Evaluating Options for Improving Drought Resilience of the Upper Flint River System

EPD Georgia Regional Water Planning Seed Grant

Final Report

May 2025

Laura Rack[1], Seth Wenger[1], Ben Emanuel[2], Rhett Jackson[3], and Mary Freeman[1]

1. Odum School of Ecology, University of Georgia

2. American Rivers

3. Warnell School of Forestry and Natural Resources, University of Georgia

Table of Contents

EXECUTIVE SUMMARY 3

INTRODUCTION 4

SCENARIO DEVELOPMENT 6

- SCENARIO 1: INCREASING INFILTRATION IN THE UPPER FLINT BASIN 7
- SCENARIO 2: AUGMENTING RIVER FLOWS WITH QUARRY STORAGE 8
- SCENARIO 3: CHANGES TO LOW-FLOW OPERATIONS 10
- COMBINED SCENARIO 11
- SCENARIO EVALUATION 11

ECOLOGICAL MODEL DEVELOPMENT 13

RESULTS 14

- SCENARIO 1 14
- SCENARIOS 2, 3, AND COMBINED SCENARIO 15
  - *Ecological outcomes* *15*
  - *Reservoir Storage and Utility Operations* *19*
- ECOLOGICAL MODEL RESULTS 30

CONCLUSIONS 32

CITATIONS 34

APPENDIX A: *PODOSTEMUM* SIMULATION MODEL FOR FLINT RIVER SHOALS 35

- I. ESTIMATING PROPORTION OF FLINT RIVER SHOAL HABITAT WITH VELOCITY <0.4 M/S IN RELATION TO DAILY FLOW , USING FIELD OBSERVATIONS IN 2001 AND 2002. 36
- II. OVERVIEW: ESTIMATING *PODOSTEMUM* DAILY GROWTH RATE IN RELATION TO SHOAL HABITAT WITH VELOCITY <0.4 M/S, USING BIOMASS TIME-SERIES OBSERVATIONS IN THE MIDDLE OCONEE RIVER. 39
- III. ESTIMATING THE PROPORTION OF SHOAL DRYING AT SPREWELL BLUFF SHOALS BASED ON THREE DISCHARGE AND DRYING POINTS. 40
- IV. MODEL CODE WRITTEN IN THE SOFTWARE R AND USING PACKAGES RJAGS AND R2JAGS. 41
- V. REFERENCES 43

APPENDIX B: *PROJECT OVERVIEW* 44

APPENDIX C: *GUIDANCE FOR EVALUATING ECOLOGICAL INDICATORS IN WATER PLANNING* 46

Executive Summary

The Upper Flint River system provides drinking water for more than 400,000 residents of south Metro-Atlanta and central Georgia. Due to the absence of impoundments along the river's mainstem, it also supports river shoal ecosystems that are important ecologically and enjoyed recreationally. In this project, we assessed the impacts of short- and long-term drought management actions on the river ecosystem and water resources, building on recommendations from the Upper Flint Regional Water Plan (2023) and actions proposed by the Upper Flint River Working Group (Emanuel 2019). We used EPD's Basin Environmental Assessment Model (BEAM) to simulate these actions and evaluated the ecological consequences for low-flow and drought events of varying severity and duration.

We developed three scenarios to represent alternative management actions that could impact low-flow and drought resilience in the upper Flint River. First (scenario 1), we used an empirical method to examine the impact of increased stormwater infiltration, which could be achieved through green infrastructure or enhanced stormwater management. Second (scenario 2), we evaluated how additional water storage in a retired quarry near the top of the basin could be used to supplement river flows during low-flow periods. In scenario 3 we explored how early drought response and shifted timing of withdrawals would impact low-flow events. Finally, we combined the green infrastructure, quarry storage, and modified operations scenarios to explore the collective impacts of all management actions. For each scenario, we were interested in the impact on low river flows compared to the baseline (based on the permitted conditions as of 2018), the predicted ecological outcome in Flint River shoals, and reservoir storage for select utilities with withdrawal operations on the Flint River or tributaries.

We found that the only way to meaningfully enhance river flow during drought events was to change low-flow operations (scenario 3) by raising the minimum withdrawal level during the summer and early fall. However, these altered low-flow operations resulted in the lowest reservoir storage levels, which is of concern for water utilities. The combined scenarios showed that the impact on reservoir storage was partially offset by releases from the repurposed quarry. Thus, the combination of actions has the best potential to improve riverine ecological conditions while maintaining adequate water supplies for human needs.

Introduction

In freshwater ecosystems, environmental flows provide an important tool for sustainable water management to meet human needs without degrading river ecosystems – which is particularly important during drought periods when water availability becomes scarce across human and ecosystem needs. Environmental flows are defined as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well- being that depend on these ecosystems" (Arthington et al. 2018). The framing and implementation of the project presented here draw from key elements of a holistic environmental flow approach, which has been recommended for Georgia's Regional Water Planning process because the holistic approach incorporates social, economic, and environmental values (ARCADIS 2019).

The purpose of this project is to identify and evaluate short- and long-term management actions to improve ecological and water resource resilience in the upper Flint River Basin building on the Upper Flint Regional Water Plan and work by the Upper Flint River Working Group (herein "Working Group"). Since their start in 2013, the Working Group has sought to improve the security of water resources of the Flint River for people and nature (Emanuel 2019). Water utilities of the Working Group have implemented projects to return water to the river, upgrade water withdrawal infrastructure, update management practices, undertake proactive drought response and engender cross-jurisdictional communication during drought (Emanuel 2019). In addition, starting in 2018, the group started focusing on the ecological impacts of drought and low flows on Flint River shoal ecosystems – the shallow, rocky expanses that support diverse and abundant fish and wildlife as well as river recreation including boating, wading and angling. In this project we build on the ecologically based low-flow thresholds developed by the Working Group (see "Guidance on Drought Resilience for People and Nature in the Upper Flint River Basin" presented to the Council in 2021).

The three main project objectives are to:

1. Develop and simulate short- and long-term drought management actions using EPD's Basin Environmental Assessment Model;
2. Predict the ecological consequences of droughts of different severity and duration; and
3. Evaluate how alternative drought-response management actions could mitigate ecosystem effects.

The findings are meant to be useful for the Upper Flint Regional Water Council (herein "Council") in identifying potential actions or combination of actions that may align with the needs or values of basin users to build drought resilience. In addition, our findings are also meant to provide a starting point for the utilities of the Working Group to identify areas of opportunity within their operations to support river flows for ecosystem outcomes. This project represents a first step in evaluating the potential impacts of various management actions that could guide subsequent detailed studies to evaluate the feasibility, cost, and benefits of such actions.

In the following sections, we provide an overview of the three management scenarios evaluated. We also detail methods for how we simulated increasing infiltration in the basin, augmenting river flows, and changing low-flow operations by the utilities in the Upper Flint Basin. For each scenario, and for a combination of all management actions, we evaluate ecological metrics, compare the predicted ecological response to a baseline condition, and evaluate modeled reservoir storage to understand how utility operations could be impacted by each management action.

Scenario Development

We leveraged Georgia's existing Flint River Basin Environmental Assessment Model (Flint BEAM) to evaluate how management actions could impact low-flow and drought resilience in the upper Flint River. The Flint BEAM is a linear routing model that simulates daily flows and provides location-specific data for water withdrawals, discharges, and reservoirs in the basin. Water is routed based on the permit limits for withdrawals and discharges and monthly average demand for municipal utilities, agricultural, and industrial permits. BEAM was developed as a long-term planning tool to assess water availability based on the operations in the basin and to evaluate challenges for meeting future demands. The inflows into the basin for Flint BEAM were based on streamflow data between 1938 and 2018, an 80-year time span that included multiple droughts. The simulation in BEAM used water withdrawal and discharge permit levels as of 2018. The water demand was set as the 2011 demand, as reported by utilities, and repeated each year of the scenario. The output of BEAM consisted of daily flows for 80 years at locations of permitted withdrawals in the basin and at long-term USGS gage sites, along with daily reservoir storage volumes. This type of model provides an important tool for planning and is not meant to simulate precisely the daily operations of each individual utility or daily system demand. Instead, it allows for a relative comparison of river flows in the basin based on permit levels and the system demand during a past drought year to identify if there will be challenges in meeting current or future water needs.

Throughout this project we solicited and received feedback from both the Council and the Working Group, in addition to staff at the Metropolitan North Georgia Water Planning District. Water utilities participating in the Working Group provided in-depth information about their own operations, especially during drought, and indicated areas in which this project could develop information of use to them in planning, management, and consideration of a range of future conditions relative to drought impacts and their own drought operations. We appreciate each of these entities for their engagement with the project. Figure 1 provides a timeline and brief description of engagement.

We developed three scenarios based on recommendations from the Upper Flint Regional Water Plan (2023) and actions discussed by the Working Group (Emanuel 2019): (1) increased infiltration across the headwaters of the basin resulting from improved stormwater management in the Atlanta metro area, (2) conversion of a quarry to a water storage reservoir that could augment flows in the river, and (3) changes to low-flow operations by water utilities. We also evaluated a combination scenario consisting of all management actions in scenarios 1-3.

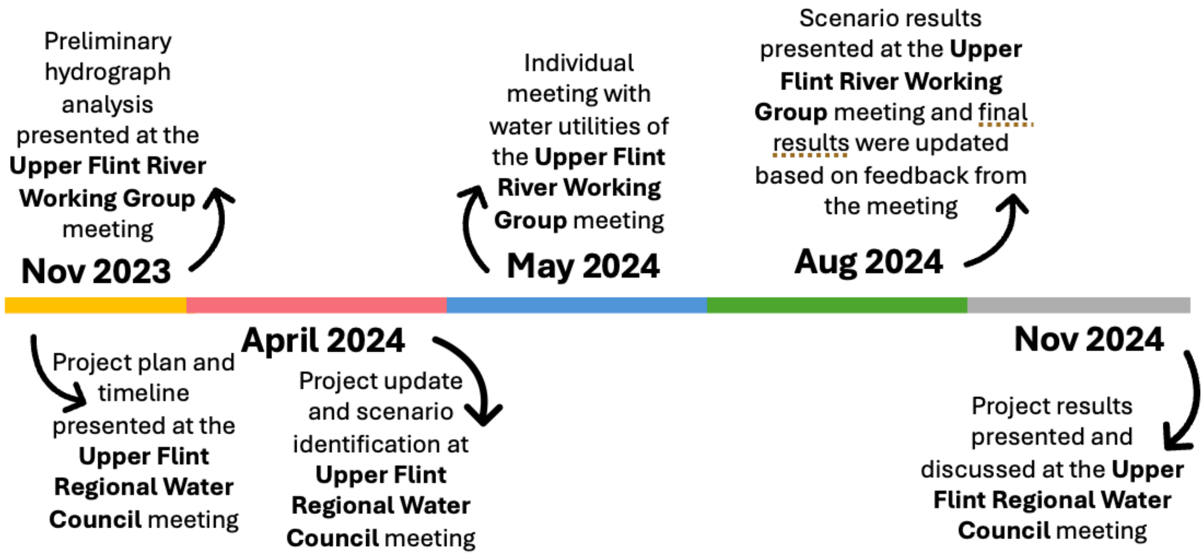


Figure 1. Timeline and overview of engagement with the Water Council and Working Group throughout the seed grant project.

