossible in river systems that follow strict regulations for adequate water supply and flood control. It is therefore all the more important that already regulated rivers are sustainably managed with respect to their structural ecological integrity. Future uncertainties such as land cover change and climate change further put in question whether dam removal is necessarily the most ecological solution to river management. What state are undammed rivers returning to? As such, the future of rivers may be even more uncertain. In deciding how to best manage lotic systems, dam management should not be disregarded by river ecologists as an ecological alternative.

**The Status Quo of Dam Reservoir Management**

Typically, reservoir managers regulate releases based on infrastructure limitations, water availability, water demand, and economic concerns (Adams et al., 2017). Many water-resource management decisions are made in contexts that are constrained by political, legal, social, and economic realities (Cartwright et al., 2017). The conventional practice of reservoir operation is
largely guided by the maximization of social-economic interests, while downplaying the requirements of the downstream ecosystem (Chen et al., 2015). During flood season, if the prescribed critical water level is reached in the reservoir, the surplus water is discarded down the spillway (Chen et al., 2015). Dams used for electricity generation are usually characterized by hydropoeaking operations independent of downstream flow requirements. This operation policy produces energy for only a few hours each day, when the energy demand is at a maximum, while the rest of the time the system produces minimal energy and stores extra inflow volumes (Rossel and de la Fuente, 2015).

Balancing dam operation objectives is challenging for managers due to the trade-offs of meeting hydropower and water supply demands (usually quantifiable), managing for drought and floods (somewhat quantifiable), and protecting the environment (Adams et al., 2017), which is more uncertain in terms of ‘know-how’. The conservative approach to ecological flow management in most reservoir operations is the simplest and most convenient: a constant minimum flow, with the aim to meet the most basic requirements of the river ecosystem (Chen et al., 2015). A typical reservoir operation strategy to protect environmental flows is to release the available water in the dam until the downstream environmental goal, such as minimum instream flow, is met (Adams et al., 2017). As case in point, the state legislature of North Carolina passed legislation in 2010 defining ecological flow as “the streamflow necessary to protect ecological integrity” (Pearsall et al., 2017). Integrity was defined as “the ability of an aquatic system to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to prevailing ecological conditions and, when subject to disruption, to recover and continue to provide the natural goods and services that normally accrue from the system” (Pearsall et al., 2017). While noble in intent, translating this requirement into flow pattern releases based on stochastic inputs of rainfall is difficult. Hence, dam management is still largely determined by minimum flow policies in practice. The most commonly used minimum flow standard in the United States is 7Q10 flow, the lowest flow occurring for seven consecutive days, with a probability of occurring once every ten years (Cartwright et al., 2017).

Another method that is commonly used worldwide is setting standards based on a fixed percentage of mean annual flow (Cartwright et al., 2017).
High water demand and growing concern about environmental change has drawn attention to the need to determine and protect flows to sustain stream ecosystems (Garófano-Gómez et al., 2012). Not only does this include establishing minimum flows that meet the habitat requirements of a target species (usually on the endangered species list), but also maintaining a range of flows that keeps entire ecosystems functioning (Garófano-Gómez et al., 2012). For holistic protection, the downstream flow requirements from a dam should vary with time to emphasize the different needs of different life stages of downstream species (Chen et al., 2015). Daily flow fluctuations under the Glen Canyon Dam, USA, were reported as having noticeable effects on the water temperature and therefore species in the river (Chen et al., 2015). In addition, the 7Q10 method of determining minimum flow was originally developed for water quality purposes and is therefore not suitable for ecosystem protection (Cartwright et al., 2017). The mean annual flow method has been criticized for failing to protect the components of natural flow regimes that are of primary ecological importance, yet it is still used widely globally (Cartwright et al., 2017). Often, water-management decisions are not adequately informed by environmental flows research, serving as a key example of the larger disconnect between conservation science and practice (Cartwright et al., 2017).

The goal of this project is to explore the effects of dam operations on downstream ecology and allow dam managers to optimize operations for given climate scenarios. Operational scenarios will be assessed based on whether they sustain a simplified food web downstream from the reservoir or whether operations cause the food web to ‘crash’ – meaning one of its trophic levels will go irreversibly extinct. We will operate under the assumption that some environmental damage (i.e. fish mortality) is inevitable, but larger damage, such as species extinction, should be avoided by dam operation (Adams et al., 2017).