Scenario 1: Increasing Infiltration in the Upper Flint Basin

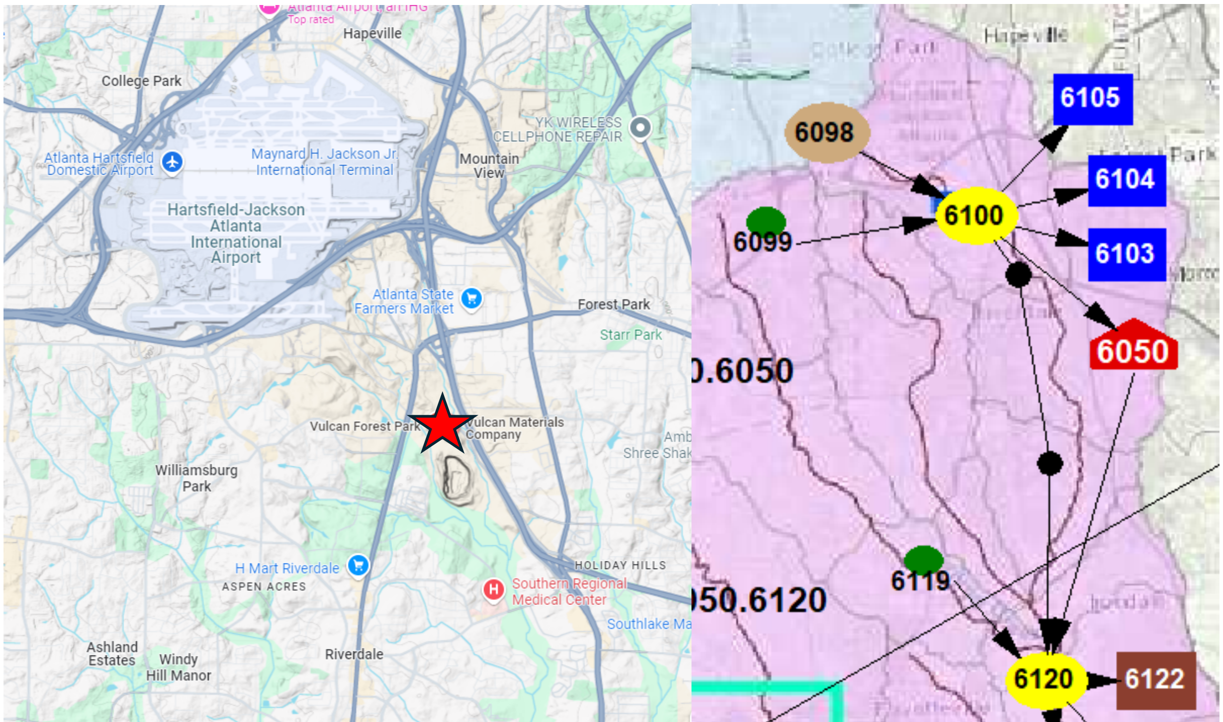
Rapid population growth in Georgia, and particularly in metropolitan Atlanta, has led to increased impervious surface area, which is associated with non-point source pollution, flooding, and degradation of waterways (Walsh et al. 2005, Jackson et al. 2023). In the Metropolitan North Georgia Water Planning District, which includes the headwaters of the Flint River, developed land was forecast to increase 40% from 2019 levels by 2040 with an 80 to 100% increase in run-off volume (Bell and Gurney 2022). Stormwater management that promotes infiltration into soils can greatly reduce the hydrologic and water quality impacts of impervious surface runoff on streams and rivers. More progressive stormwater regulations that have come about since approximately 2018 in Georgia, and apply to most of the Flint River headwaters, will likely increase infiltration in new development, but the Upper Flint has large areas of impervious cover that predate these rules. We were interested in evaluating the effects of retrofitting stormwater management structures or other methods to improve stormwater management in the upper basin.

We used an empirical method to estimate the effect of three levels of increased stormwater infiltration across the basin: 30 mm (1.18 in), 22.5 mm (0.87 in), and 15 mm (0.59 in). River flows in the region typically display baseflow recession from spring through fall due to the drainage of groundwater from the landscape following winter groundwater recharge and high evapotranspiration rates during the summer. Using the fractional drop in monthly flows between April and October over the period of record, we developed representative month-to-month recession rates, excluding those periods where substantial spring/summer rainfall or severe droughts rendered the recession rates negative or very large. We apportioned the basin-wide volume of increased winter stormwater infiltration depths across the months of April-October using these monthly recession rates, and we added the monthly volumes to the observed baseflows over the period of analysis. The three levels of infiltration we estimated represented modest additions to infiltration that could be achieved through broader application of existing stormwater management practices. To achieve 30 mm of increased winter infiltration, for example, we would need to infiltrate an overage of 1.36 mm (about 1/20th of an inch) each for 22 winter storms.

Scenario 2: Augmenting river flows with quarry storage

Vulcan Materials Company operates a large rock quarry in the headwaters located just south of the Hartsfield-Jackson Atlanta International Airport, near the Flint River and Mud Creek confluence (CH2M Hill 2018). Some basin stakeholders have suggested the quarry could serve as a potential reservoir storage for the Upper Flint Basin that could provide water supply, low-flow augmentation, and/or flood control. Although the quarry does not have a decommissioning schedule and there is no formal plan to convert it to use for water storage, the concept has spurred interest and discussion in the basin for several years. Our objective was to estimate the effect of releasing water stored in the quarry on the shoal ecosystems downstream during low-flow periods. To simulate storage operations at Vulcan Quarry, we created a new "reservoir node" in the Flint BEAM (Reservoir Node 6050, Figure 2).

Due to the small size of the Flint River and Mud Creek at the quarry site, the quarry would likely need to be filled using a diversion structure rather than pumps (CH2M Hill 2018), however we simulated quarry operations in BEAM by setting bounds on pumping into the reservoir. When selecting the bounds for when to fill the quarry, our goal was to preserve the median flows in the rivers. We therefore set a maximum daily pumping rate into the quarry and set a pass-by flow between nodes 6100 and 6120 to ensure we were not diverting all water to the quarry (Figure 2, Table 1). When setting rules for water release, we did not want to release extremely high flows into small channels. We therefore set a maximum daily release rate and set releases to occur when the USGS Carsonville gage in the BEAM scenario was less than 250 cfs, which represents a low summertime flow. All other operations were left the same as in the baseline BEAM with 2011 municipal, industrial, and agricultural demand. The scenario assumed no changes to operations, which meant that quarry releases were available to all downstream users for withdrawals.



Quarry Characteristics	
Location	33°35'49.9"N 84°23'45.8"W
Volume	5 billion gallons; 14,300 ac-ft capacity

Figure 2. Location of Vulcan Quarry in the Flint Basin (left) represented by the red star and as it was represented in BEAM (right) as a red pentagon. The Quarry is situated at the very top of the headwaters, just south of the Atlanta Airport, with a storage capacity of 5 billion gallons (Table).

Table 1. The operations set in BEAM to control the quarry filling and releases

Operations	Minimum flow	Maximum daily flow
Filling	*Set as a pass-by between nodes 6100 and 6120*: minimum flow is 10 cfs	*Tiered pumping operations:* No pumping when inflow to 6100 is 10 cfs Daily pumping can take 50% of inflow to 6100 when inflows are between 11-45 cfs, Daily pumping max is 20 cfs when inflows to 6100 are greater than 45 cfs
Releases	No minimum flow	Release 0 when Carsonville (node 7281) is greater than 250 cfs Release 50 cfs when Carsonville (node 7281) is less than 250 cfs

Scenario 3: Changes to low-flow operations

In this scenario, our objective was to maintain greater instream flows in the river during low-flow periods. Once flows start declining in the river, the only way to maintain instream flows is to stop pumping water out, so we simulated an increase in the minimum flow level required for municipal water utility operations. We could not simulate drought response actions directly in BEAM because they are primarily based on demand reduction, and we did not have data available to estimate the reduced demand based on such actions. Furthermore, each water utility in the Upper Flint has unique triggers for drought response based on their infrastructure and operations, making drought responses complex to simulate in BEAM. Instead, we changed the low-flow withdrawal limit for each utility to the mean June-October 20th percentile flow (Tables 2-4). We calculated the 20th percentile flow from the inflow to the relevant reservoir or junction node in the BEAM baseline. It is important to note that these are not recommended changes to permits or operations; this scenario was intended solely as a first-order approximation of the potential effect of operational changes on the ecological outcomes in Fint River shoals. Although water utilities account for the largest combined volume of water withdrawn in the basin, there are smaller agricultural withdrawal permits that were not changed in any scenario. In addition, non-permitted operations (withdrawals below 100,000 gallons per day from surface water do not require permits) are not represented in BEAM, although they may have a measurable influence on small streams and tributaries used for water supply.

Table 2. Pass-by flows required for reservoirs as they are set up in BEAM; utilities can withdraw water if flows passing downstream are at least this level.

Junction/ Reservoir Node	Name	Utility	Operation in baseline	Operation in Scenario 3
6260	Horton Creek Reservoir	Fayette	Pass-by flow: 30 cfs	Pass-by flow: 42.36 cfs
6300/6305	Heads Creek Reservoir	Griffin	Pass-by flow: 10 cfs	Pass-by flow: 46.94 cfs
6680	Still Branch	Griffin	Minimum pass-by flow when reservoir storage is below 70%: Monthly pass-by flow (cfs): June - 60 July - 60 August – 60 September – 60 October – 60 November - 60	Minimum pass-by flow when reservoir storage is below 60%: Monthly passby flow (cfs): June - 213 July - 171 August - 129 September - 122 October – 122 Nov - 187
6640	White Oak Creek withdrawal	Newnan	Pass-by flow: 1.9 cfs	Pass-by flow: 11.6 cfs

Table 3. Tiered pass-by flows based on pumping volumes and river flows; water can be withdrawn when flows are at or above this level.

Reservoir Node	Name	Utility	Operation in baseline	Operation in Scenario 3
6180	J. W. Smith Reservoir	Clayton	Tiered minimum based on pumping rates: 1st tier pumping 0-6MGD Pass-by flow: 12 cfs	Tiered minimum based on pumping rates: 1st tier pumping 0-6MGD Pass-by flow: 26.5cfs No change to 2nd and 3rd tier
6340	Line Creek withdrawal	Newnan	Tiered pumping structure based on river flow: Withdrawal 0: 0 – 2 MGD in river Withdraw up to 50% of river flows: 2-24 MGD in river Withdrawal 12 MGD: 24 MGD and up	Tiered pumping structure based on river flow: Withdrawal 0: 0–3.7 MGD in river Withdraw up to 25% if river flows: 2-24 MGD in river Withdrawal 12 MGD: 24 MGD and up

Table 4. Required outflow from reservoirs. This was set as the annual 15th percentile flow, and the release rate is the smallest value based on the inflow or the value in the table

Reservoir Node	Name	Utility	Operation in baseline	Operation in Scenario 3
6260	Lake Horton	Fayette	2.6 cfs or natural inflow	4 cfs or natural inflow
6380	Lake McIntosh	Fayette	4.64 cfs or natural inflow	13 cfs or natural inflow
6440	Lake Kedron	Fayette	1.6 cfs or natural inflow	4 cfs or natural inflow

Combined Scenario

We wanted to examine the combined impact of all actions on river flows and ecological outcomes in Flint River shoals. We conducted a run in the Flint BEAM that included Vulcan Quarry operations and the changes to the low-flow operations for utilities operating withdrawals in the Upper Flint Basin. We then added the daily infiltration values to the flow values for all years of the model run.