**Methods**

To inquire about the impacts of reservoir management on the stability of a simplified food web, a lumped three-part model will be developed and used to quantify the impacts of random inflow into a reservoir with changing precipitation distributions used as a proxy for climate change (Figure 1). First, precipitation inflow into the watershed will yield an outflow that feeds the reservoir. This bridge will link watershed and reservoir properties using a unit hydrograph. Second, nonlinear
reservoir operations will be modeled to determine the optimum streamflow variability needed to maintain the downstream ecosystem. Last, the dynamics of a three species food web will be modeled to determine whether upstream conditions can sustain downstream food-web stability. The modeled ‘in-silico’ watershed and reservoir properties were derived from information on reservoir shape and precipitation statistics from the Kerr Scott reservoir (in North Carolina, USA). The three models will be combined and operated under five dam management scenarios, such as natural flow, flood management, drought management, run of river, and minimum flow. In addition, predictions from the IPCC AR5 Report (2013) are used to evaluate changes in precipitation due to long term shifts in the climate.

Figure 1. Description of the lumped 3-part model processes used to examine food web dynamics downstream from the dam. The ? indicates one of the 5 dam management scenarios to be explored.

Hydrologic Model

Through the use of a simplified unit hydrograph approach, watershed properties and precipitation will be linked to produce reservoir inflow. The hydrologic model is ‘spatially lumped’, meaning that the effects of space will be aggregated and encoded as probabilistic travel times for water molecules originating from the watershed to the reservoir inflow point (e.g. unit hydrograph). Synthetic precipitation is used to allow various climate scenarios to be conducted by varying the interstorm period but maintaining total annual amounts constant throughout. The synthetic daily precipitation is assumed to be represented by a marked Poisson process with specified mean
duration between storms and mean depth per storm. These daily precipitation values are ‘downscaled’ in time to a mean storm duration of 4 hours. Each storm independently generates an inflow to the reservoir using a unit hydrograph describing the probability of travel times of water molecules. To eliminate the effects of initial conditions in the watershed and in the reservoir, and to ensure viable statistics for computations of outflow, the total duration of the lumped model is 200 years, with each time step representing some 14 minutes. The unit hydrograph is assumed to be approximated by a gamma function, distributed over a maximum duration (x) of 20 days, where k is a dimensionless shape parameter and θ is a scaling parameter (Thompson and Katul, 2012). This function is given by

\[
UH = \frac{1}{\Gamma(k)\theta^k} x^{k-1} e^{-\frac{x}{\theta}},
\]

where the mean value is \(k\theta\) and the mode is \((k - 1)\theta\). The UH is used to route rainfall to the outflow point in the watershed that serves as the inflow to the reservoir. As earlier noted, random daily rainfall is generated with depth and interpulse duration parameters derived from a marked Poisson process. Here, it is assumed that the duration of a single rainstorm event should not exceed 24 hours with a mean of 4 hours and that annual precipitation is set to 1200 mm/year uniformly distributed across years. No seasonal patterns to rainfall is imposed, which is common to the Southeastern US. The 14 minute rainfall time series \((P_r)\) is then constructed and converted to inflow to the reservoir through the use of the aforementioned unit hydrograph \((UH)\). To account for losses in runoff, an estimated runoff coefficient \((C_r)\) for the watershed area \((A_{ws})\) was used. For this model, the runoff coefficient is assumed to be constant \((C_r = 0.4\) ) over the 200 year period, indicating no change in the overall land-cover type. The SCS Runoff Curve Number Method can be used to determine \(C_r\) if the landcover characteristics are known or their variation in time is available (Hjelmfelt, 1991).

The parameters of the hydrograph are shaped and scaled using a root mean square optimization scheme to the inflow. The data used for generating such UH are based on the available Kerr-Scott inflow data. A convolution is then used to evaluate the reservoir inflow from \(P_r(t)\) and \(UH\) using a Fast Fourier Transform (FFT). This step must be scaled by \(\sigma = A_{ws} C_r\) to obtain the total amount of water fallen over the watershed – not just its temporal distribution. Hence, the inflow to the reservoir \(I(t)\) is given by
\[ I(t) = \sigma \int_{0}^{\infty} P_{r}(\tau) UH(t - \tau) d\tau, \]

where \( t \) is time and \( \tau \) is a dummy integration variable.