Scenario Evaluation

We used two approaches to evaluate the impact of management actions on ecological outcomes. First, we assessed the number of days river flow was below 100 cfs and 200 cfs at the USGS Carsonville gage for each scenario and compared them to the BEAM baseline scenario. These environmental flow thresholds were developed for the aquatic macrophyte riverweed (see below) and presented to the Council in 2021 in the document "Guidance on Drought Resilience for People and Nature in the Upper Flint River Basin." The 100 cfs threshold represents a condition of "more rocks than water" in the river at Sprewell Bluff, i.e., significant drying in the shoals, and was evaluated in the 2023 Upper Flint Regional Water Plan. We also evaluated 200 cfs, the point at which about 50% of the shoal at Sprewell Bluff is exposed, to understand how actions were affecting low-flow levels that occurred more frequently. Second, we developed and applied a predictive model for day-to-day change in riverweed biomass based on flow conditions to the flow outputs from each scenario to simulate the resulting biomass in a typical Flint River shoal. Model development and evaluation are discussed in more detail in the following section.

We evaluated the effect of scenarios 2 and 3 on the water availability and reservoir storage levels of four utilities: Clayton County Water Authority, Fayette County Water System, Newnan Utilities, and City of Griffin. These utilities had water withdrawal operations on the upper Flint River or tributaries and were also members of the Upper Flint River Working Group. We reported the number of days each year reservoir storage was at or below drought level 2, based on levels identified in the utilities' Drought Contingency Plans. We also solicited information about individual reservoir or combined storage levels that were of concern for the utilities' operations and summarized the impact on reservoir storage.

Ecological Model Development

We developed an ecological model for Flint River shoal ecosystems using the response of the submerged aquatic plant riverweed (*Podostemum ceratophylum*), that grows abundantly in shoal ecosystems (Nelson and Scott 1962, Grubaugh and Wallace 1995). Riverweed grows in swift flowing water and provides habitat for aquatic invertebrates and fishes; it is also vulnerable to low flows and desiccation (Wood et al. 2019, Pahl 2009, Argentina et al. 2010). Riverweed has been referred to as a foundation species (Wood and Freeman 2017) and serves as a promising low-flow indicator for shoal ecosystem condition both due to its key ecological role and because past studies make it possible to develop quantitative relationships between flow variables and riverweed biomass.

We estimated growth rate of riverweed biomass in relation to shoal water velocities using data from the Middle Oconee River near Athens GA (Appendix A), which is similar in size and geology to the Upper Flint and has been the site of four separate studies of monthly changes in riverweed biomass. We then used the relationship between discharge and velocities in the Flint River shoals to estimate change in biomass of riverweed based on flow conditions.

Our model had two components:

1. Daily flows for a scenario were used to project daily net change in riverweed biomass for the years 2009 to 2018. Daily net change in biomass was used to simulate biomass standing stock during each annual growing period, from an arbitrary beginning amount (e.g., 1000 mg ash-free dry mass per square meter).
2. Simulated standing stock biomass at the end of each autumn was multiplied by the lowest 30-day average proportion of shoal width estimated to maintain flow in the Flint River shoals at Sprewell Bluff. We assumed that drying for 30 days leads to complete loss of the plant (Pahl 2009), and so the smallest area of shoal that retained flow across the season (drying for less than 30 days) was the area that could support the simulated standing stock riverweed biomass.

We used the outputs at the USGS Carsonville gage for all scenarios from 2009 to 2018 to predict riverweed biomass. This time-period encompassed a one multi-year drought from 2011-2012 and a flash drought that occurred in the summer of 2016.

We include expanded methods and R and Jags code for the model in Appendix A.

Results

The Flint BEAM does not simulate the daily actions by the permittees. We therefore used BEAM to evaluate the relative change between the baseline scenario and our three management action scenarios for ecological metrics and reservoir storage for utilities. In the baseline scenario, flows below 200 cfs occurred in 26 years of the 80-year model period, often during drought periods. The annual duration ranged from one day to 160 days, with longer annual durations of flows below 200 cfs after the year 2000 compared to the previous years. Flows below 100 cfs occurred in 10 years of the 80-year model period, starting in 1986, with annual duration ranging from 6 to 80 days.

Scenario 1

When we estimated the impact of increased infiltration in the basin, we saw the greatest contributions to baseflow in the early spring. Effects tapered off through summer and fall (Tables 5 and 6). Based on the median monthly discharge from the baseline scenario, 30 mm of increased infiltration annually at the Carsonville gage would result in a 40% increase for the median April flow and a 15% increase in October (Table 6). We chose not to evaluate this scenario using the 100 and 200 cfs thresholds at Carsonville since these severe low-flow levels are not appropriate metrics for the time of year (i.e., early spring) that infiltration has the greatest impact on baseflow. Because our estimated values for infiltration were added to BEAM outputs, we were unable to evaluate the impacts on water utilities (i.e., for meeting system demand and reservoir storage).

Table 5. The median monthly flow and the monthly additions to baseflow in CFS for the Carsonville and Molena gages based on additional storage of 30mm, 22.5mm, and 15mm in the basin.

Site	April	May	June	July	Aug	Sept	Oct
Carsonville	2799	1542	1195	1090	906	659	668
30mm	1228	737	442	309	247	124	99
22.5mm	921	552	331	232	186	93	74
15mm	614	368	221	155	124	62	49
Molena	1103	558	357	354	218	227	240
30mm	640	372	192	111	78	40	27
22.5mm	480	279	144	84	58	30	20
15mm	320	186	96	56	39	20	14

Table 6. The percent increase in monthly median discharge with 30mm of additional storage for the Carsonville and Molena gages.

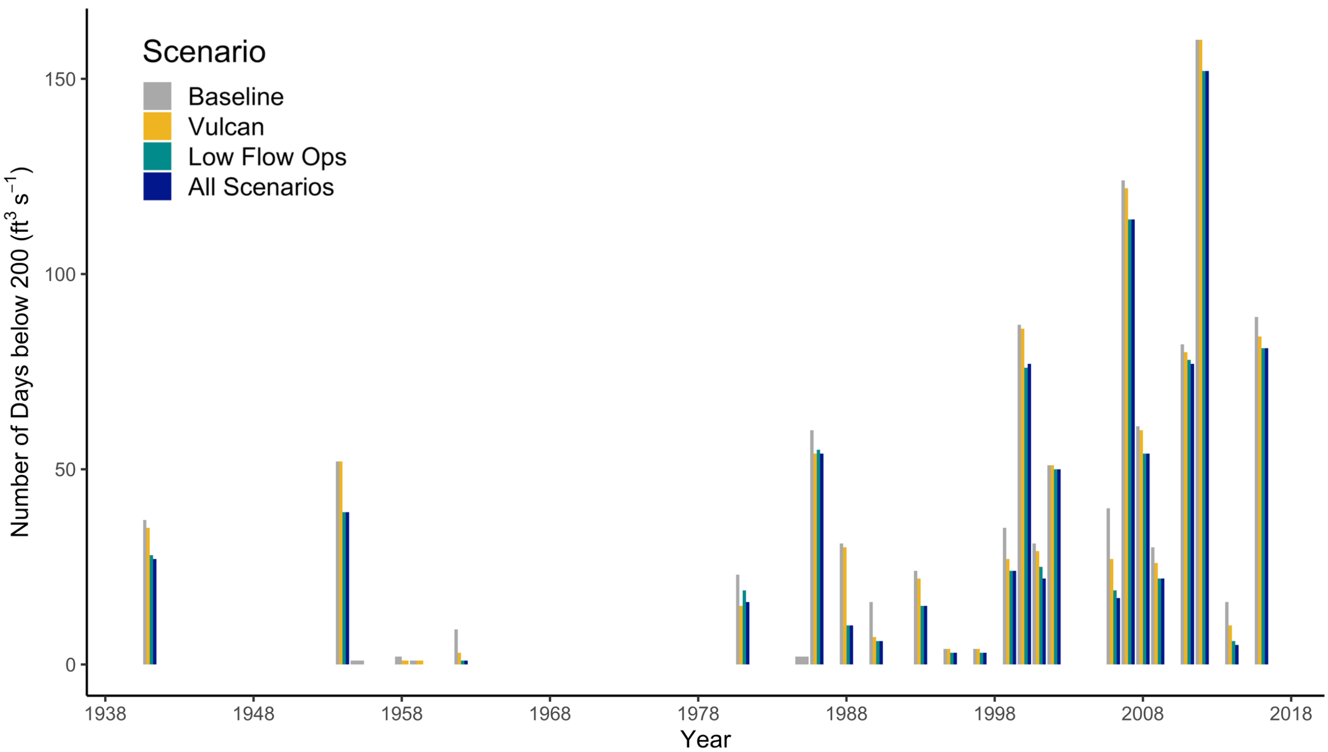
Site	April	May	June	July	Aug	Sept	Oct
Carsonville							
30mm	40%	48%	37%	28%	27%	19%	15%
Molena							
30mm	58%	67%	54%	31%	36%	18%	11%

Scenarios 2, 3, and combined scenario

We present the results of scenarios 2, 3, and the combined scenario together since we could evaluate the interactions among river flows, ecological outcomes, and water allocation.

Ecological outcomes

Changes to low-flow operations, scenario 3, had the greatest impact on river flows. We saw reductions in the number of days and years with flows below 100 cfs and 200 cfs (Figures 3 and 4). Quarry operations, scenario 2, also resulted in a decrease in the number of days below 200 cfs, but did not change the days below 100 cfs. This is because we did not change utility operations for the quarry scenario (scenario 2), so the additional water released from the quarry was available for use by utilities, and the simulation indicated that most of the released water would be withdrawn. The combined scenario primarily reflects the changes to river flows from the low-flow operations. Our results reflect that once flows start to decline there are limited options to keep water in the river, so early actions that support reducing withdrawals have the largest impact on instream flows.