Once the inflow \( I(t) \) to the reservoir is determined, reservoir operation can be evaluated using the mass balance of the reservoir. A model of the nonlinear reservoir dynamics will be built by varying the depth and inter-pulse duration of precipitation events for various air temperature regimes. There are several components that will be factored into this model. Reservoir geometry will be kept at maximum simplicity and is assumed to be a rectilinear box with constant width \( W \) and length \( L \) so that all the variability in storage \( S(t) \) is surrogated to water depth \( h(t) \) in the reservoir (Figure 2). That is,

\[ S(t) = L \ W \ h(t). \]

Outflow \( O(t) \) from open dam gates is assumed to be frictionless, meaning that all the potential energy head \( h(t) \) being stored behind the dam is converted to kinetic energy head at the outflow point from the dam. Hence,

\[ \frac{V(t)^2}{2g} = h(t); \text{or } V(t) = \sqrt{2gh(t)} = \sqrt{\frac{2g}{L \ W}} [S(t)]^{1/2}. \]

To move from velocity at the gates to a volumetric outflow rate into the stream after the dam, the open gate area \((A_{\text{gates}})\) beneath the dam is defined so that

\[ O(t) = V(t)A_{\text{gates}}. \]

Reservoir management is now surrogated to the specification of \( A_{\text{gates}} \) with \( A_{\text{gates}} = 0 \) setting the conditions of no outflow in the downstream. The hydrologic balance for the reservoir is given by

\[ \frac{dS}{dt} = I(t) - O(t), \]

where

\[ O(t) = A_{gates} V = A_{gates} \sqrt{2gh(t)} = A_{gates} \sqrt{\frac{2g S(t)}{L \ W}}. \]
Figure 2. Dimensions of the model reservoir used in this approach. The dimensions are selected to match the Kerr-Scott reservoir in North Carolina.

Five reservoir management scenarios will be modeled to determine downstream impacts of $O(t)$ on a food web. These scenarios represent different operations of $A_{gates}$ in time depending on the inflow and/or storage amounts. First, a natural variability scenario will be run, assuming that no dam is in place and that the inflow to the reservoir is equal to the outflow of the reservoir ($dS/dt=0$). This will set a baseline for the food web model to compare against and is presumed to represent the natural variability in the absence of a dam. Second, run of river reservoir management will be represented. Run of river dams are driven by the depth of storage in the reservoir, generating higher outflow for a preset storage. This scenario can be readily achieved by fixing $A_{gates}$ to a single constant or pre-set value. Third, a flood management scenario is employed. In this case, when the water level in the storage pool reaches 50% of the storage capacity, the gates will be opened to allow excess water to leave the reservoir. Fourth, a drought management scenario is run where the water level in the storage pool is never allowed to drop below 50% capacity to ensure sufficient water supplies stay in the reservoir at all times. Finally, a minimum flow scenario in the form of mean annual inflow will be examined. This scenario is employed to assess the impacts of traditional ecological flow management (e.g. mean annual flow) on a downstream food web.
Food Web Model

Two main inputs from the reservoir were used to drive the food web model: water quantity and water quality. Water quantity was modeled to determine the impacts of downstream water depth on predator-prey interactions representing trophic interactions. Water quality was used to examine the relation between outflow and nitrate and implications for species carrying capacities.

Water quantity was examined using a search distance model. In this model, the amount of outflow flowing from the dam was related to the depth of the stream ($y$) using Manning’s Equation for uniform flow. This approach takes into account outflow ($O(t)$), Manning’s roughness ($n$), bed slope ($s_o$), and river width ($w$), to determine the depth of the water in the river. This depth was then normalized ($y_{\text{norm}}$) by the maximum depth observed in ‘natural’ or no-dam conditions to allow the range of values to vary between 0 and 1 for the final food web model.

$$y = \frac{O(t)n^{3/5}}{\sqrt{s_o w}}; \quad y_{\text{norm}} = \frac{y}{\max(y)}$$