A

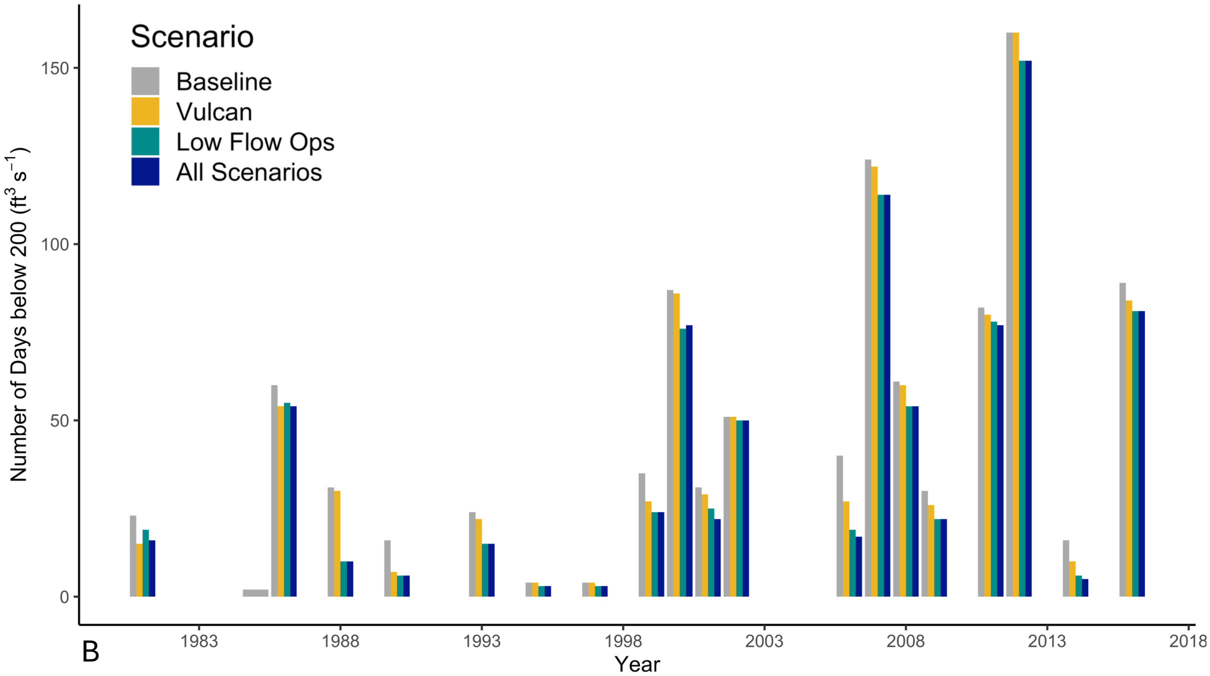


Figure 3. The number of days below 200 cfs at the Carsonville gage site in the baseline BEAM scenario and scenarios 2 , 3 and all scenarios from 1939-20018 (A). We observed below 200 cfs more consistely after 1978 (B) and we see the fewest days each year with the Low Flow Ops (scenario 3) and All Scenarios

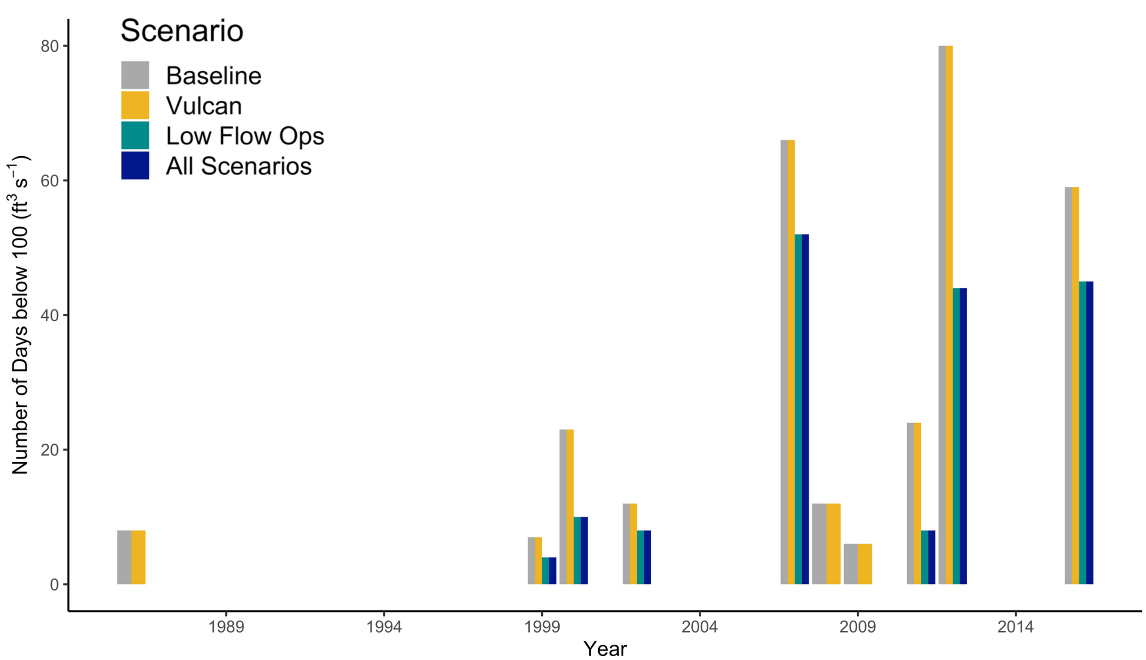


Figure 4. The number of days below 100 cfs (bottom) at the Carsonville gage site in the baseline BEAM scenario and scenarios 2, 3, and all scenarios. Days below 100 cfs did not begin until the mid 80’s and again we see that the fewest days occurred under scenarios 3 and the combined scenario.

The duration, magnitude, and frequency of events are important factors to evaluate for ecological metrics. We evaluated the 80th and 90th percentile annual number of days below 200 cfs, which is a very low flow but one that occurs more often than 100 cfs during the period of record, for the 80-year run in BEAM. Since these events do not occur in most years, we wanted to compare how long events occur (the duration) when they happen. We observed that quarry operations resulted in shorter events (# of days per year) for the 80th percentile (but not the 90th percentile) number of days. The low flow operations (scenario 3) and all scenarios reduced both the 80th and 90th percentile annual number of days below 200 cfs by more than 10 days (Figure 5).

Scenario	Annual number of days below 200 cfs (80th percentile)	Annual number of days below 200 cfs (90th percentile)
Baseline	23.2	51.1
Vulcan	16.4	51.1
Low Flow Ops	11	40.1
All scenarios	11	40.1

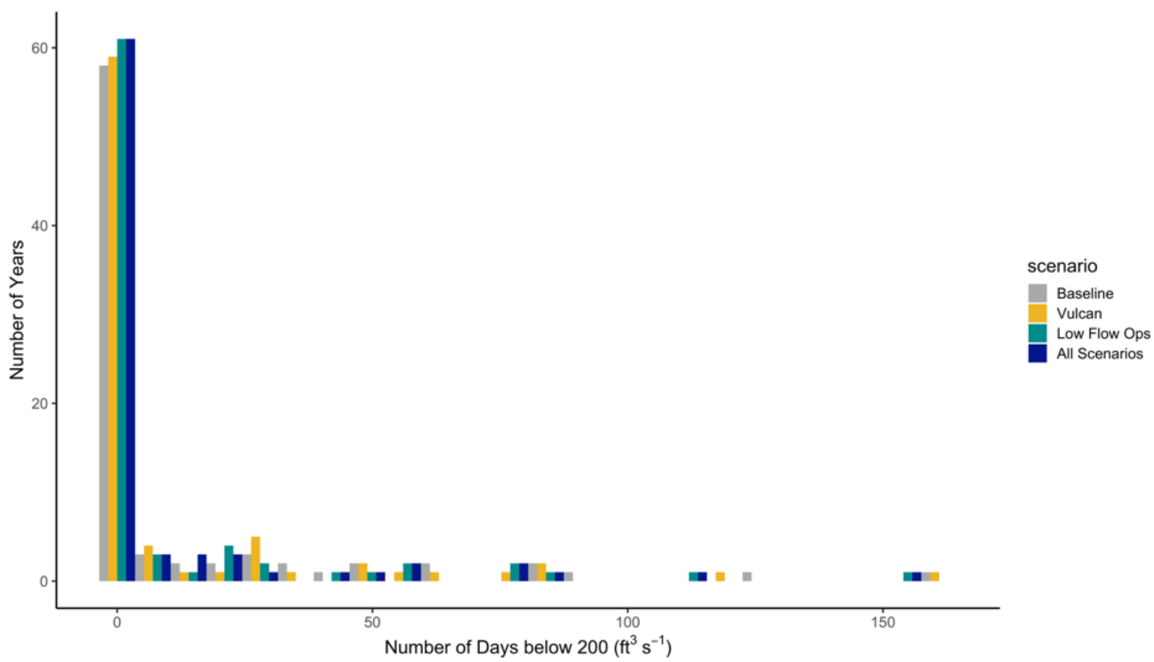


Figure 5. The 80th and 90th percentile annual number of days with flow below 200 cfs (Table) and histogram of the annual number of days below 200 cfs for each scenario. In most years flows below 200 did not occur. We observed the greatest reduction the number of years and the number of days below 200 cfs from the low flow operations and all scenarios. Vulcan quarry operations also reduced the number of days and years under 200 cfs.

Similarly, 100 cfs is an even more extreme low flow in the Flint River and only occurred in 10 years of the 80-year run in BEAM. Changing the low flow operations (scenario 3) reduced the duration of low-flow events and eliminated some years with excursions below 100 cfs (Figure 6). Quarry operations did not change the number of years (frequency) or duration of events below 100 cfs (Figure 6).

Scenario	**Annual number of days below 100 cfs (80th percentile)**	**Annual number of days below 100 cfs (90th percentile)**
Baseline	0	7.1
Vulcan	0	7.1
Low Flow Ops	0	0
All scenarios	0	0

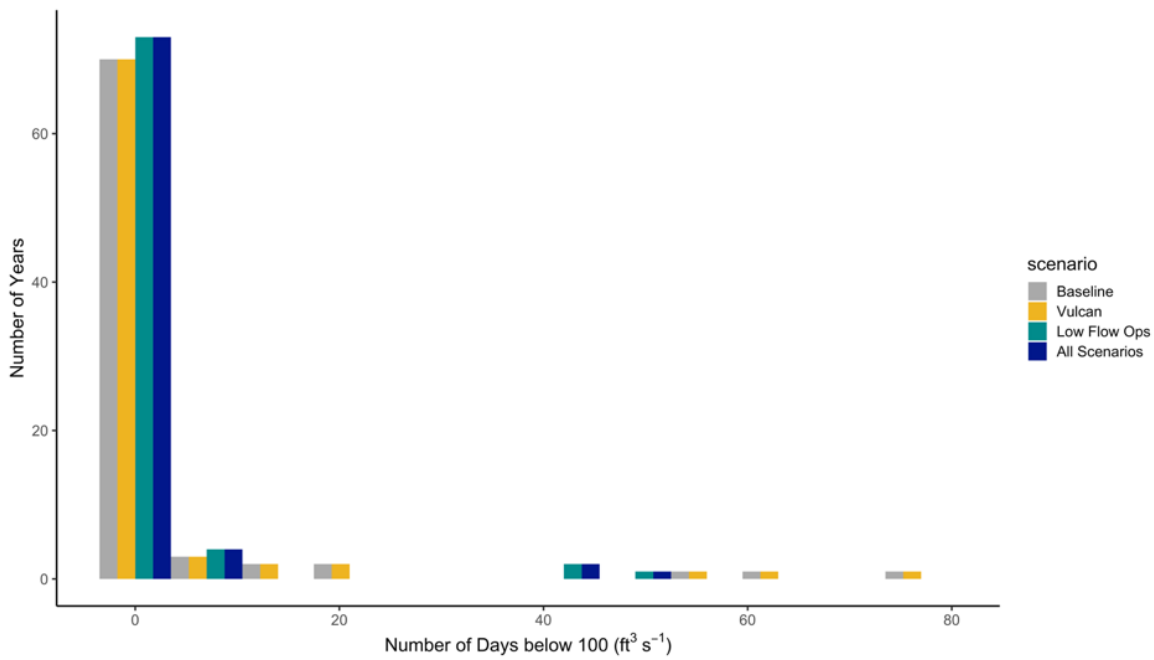


Figure 6. The 80th and 90th percentile annual number of days with flow below 100 cfs (Table) and histogram of the annual number of days below 100 cfs for each scenario. Flows below 100 did not occur in most years. We saw a reduction in annual number of days and years under 100 cfs with low flow operations and all scenarios, which eliminated more than 50 days of flow below 100 cfs. We did not see a change with Vulcan quarry.