A nutrient budget for the reservoir was created to model the impacts of water quality on the downstream food web. It was assumed that a concentration of 0.6 mg/L of Nitrate is input into the watershed during each rainfall event ($C_{in}$). However, if the precipitation exceeds a threshold, then there is a washout event in the watershed, removing nutrients from the inflow to the reservoir. To model this, an indicator function $I_{fn}$ was created, stating that if the deviation from mean inflow is five times higher than the standard deviation, then no nutrients will be delivered from the watershed ($I_{fn} = 0$). If the inflow is lower than this threshold, then the nutrients from the watershed will be transported into the reservoir with a constant $C_{in}$. The nutrient budget consists of inflow of nutrients to the reservoir in the form of runoff and decay of nutrients ($C(t)$) in the form of outflow from the reservoir and biochemical decay at a rate of $k$ to the reservoir’s sediments. That is,

$$\frac{d}{dt} (CS) = I(t) \ C_{in} I_{fn} - (O(t) C(t) + k S(t) C(t)).$$
The nutrient budget derived from the inflow and outflow is used to determine the abundance of resources downstream from the dam. Data on phytoplankton and nitrate concentrations upstream from a reservoir were obtained from the National Water Information System (NWIS) operated by the United States Geological Survey (USGS). A non-linear least squares distribution was fit to the data and then used to model the relation between nutrients removed with the outflow from the reservoir with phytoplankton densities (Figure 3). This logistic relationship was used to determine a dynamic carrying capacity $K(t)$ of the resource in the food web given a certain downstream nutrient concentration and is given by

$$K(t) = \frac{3284}{1 + \exp(-45.14 - 185 \cdot \text{Nitrate}(t))}$$

**Figure 3.** Derived relation between measured phytoplankton concentration and nitrate concentration showing saturation at around 3284 cells/ml. The logistic form of this expression is used to represent the changes in carrying capacity with nitrate levels after normalizing by the maximum carrying capacity.

To unfold the implications of dam operations on downstream ecosystem health, the water quality and quantity models were combined with a simplified three species food chain to model food web stability. The three species food chain will have a resource ($R$), consumer ($C$), and predator ($P$), with $R_o$ and $C_o$ indicating initial conditions for the resource and consumer. That is,

$$f(Q) = \frac{x_t y_t CR}{R + R_o}$$
\[
\frac{dR}{dt} = R(K - R) - x_c y_c \frac{CR}{(R + R_o)y_{norm}}
\]

\[
\frac{dC}{dt} = x_c C \left[ -1 + y_c \frac{R}{R + R_o} \right] - x_p y_p \frac{PC}{(C + C_o)y_{norm}}
\]

\[
\frac{dP}{dt} = x_p P \left[ -1 + y_p \frac{C}{C + C_o} \right].
\]

The above model was originally described in Hastings and Powell (1991) and McCann and Yodzis (1994). It generates a naturally chaotic food web in which a resource population with density \( R \) is eaten by a consumer with density \( C \), who is eaten by a predator with density \( P \) (not to be confused with precipitation). The parameters \( x_c \) and \( x_p \) indicate the mass-specific metabolic rate of the species measured relative to the production-to-biomass ratio of the resource population. The parameters \( y_c \) and \( y_p \) are a measure of the ingestion rate per unit metabolic rate of the species.

Instead of choosing parameters for specific species, parameters are chosen for various metabolic types, such as endotherm, vertebrate ectotherm, invertebrate ectotherm. This enables an easier translation of the model to multiple ecosystems. Three key assumptions will be made. First, the resource will adjust quickly to changes in flow rate when compared to the consumer. Second, the resource attains carrying capacity based on the flow rate. Third, the probability of predators finding prey depends on the size of the domain (i.e. volume of water in the stream). These assumptions can be met by matching the model to a Holling Type II Functional Response when setting food density and consumption parameters.

**Climate Change Scenarios**

Precipitation, routed through the watershed and modeled by the unit hydrograph, determines the storage of the reservoir and could hence affect the stability of the food-web downstream. Changes in climate, and subsequently precipitation, will affect storage and either allow for or limit outflow. This model will use different climate scenarios to test the effect of a changing climate on reservoir
operations. The scenarios to be used in this model were designed and presented in the most recent IPCC report (IPCC, 2013).

It is expected that under climate change scenarios pertinent to the Southeastern US (used as a case-study here), the annual precipitation will remain roughly the same but the frequency (return period) and amount of daily rainfall (rainfall depth) will change. Hence, the precipitation scenarios used in this model will span more frequent and less intense to less frequent and more intense rainfall events while maintaining the same total amounts. Return period values \((T_r)\) between 2-30 days will be explored and will span a range far exceeding those reported by the IPCC. However, elevated atmospheric CO\(_2\) and elevated air temperature are not explicitly considered. These climate drivers require modeling of water uptake by the vegetated in the watershed and evaporative losses from the reservoir, both are kept as topics for future inquiry. The frequency and depth of rainfall are altered with each return period to generate 29 different scenarios to be examined (Figure 4).

**Figure 4.** Probability density function (PDF) of the synthetic precipitation time series for each scenario \((T_r = 2-29)\) shifting from more frequent, less intense events (blue) to less frequent, more intense events (red). Note the amplification at the PDF tails with increasing \(T_r\) (i.e. red).
Results

Natural Variability

Under a background or *natural variability* scenario $I=O$, and no storage accumulates (Figure 5). The log-transformed Probability Density Function (PDF) sheds light on how probable different outflow rates are to occur (Figure 6).
Minimum Flow

Drought Management

Flood Management

Figure 5. Synthetic precipitation time series, modeled inflow, normalized storage, and outflow for all five management scenarios tested.
Figure 6. Outflow probability density function (PDF) for precipitation return periods $T_r = 1, 15,$ and 29 days.

For $T_r = 1$, low-magnitude flows are highly probable to occur. As $T_r$ increases, the PDF shifts to storms of higher magnitude indicating fewer but more intense streamflow rates consistent with logical expectations.

Table 1. Total percent of time that the Predator maintains a finite population for low, medium, and high $T_r$.

<table>
<thead>
<tr>
<th></th>
<th>Percent of Time Above 0 Population Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_r = 1$</td>
</tr>
<tr>
<td>Natural Variability</td>
<td>95.68</td>
</tr>
<tr>
<td>Run of River</td>
<td>99.30</td>
</tr>
<tr>
<td>Minimum Flow</td>
<td>82.10</td>
</tr>
<tr>
<td>Drought Management</td>
<td>94.89</td>
</tr>
<tr>
<td>Flood Management</td>
<td>98.48</td>
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</tbody>
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Driven by internal dynamics, water quantity, and water quality, the food web model chosen for this analysis is naturally chaotic. The minimum number of dimensions (i.e. axes needed to describe the phase-space in Figure 7) is three so as to obtain chaotic dynamics for certain parameter values. By examining the behavior of this chaotic three-species food web under natural variability (Tr = 1 day), it is possible to establish a baseline scenario for how the river ecosystem would behave in the absence of a dam. Under the Tr = 1 day scenario, no species in the food web appear to crash, however they fluctuate rapidly between dominant trophic levels as expected from a chaotic system (Figure 7).

**Figure 7.** Food web dynamics for the natural variability scenario (I=O) for a Tr = 1 day (top left) and its associated phase-space (top right). The initial conditions in time and phase-spaces are shown as open red-circles. The mean populations (i.e. time-averaged over 200 years) as a function of increasing Tr are also shown (bottom left). Three sample phase-space plots for Tr = 1, 15, and 29 are also shown (bottom right) for illustration.
As Tr increases, the food web in the river ecosystem is impacted and there is a clear loss in resilience in the consumer and predator species (Figure 7). In the first return period, the predator population is sustained 95.68% of the time (Table 1), however, after the first return period, the predator population drops, while the consumer population begins to decline. After an initial drop in the second return period, the resource population is statistically stable for all other Tr scenarios. When examining the interactions of the trophic levels over time, it appears that once the predator population crashes, it does not recover.

Run of River

In a run of river scenario, where the river is dammed and outflow is driven by storage alone (gate size remains constant), the maximum outflow is reduced by an order of magnitude compared to maximum inflow (Figure 5). The reservoir dams the variability of flow rates as expected (Figure 5). Compared to a natural variability scenario (I=0), outflow rates in a run of river scenario are constrained to a small bandwidth (4.5 - 5.5 $10^5$ m$^3$/d) of possible outflows. As Tr increases, probabilities experience a minor shift to more intense outflows, however, not in comparison to previous undammed streamflow (Figure 8).