Reservoir Storage and Utility Operations

The average monthly system demand, as reported by utilities in 2011, was met for the baseline, scenarios 2-3 and all scenarios combined. In the baseline scenario only Clayton County Water Authority combined reservoir storage was below drought level 2 during the model period; the other utilities' storage did not drop below their drought level 2 threshold. The change in operations we simulated (scenarios 2 and 3) did not impact the ability to meet the volume of water demand at the utility locations we evaluated in the basin, however there were differences in reservoir storage levels between scenarios, with the quarry operations supplementing reservoir storage and the low-flow operations resulting in storage levels that would cause concern for utility operations.

There are often multiple factors, e.g., river flows, reservoir storage, previous rainfall conditions, etc., in municipal utility drought contingency plans used to trigger drought response. We compared the annual number of days at or below drought level 2 reservoir storage for the 80-year simulation to the baseline scenario for all utilities (Table 7). We found that the low-flow operations (scenario 3) increased the number of years reservoir levels were at or below drought level 2, but the number of days and storage volumes were offset by quarry releases in the combined scenario for Clayton County Water Authority, Fayette County Water System, and City of Griffin. Quarry operations did not impact the withdrawal location for Newnan Utilities. The degree of impact on reservoir storage varied by utility. Clayton County Water Authority experienced the greatest decline in reservoir storage with the change in low-flow operations, followed by Fayette County Water System, and the Heads Creek Reservoir for the City of Griffin.

Table 7. Reservoir storage volumes associated with drought level 2 for the four utilities with withdrawals in the upper Flint River.

Utility	Drought level 2 reservoir storage	Additional storage volumes to evaluate
Clayton County Water Authority	75%	85%
Fayette County Water System	5 ft	2 ft
Newnan utilities	70%	NA
City of Griffin	60%	70%

Clayton County Water Authority

Clayton County combined reservoir storage was at or below 75% (drought level 2) in 7 years out of 80 years for the baseline scenario, 4 years for the quarry scenario, 19 years in the low-flow operations scenario, and 15 years in the combined scenario. Low flow operations increased the number of days and years under 75% and resulted in lower storage volumes in the reservoir. Quarry operations reduced the number of years below 75% compared to baseline. The combined scenario reduced the number of years below 75% and increased the minimum reservoir storage compared to low-flow operations alone (Figure 7, Table 8).

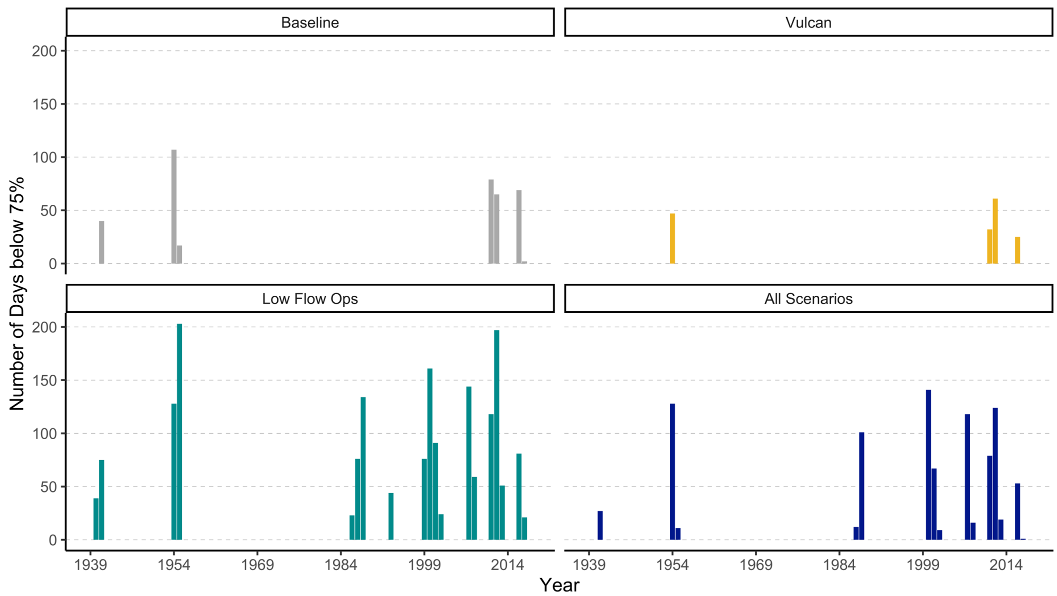
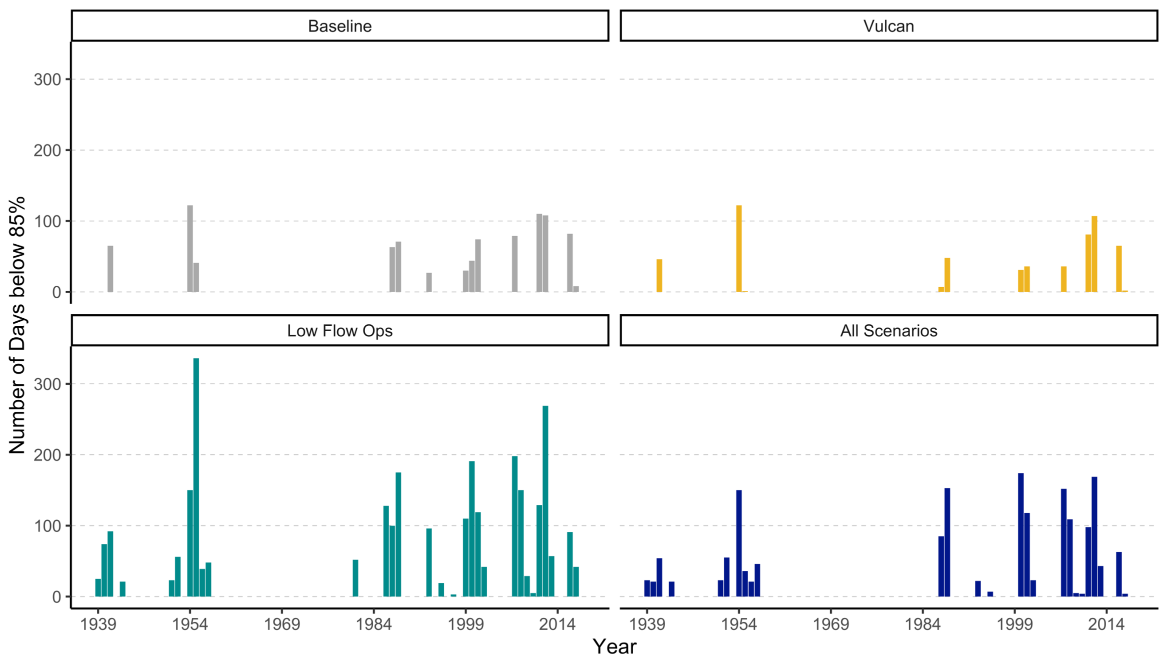


Figure 7. Number of days with combined reservoir storage below 75% for Clayton County reservoirs in each scenario in Flint BEAM.

Table 8. The years Clayton County combined reservoir storage was under 75% and the minimum combined storage volume and percent storage in parentheses for each scenario in BEAM. The total number of years below 75% for a scenario is in parentheses.

Year	Baseline (7)	Quarry (4)	Low flow ops (19)	All scenarios (15)
1940			6601 (71%)	
1941	6485 (70%)		4437 (48%)	6307 (68%)
1954	3447 (37%)	6370 (68%)	404 (4%)	4342 (47%)
1955	4836 (52%)		1637 (18%)	5617 (60%)
1986			6629 (71%)	
1987			5541 (60%)	6838 (73%)
1988			5418 (58%)	5916 (64%)
1993			5584 (60%)	
1999			6212 (67%)	
2000			5165 (55%)	5579 (60%)
2001			4612 (50%)	5694 (61%)
2002			5407 (58%)	6491 (70%)
2007			4150 (45%)	4690 (50%)
2008			5580 (60%)	6122 (66%)
2011	5798 (62%)	6656 (71%)	3252 (35%)	5325 (57%)
2012	6151 (66%)	6259 (67%)	1899 (20%)	3100 (33%)
2013			4446 (48%)	5670 (61%)
2016	4754 (51%)	6001 (64%)	2760 (30%)	5360 (58%)
2017	6400 (69%)		4316 (46%)	6939 (75%)

Clayton County combined storage at or below 85% was of interest to the utility and followed a similar pattern to storage below 75%. Low-flow operations increased the number of days and years below 85%, but these were partially offset in the combined scenario with the quarry. Quarry operations reduced the number of days and years below 85% (Figure 8).

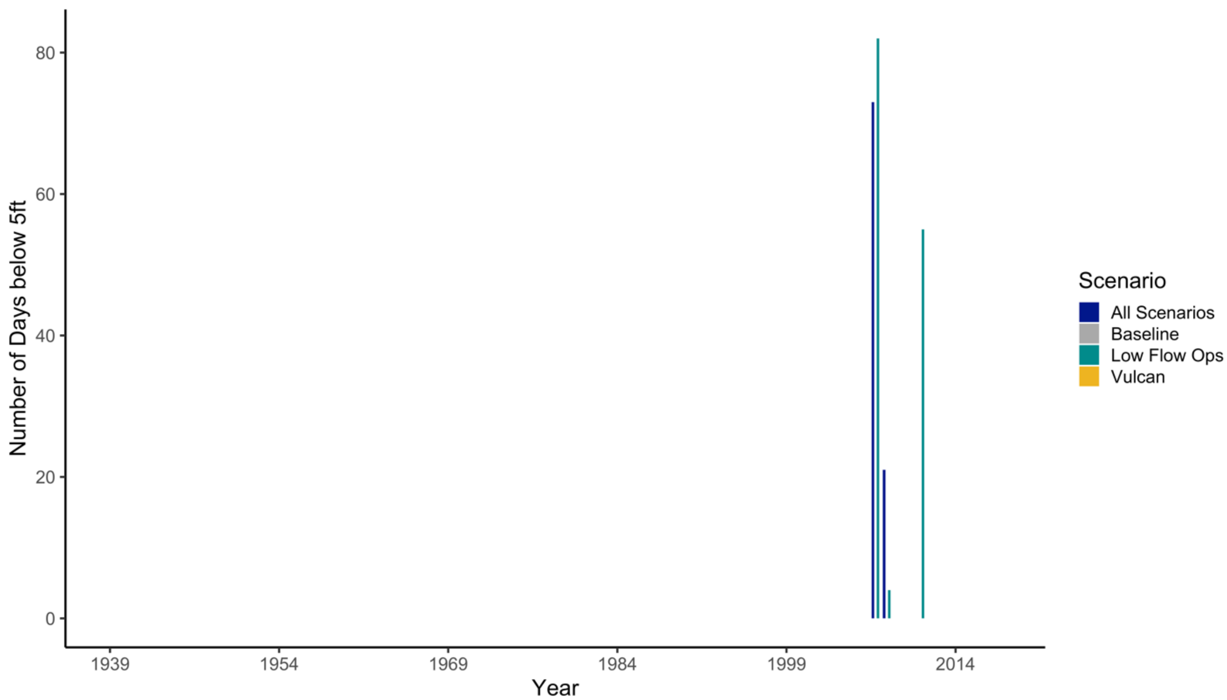


Scenario	Number of years below 85%
Baseline	14
Vulcan quarry	12
Low flow ops	30
All scenarios	26

Figure 8. Number of days with combined reservoir storage below 85% for Clayton County reservoirs in each scenario in Flint BEAM. We summarized the total number of years below 85% combined storage for each scenario (Table).