Figure 8. Comparison of outflow probability density functions (PDF) of the natural variability (I=0, blue) and run of river scenarios (green) for low (=1 d), intermediate (=15 d) and large Tr (=29 d) return periods.
Figure 9. Food web dynamics for the run of river scenario for Tr = 1 day (top left) and its associated phase-space (top right). The initial conditions in time and phase-spaces are shown as open red-circles. The mean populations (i.e. time-averaged over 200 years) as a function of increasing Tr are also shown (bottom left). Three sample phase-space plots for Tr = 1, 15, and 29 are also shown (bottom right).

The food web under a run of river scenario appears to behave similarly to the natural variability scenario, however, the magnitude of population fluctuations is much larger (Figure 9). No species crash in the Tr = 1 day, however, it is seen that there is a clear quasi-oscillatory pattern when looking at the dominant trophic level. While the food web does not reach stationarity with increasing Tr, the statistics of the population levels remain constant for a longer period of time than in a natural variability scenario.

When the food web is impacted by Tr, it is seen that the constant oscillations in the food web dynamics are not maintained, but rather that the predator species becomes extinct in return period
11 (Figure 9). This is apparent, as the predator population shifts from being present 99.3% of the time to 0.5% of the time (Table 1). All three species experience a loss in resilience, with their mean densities declining rapidly with each return period increase. The resources time series do reach a quasi-stationary state at return period 11 with increased return period, which could be due to the diminished top down pressure in the ecosystem. This system is less resilient to changes in Tr than the natural variability scenario, but fewer trophic levels are seen to crash in the long term.

**Minimum Flow**

In a minimum flow scenario, where outflow is determined by the opening and closure of dam gates, outflow sees a reduction in peak flows (Figure 5). The rapid opening and closure of gates is the predominant source of flow variability. The PDF illustrates high probabilities of low-magnitude flows (Figure 10). Under increasing Tr, flow rates experience a subtle shift to higher streamflows, however, incomparable to natural variability.

![Minimum Flow](image)

**Figure 10.** Comparison of outflow probability density functions (PDF) of the natural variability (I=O, blue) and minimum flow scenarios (green) for low (Tr=1 d), intermediate (Tr=15 d), and large (Tr = 29 d) return period.
Figure 11. Food web dynamics for the *minimum flow* scenario for Tr = 1 day (top left) and its associated phase-space (top right). The initial conditions in time and phase-spaces are shown as open red-circles. The mean populations (i.e. time-averaged over 200 years) as a function of increasing Tr are also shown (bottom left). Three sample phase-space plots for Tr = 1, 15, and 29 are also shown (bottom right).

The food web under the current climate (Tr = 1 d) appears to have rapid spikes in population levels for all three trophic levels. When compared with the *natural variability* scenario, where all population densities were between 0 to 1, the *minimum flow* scenario reaches values up to 5 (Figure 11). This could be attributed to the peaking operations associated with this scenario of dam management, causing large shocks to the system in terms of water level and nutrients. When examining the dynamics of the three species together, there is a similar quasi-oscillatory pattern to that of the *run of river* scenario, however the transitions between dominant species are not as smooth, indicating that there each species has a buffering capacity to extinction.
Under *minimum flow* management, the consumer is the most resilient to climate change, maintaining a stable mean density for each return period. As the return period for rainfall begins to increase, the resource and predator populations begin to decline rapidly. However, this scenario is the best for the top trophic level, with predators remaining present 33.6% of the time in the face of increasing Tr (Table 1). By looking at how the species interact, the rapid decline of the resource and predator with increasing storm return period can be observed, while the consumer species continues to oscillate (Figure 11). During the last four return periods, the consumer population appears to begin decreasing, indicating it could be under threat from extreme shifts in precipitation statistics towards high intensity large return periods.

**Drought Management**

In a *drought management* scenario, where storage is not allowed to drop below half capacity of the dam, outflow follows two possible modes of flow (Figure 5). Similar to previous dammed scenarios, flow rate is limited and variability is much restricted compared to undammed river flow (Figure 12). With increasing Tr, flow rates seem to somewhat expand in variability, however, not noticeably in comparison to a *natural variability* scenario.