Fayette County Water System

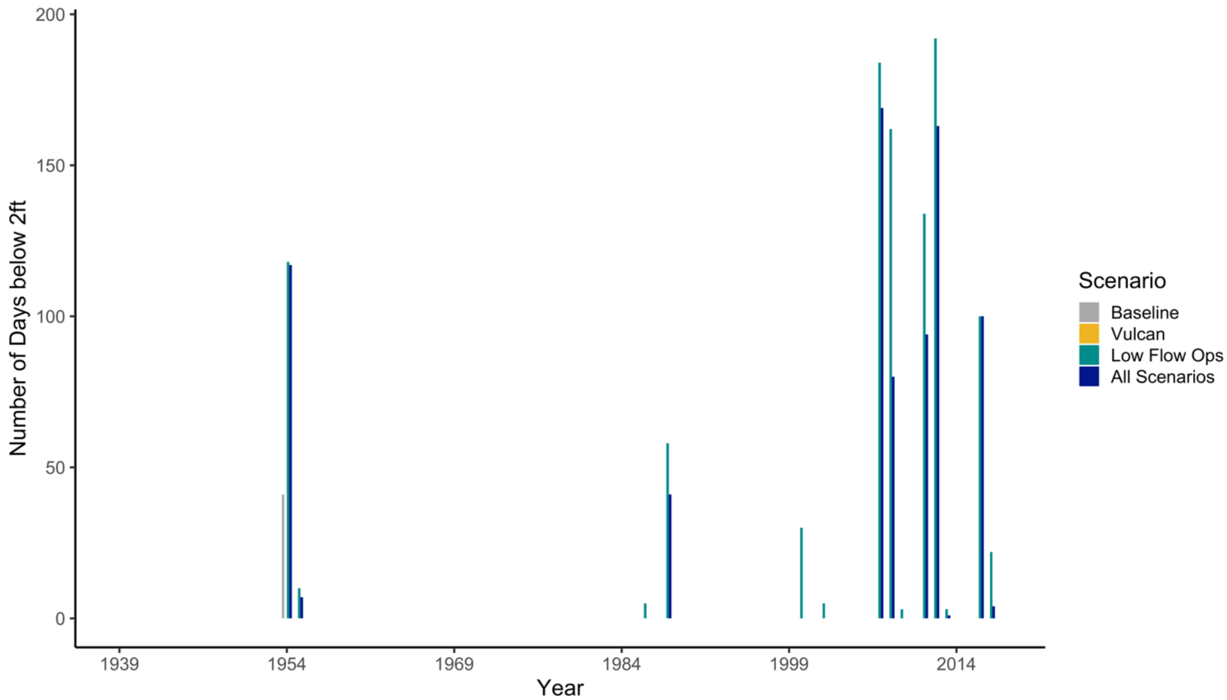
We evaluated the storage volume in Lake Horton to represent the series of reservoirs operated by Fayette County. Reservoir storage in drought level 2, or 5 ft below reservoir pool level, occurred in three years in the low-flow operations (scenario 3) and two years in the combined scenario. There were zero years with days below 5ft for the baseline and quarry scenario (Figure 9).



Year	Baseline	Quarry	Low flow ops (3)	All scenarios (2)
2007			773 (57%)	771 (48%)
2008			774 (63%)	772 (53%)
2011			774 (63%)	

Figure 9. Number of days 5ft below pool at Lake Horton reservoir in Fayette County Water System for each scenario in BEAM. The minimum pool elevation and percent storage in parentheses for each scenario in BEAM. The total number of years with 5 ft below pool for a scenario is in parentheses.

Reservoir elevation for Lake Horton was 2 ft below pool in one year in the baseline scenario. The quarry scenario reduced this to zero years, whereas the low-flow operations scenario had 14 years below the threshold and the combined scenario had 10 years below the threshold (Figure 10).



Year	Baseline (1)	Quarry (0)	Low flow ops (14)	All scenarios (10)
1954	777 (79%)		775 (68%)	775 (68%)
1955			777 (79%)	777 (79%)
1986			777 (79%)	
1988			776 (74%)	777 (79%)
2000			777 (79%)	
2002			777 (79%)	
2007			773 (57%)	771 (48%)
2008			774 (63%)	772 (53%)
2009			777(79%)	
2011			774 (63%)	776 (74%)
2012			775 (68%)	775 (68%)
2013			777 (79%)	777 (79%)
2016			775 (68%)	776 (74%)
2017			776 (74%)	777 (79%)

Figure 10. Number of days 2ft below pool at Lake Horton reservoir in Fayette County Water System for each scenario in BEAM. The minimum reservoir elevation and percent storage in parentheses for each scenario in BEAM. The total number of years with pool below 2ft for a scenario is in parentheses (Table).

We also tracked how pool levels changed in Lake Horton and Lake Kedron for all scenarios in BEAM (Figures 11-14). Monitoring how closely the reservoir levels tracked through the scenarios was of interest to the utility.

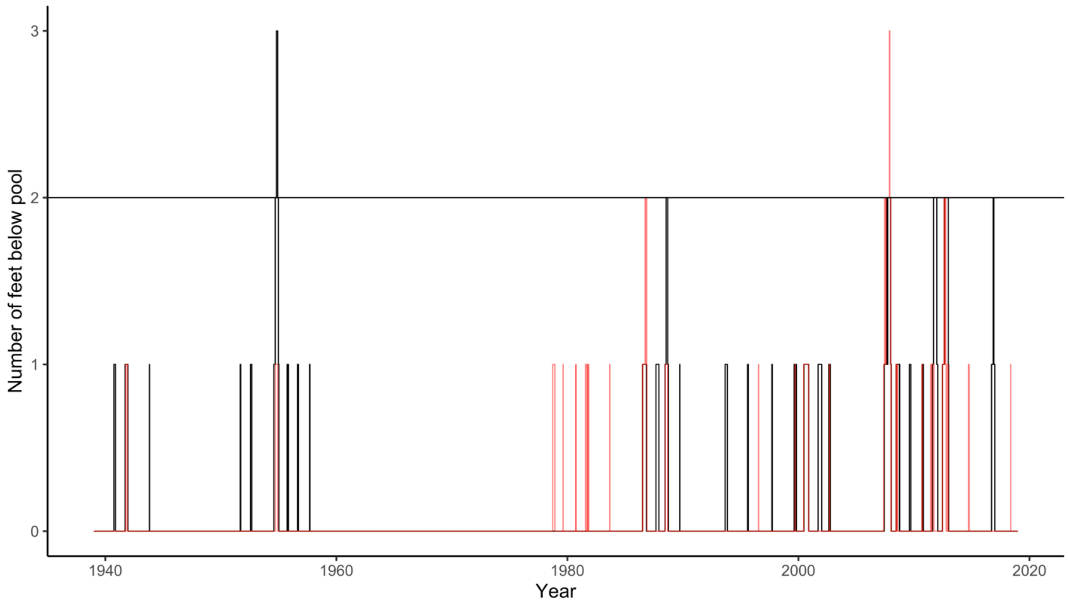


Figure 11. The number of feet below full pool for Lake Horton (black) and Lake Kedron (red) for the baseline scenario. The horizontal black line is at 2 feet below pool.

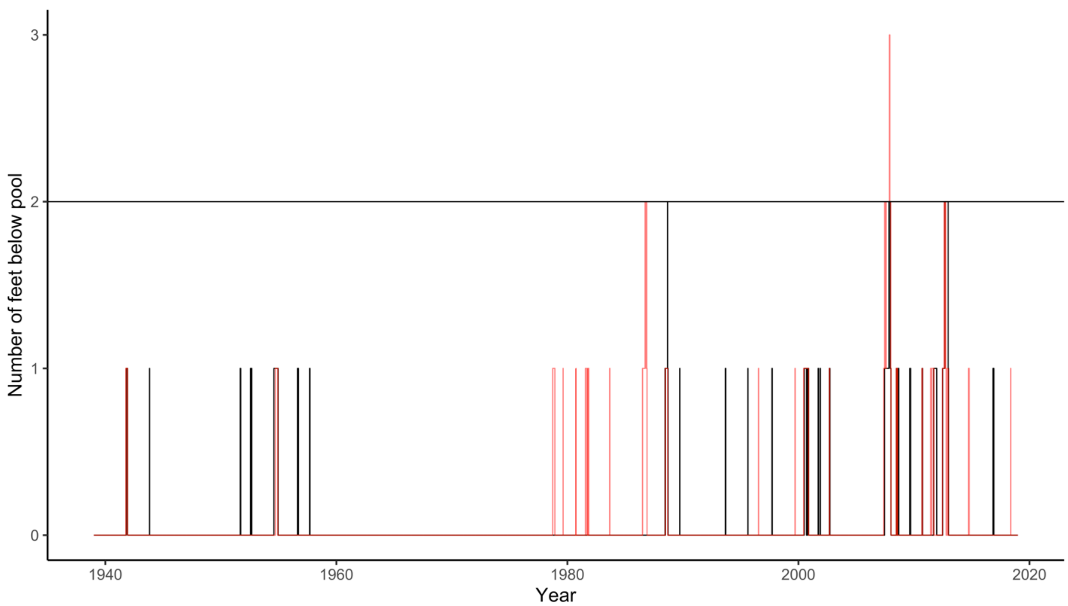


Figure 12. The number of feet below full pool for Lake Horton (black) and Lake Kedron (red) for the Vulcan quarry scenario. The horizontal black line is at 2 feet below pool.

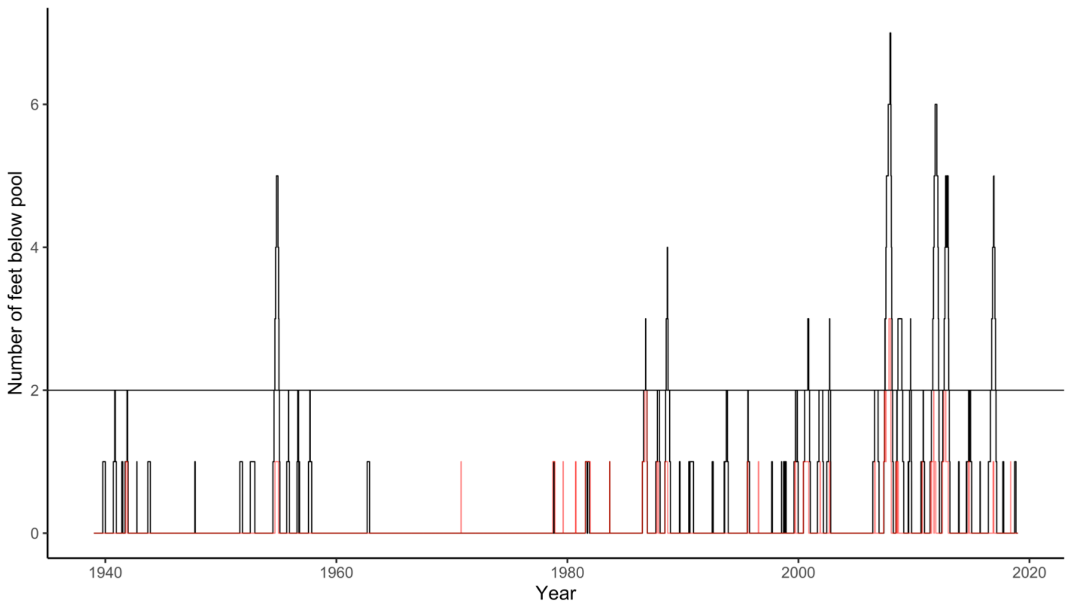


Figure 13. The number of feet below full pool for Lake Horton (black) and Lake Kedron (red) for the changing minimum flow scenario. The horizontal black line is at 2 feet below pool.

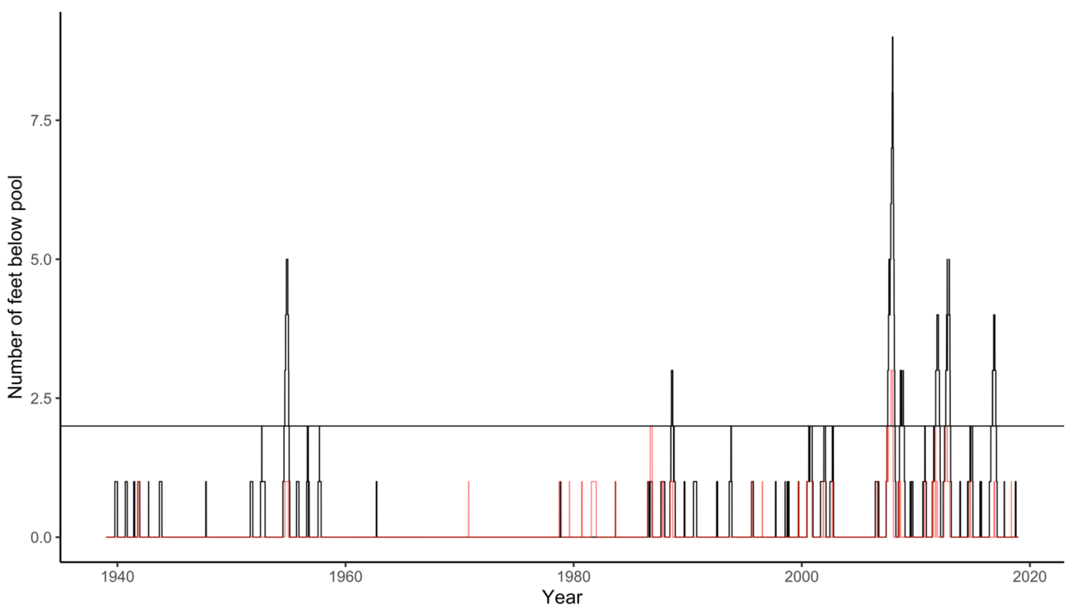
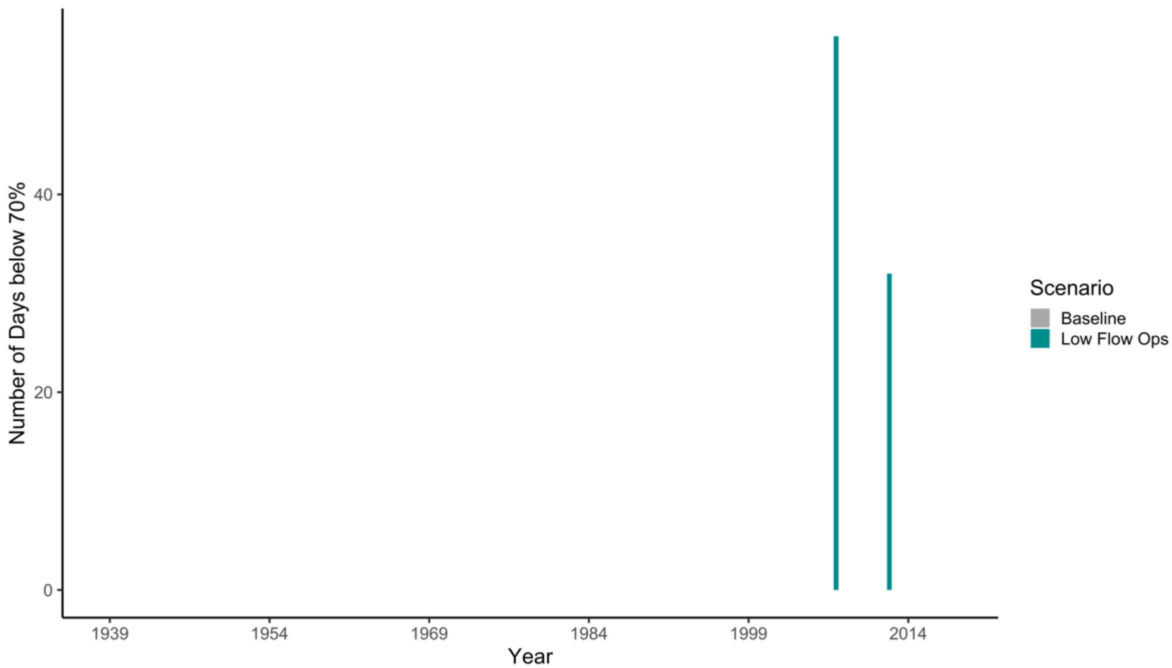


Figure 14. The number of feet below full pool for Lake Horton (black) and Lake Kedron (red) for the combined scenario. The horizontal black line is at 2 feet below pool.

Newnan Utilities

There were zero years with reservoir storage below 70% for the baseline scenario and two years in the low-flow operations scenario (Figure 15). Newnan's operations in the Flint Basin are unaffected by the quarry releases.



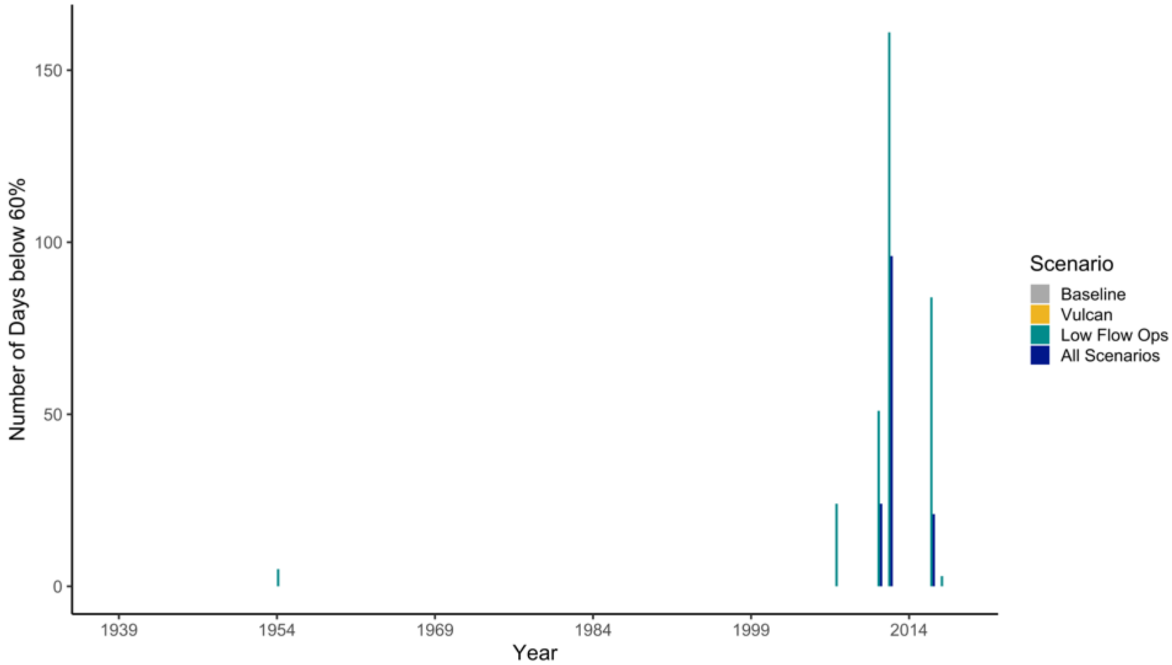
Year	Baseline	Low flow ops
2007		2252 (58%)
2012		2485 (64%)

Figure 15. Number of days with combined reservoir storage below 70% for Newnan Utilities for each scenario in Flint BEAM. We summarized the reservoir storage for years below 70% combined storage (Table).

City of Griffin

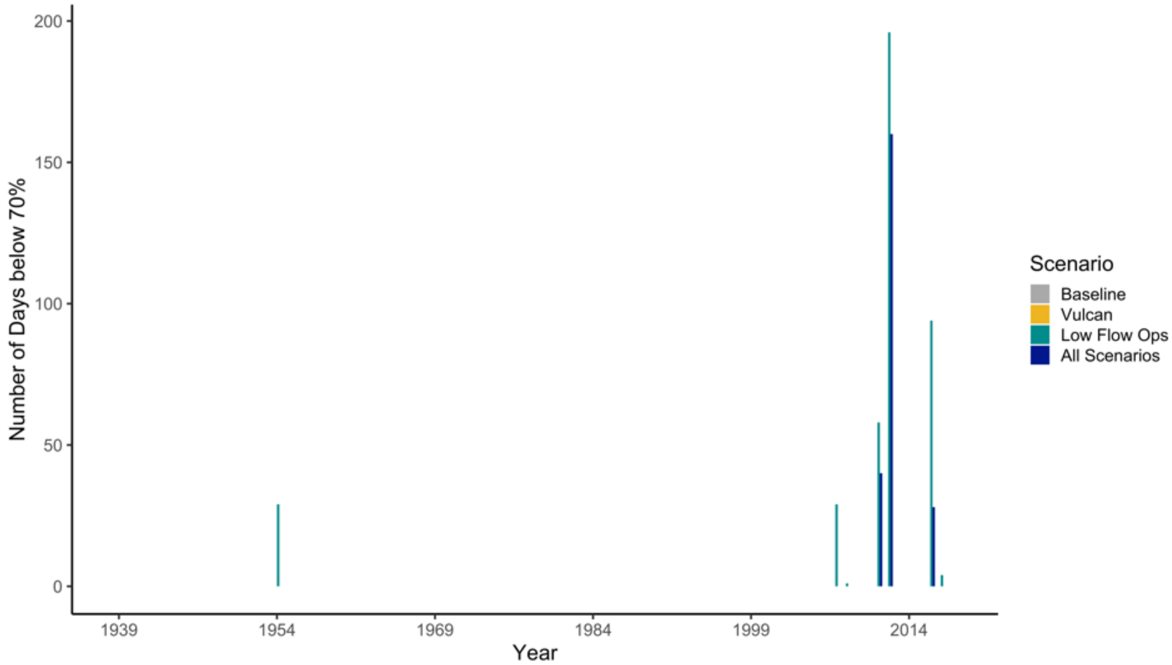
The City of Griffin's Still Branch Reservoir showed the smallest impact from the low-flow operations (scenario 2). Combined storage was not below the 60% or 70% storage level for baseline or any scenario in BEAM. The combined storage of the Still Branch and Heads Creek Reservoirs was also not below the 60% or 70% storage level for the baseline or any scenario in BEAM.

Heads Creek Reservoir was below the 60% storage for 6 years for the low-flow operations (scenario 3) scenario and 3 years during the combined scenario, and primarily occurred during the recent droughts in the 2000's (Figure 16). The results were similar for years below 70% storage, with 7 years for the low-flow operations (scenario 3) and 3 for the combined scenario (Figure 17). Heads Creek Reservoir was not below 60% or 70% for the baseline or quarry scenario (Figures 16 and 17).