![Drought Management](image)

**Figure 12.** Comparison of outflow probability density functions (PDF) of the *natural variability* (I=O, blue) and *drought management* scenarios (green) for low (Tr=1 d), intermediate (Tr=15 d), and large (Tr = 29 d) return period.
Figure 13. Food web dynamics for the *drought management* scenario for Tr = 1 day (top left) and its associated phase-space (top right). The initial conditions in time and phase-spaces are shown as open red-circles. The mean populations (i.e. time-averaged over 200 years) as a function of increasing Tr are also shown (bottom left). Three sample phase-space plots for Tr = 1, 15, and 29 are also shown (bottom right).

The dynamics of the *drought management* time series is similar to the *minimum flow* scenario, however, the magnitude of the fluctuations in species density is much smaller and more closely resembles the dynamics of the *natural variability* scenario (Figure 13). There are rapid shifts in the dominant trophic level, and the food web dynamics do not reach a stable endpoint. There is a population of predators present 94.89% of the time (Table 1). The transitions between dominant species are smoother than the *minimum flow* scenario, indicating that the species existing under *drought management* do not have as high a resistance to change.
The resilience of the food web under *drought management* is similar to the *run of river* scenario in the face of increasing Tr. After return period 11, the predator species crashes to 0.50%, the resource reaches a stable state, and the consumer population continues to slowly decline (Figure 13, Table 1).

**Flood Management**

In a *flood management* scenario, where storage is consistently forced below half capacity, outflow is exclusively driven by the opening and closure of gates (Figure 5). Flow follows two modes: 3.5 and 6.5 \(10^5\) m\(^3\)/d (Figure 14). For increasing Tr, outflows are more probable to vary over a greater range of flow rates indicating a less frequent opening and closure of gates (the less frequent gates size changes, the more impact storage is allowed to have on flow rates).

![Flood Management](image_url)

**Figure 14.** Comparison of outflow probability density functions (PDF) of the *natural variability* (blue) and *flood management* scenarios (green) for low (Tr=1 d), intermediate (Tr=15 d), and large (Tr = 29 d) return period. The bimodality is due to the accumulation-release flow rate by gate adjustments associated with modeled storage crossing 50% capacity.
Figure 15. Food web dynamics for the flood management scenario for $Tr = 1$ day (top left) and its associated phase-space (top right). The initial conditions in time and phase-spaces are shown as open red-circles. The mean populations (i.e. time-averaged over 200 years) as a function of increasing $Tr$ are also shown (bottom left). Three sample phase-space plots for $Tr = 1$, 15, and 29 are also shown (bottom right).

The dynamics of the food web under flood management are similar to the drought management scenario. However, when examining how the three trophic levels interact, it can be seen that there is more resistance to shifts in the dominant trophic level, indicating the species have a high buffering capacity to change (Figure 15). The predator population has a mean above zero 98.48% of the time (Table 1).

When faced with changing $Tr$, the food web begins to lose resilience after return period 11 (Figure 15). The predator population quickly crashes, only present 0.50% of the time (Table 1). However,
the consumer species is much more resilient than in the drought management scenario, as its mean does not decline as quickly over time.

**Discussion**

To maintain ecological integrity, as defined by the state legislature of North Carolina, in a changing climate, five reservoir management scenarios were tested on an ‘in-silico’ reservoir supplied by water and nutrients from a watershed and supplying water and nutrients downstream to a foodweb. The five scenarios that dictate the gate operation of the reservoir are: natural variability (no reservoir storage), run of river, minimum flow, drought management, and flood management. It was found that, as expected, flow variability decreased substantially in each of the four dammed scenarios. In addition, with changes in return period of storms, the outflow from the reservoir shifted towards less frequent, higher magnitude flow rates. Dammed rivers do not maintain the natural variability of unregulated rivers but will be impacted in more subtle ways when precipitation statistics shift.

In testing the stability of the downstream food web, none of the scenarios tested maintain populations in all trophic levels throughout the entire modeling period when faced with varying storm return period. Species dominating food web dynamics varied in the different scenarios. For low intensity and frequent storm scenarios, reservoir managers operating their dams under run of river or flood management techniques will achieve the greatest downstream ecological integrity. However, as precipitation patterns begin to change, these reservoir types are at risk to ecological degradation. In natural variability, run of river, drought management, and flood management scenarios, nearly all predator populations depleted with increased storm return period (high disturbance regime). In contrast, reservoirs being operated for minimum flow management show low levels of downstream ecological integrity in conditions experiencing frequent but low intensity rainfall. However, the food web appeared to be the most resilient to changes in the hydrologic regime in a minimum flow scenario, indicating that current management practices used to preserve “ecological integrity” might be advantageous in an unstable and uncertain future.

The results support the medium disturbance hypothesis previously introduced in this paper. The model indicates that frequent-low intensity storm scenarios that promote natural flow variability
fostered stable food web dynamics. However, scenarios that limit variability and regulate flow seem to be more ecological as climate conditions become more extreme as may be associated with large return period – high intensity storm (high disturbance). Consequently, we can conclude that the food web is most stable under some disturbances, i.e. flow variabilities, that are neither too large nor too small – and perhaps reservoir managers may attempt to seek this level as a best management practice.

This study was the first attempt at mathematically linking climate change (mainly precipitation statistics), hydrology (water routing in a watershed using unit hydrograph analysis), reservoir management (gate operations) and ecology (food-web). This will allow dam operators to gain some insight into the effects of their operations on downstream food web dynamics as well as any changes that can be anticipated under shifts in precipitation statistics. Therefore, any findings – even those derived from theoretical models – may be deemed as a novel contribution to the field of eco-hydrology and reservoir management. Previous empirical studies of reservoir-food web relations have shown that downstream ecosystems are not resilient under current ecological flow management practices. This study supports those findings, but extends them by stating that in a changing climate, minimum flow management should not be eliminated as a potential management tool for ecological integrity.

While the model’s findings support that minimum flow regulation may be the best management protocol for high intensity storms, it should be noted that the top trophic level is only maintained for 33.6% of the modeling time period. Hence, continued efforts should be directed at improving management scenarios to optimize ecological integrity in an uncertain climate future. Since this has been the first model of its kind, there are a number of avenues for model improvement. First, the runoff coefficient could be altered from a single value to a series of different values to reflect the impacts of urbanization on land cover and runoff timing and magnitude. In addition, the nutrient budget could be expanded upon to involve multiple types of nutrients, as well as adding more complex chemical reactions. The food web model could further be enlarged by including additional species to the trophic cascade currently involving only three species. To test the model for specific ecologies and watersheds, parameters can be adjusted to match specific catchment, reservoir and species characteristics. Finally, regional climate change models could be used to
enhance the realism of future climate scenarios. By providing the opportunity to build these complexities into the model, it is envisaged that reservoir managers can use this framework to evaluate ecological impacts of their current reservoir operations, as well as determine the effects of climate change.

**Potential Implications**

With regards to the future of process-based approaches to environmental flow specifications from dams, the link established between hydrology, ecology and reservoir management can be imperative in informing future dam management. The model may be used to allow reservoir managers to optimize gate operations to maximize predator populations. Allowing managers to model and predict fish populations helps them fine-tune their chosen modes of gate operations, largely determined by socioeconomic factors, for optimal ecological river management. This is a particularly interesting line of inquiry since there are inherent academic struggles to link the stochastic inflow to the chaotic behavior of fish population. Intellectually pertinent on academic grounds, the problem has substantial implications in the real-world applications of dam management.

**Conclusion**

As a first attempt at bridging hydrology, ecology and reservoir management, this model builds a structural understanding of how dam operations interact with downstream ecological integrity. For all five dam scenarios tested, it was found that increasing storm duration period will increase the uncertainty in downstream food web stability. While scenarios that promote flow variability create healthy ecological conditions in a stable hydrological regime, *minimum flow* management has been found to best preserve ecological integrity in an uncertain climate future that is associated with high flow disturbances. This research can serve as a blue-print framework for future explorations of dam management as a tool for enhancing ecological river health.
Supplementary Material

All data and MATLAB scripts used in this analysis can be found on the following public github repository: https://github.com/nabib/ecological-flows

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References