Year	Baseline	Quarry	Low flow ops	All scenarios
1954			962 (58%)	
2007			671 (41%)	
2011			203 (12%)	587 (36%)
2012			115 (7%)	251 (15%)
2016			0	535 (32%)
2019			625 (38%)	

Figure 16. Number of days with Griffin Counties' Heads Creek Reservoir below 60% in each scenario in Flint BEAM. We summarized the minimum storage volume and percent storage for years with storage below 60% (Table).



Year	Baseline	Quarry	Low flow ops	All scenarios
1954			962 (58%)	
2007			671 (41%)	
2008			1118 (68%)	
2011			203 (12%)	587 (36%)
2012			115 (7%)	251 (15%)
2016			0	535 (32%)
2019			625 (38%)	

Figure 17. Number of days with Griffin Counties' Heads Creek Reservoir below 70% in each scenario in Flint BEAM. We summarized the minimum storage volume and percent storage for years with storage below 70% (Table).

Ecological Model Results

The ecological model provided a simulation of riverweed dynamics under the different management scenarios. Our model of Flint River riverweed biomass from 2009 to 2018 showed that biomass peaked in the winter and was lowest in the summer. The summer and winter biomass values were lower during drought years (2011, 2012, and 2016, Figure 18). These patterns were consistent across all scenarios and illustrated general growth dynamics, so we only displayed the daily biomass for the baseline scenario (Figure 18). For each scenario, we compared the annual minimum standing stock biomass of riverweed adjusted for the extent of shoal drying (Figure 19). In our three drought years, we saw the greatest increase in riverweed biomass in 2016 from the low-flow operations (scenario 3) and the combined scenario as compared to the baseline, with a 54 and 50% increase respectively. We also saw some increases in non-drought years, such as in 2009 when the flows from scenario 3 and the combined scenario once again led to the greatest increase in biomass compared to the baseline. It is also worth noting that we see small increases in biomass for scenarios 1 and 2 in most years. This is likely due to their effects on moderately low flows, which were important for determining the extent of the shoal that was wet during the summer.

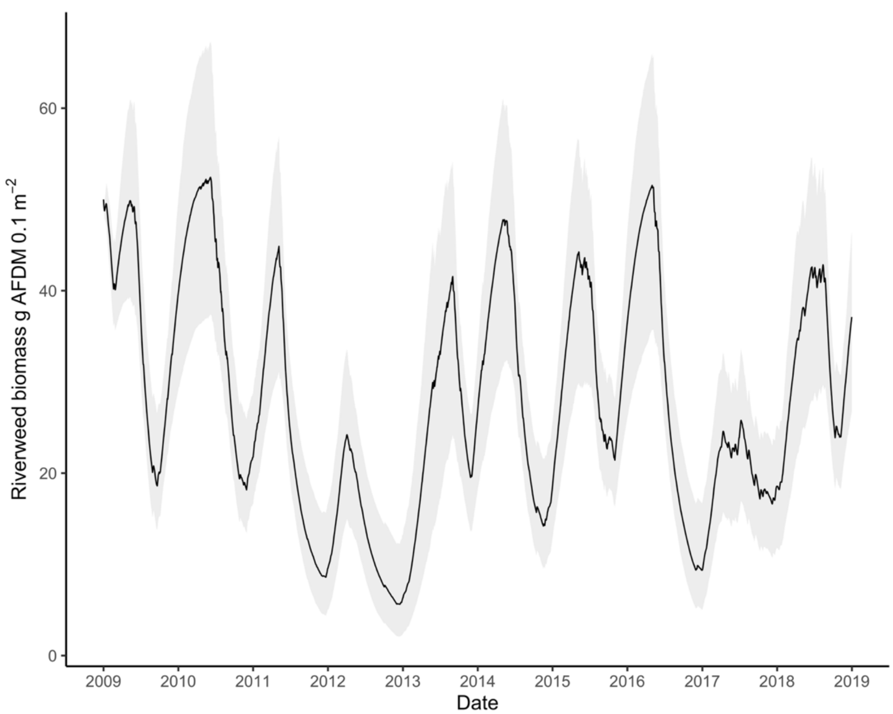


Figure 18. Change in riverweed biomass simulated at a daily time-step as driven by the discharge levels at the Carsonville gage site from the output of the Flint baseline scenario. Discharge was used to estimate the velocity conditions in the shoal which in turn influenced the growth rate of the plant. At lower velocities the plant was vulnerable to grazing, a mechanism of biomass loss in our model.

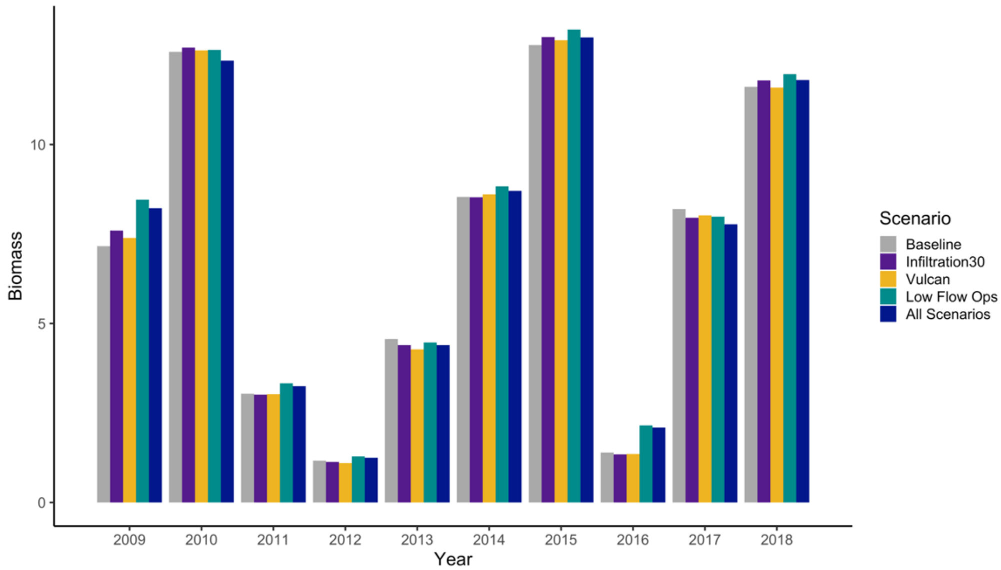


Figure 19. The minimum monthly biomass (g AFDM per 0.1 m^2, weighted by proportion of shoal habitat wetted for at least 30 d) for each scenario from 2009 to 2018. In most years, the scenarios with management actions showed slightly higher biomass than baseline, with the largest increase from the baseline seen during the 2016 drought.

Conclusions

We evaluated the relative impact of management actions on aquatic ecosystems and water utility operations during low-flow and drought periods, when it is challenging to meet human water needs and support aquatic ecosystems. We found that each of the three scenarios, and the combined scenario, provided unique but often complementary outcomes for the Upper Flint River Basin. Changes to low-flow operations (scenario 3) was the only scenario to mitigate extreme low flows in the Flint River, with reductions in number and duration of events under 200 and 100 cfs. This scenario also resulted in the lowest reservoir storage, but we found the storage declines were partially offset in the Combined Scenario due to augmentation to river flows from the quarry. Quarry operations alone (scenario 2) provided modest flow increases in the river, but our model indicated that most of the released water would be withdrawn by utilities, buffering their storage capacity. Increasing infiltration (scenario 1) had the greatest impact on springtime river flows between April and June. While converting water to baseflow rather than runoff is important for the river ecosystem, we could not assess the impacts to utilities since the results were applied to BEAM outputs, rather than simulated within BEAM. To make our findings more accessible to the Water Council members and public, we created a summary document that highlights the general findings from the project and directs viewers back to this report for details about the approach and findings (Appendix B)

The development and implementation of the Flint BEAM for water planning allowed us to evaluate water quantity at the scale of individual water utilities and the relative difference in water availability under alternative management actions. BEAM was useful for investigating the relative difference of management actions on utility operations and ecological outcomes, and for identifying when it may be useful to conduct more detailed study on specific operations. We found BEAM was most useful for exploring how different management actions could impact streamflow and reservoir storage on average. However, to understand how specific operations impact river flow, reservoir storage levels, and system demand on a daily time step would require additional information to input into BEAM or an alternative model outside of BEAM. For example, BEAM currently routes water based on the permitted limits and the daily time step is based on the monthly data reported by utilities. To more closely reflect the operation by specific utilities, we would need to develop information with utilities about general day-to-day operations based on a combined reservoir and river level during different times of year, which could then be translated to operations in BEAM. This general approach could be useful to other regional planning councils to evaluate management alternatives that are specific to each basin (also see Appendix C for general guidance for evaluating ecological indicators in regional water planning).

Water utilities in the Working Group have seen growth in their customer base since the 2022 planning cycle and are expecting continued growth in certain areas of the Flint Basin. With this in mind, utilities are interested in updating the drought demand values (which are based on year 2011) to evaluate meeting water needs during low-flow periods. In addition, “flash droughts” or periods of high heat and a sudden lack of rainfall have become more common during the summers and have created a different type of management challenge. Recognizing that this type of event will continue, Working Group participants are interested in exploring how these types of events may interact with regard to drought planning. In future iterations of Flint BEAM, it would also be helpful to investigate how the drought response plans could be simulated within the BEAM framework. Since the plans are utility-specific and partly based on actions that lead to reduced demand from customers, a combination of information may be needed to simulate changes to demand in BEAM alongside operations shifts.

Citations

ARCADIS. 2019. Methods for flow regime evaluation, Ocmulgee River, Georgia. Prepared for Georgia Environmental Protection Division

Argentina, J. E., M. C. Freeman, and B. J. Freeman. 2010. The response of stream fish to local and reach-scale variation in the occurrence of a benthic aquatic macrophyte. Freshwater Biology **55**:643-653.

Arthington, A. H., A. Bhaduri, S. E. Bunn, S. E. Jackson, R. E. Tharme, D. Tickner, B. Young, M. Acreman, N. Baker, S. Capon, A. C. Horne, E. Kendy, M. E. McClain, N. L. Poff, B. D. Richter, and S. Ward. 2018. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). Frontiers in Environmental Science **6**.

Bell, D. B. and R. Gurney. 2022. Stormwater Forecast – Technical Approach and Results. Metropolitan North Georgia Water Planning District. Jacobs.

Grubaugh, J. W., and J. B. Wallace. 1995. Functional structure and production of the benthic community in a Piedmont river: 1956-1957 and 1991-1992. Limnology and Oceanography **40**:490-501.

Jackson, C.R., Wenger, S.J., Bledsoe, B.P., Shepherd, J.M., Capps, K.A., Rosemond, A.D., Paul, M.J., Welch-Devine, M., Li, K., Stephens, T. and Rasmussen, T.C., 2023. Water supply, waste assimilation, and low-flow issues facing the Southeast Piedmont Interstate-85 urban archipelago. Journal of the American Water Resources Association, **59**(5), pp.1146-1161.

Nelson, D. J., and D. C. Scott. 1962. Role of Detritus in The Productivity of a Rock-Outcrop Community in a Piedmont Stream. Limnology and Oceanography **7**:396-413.

Pahl, J. 2009. Effects of flow alteration on the aquatic macrophyte *Podostemum ceratophyllum* (riverweed); local recovery potential and regional monitoring strategy. MS Thesis, University of Georgia.

Wood, J., and M. Freeman. 2017. Ecology of the macrophyte Podostemum ceratophyllum Michx. (Hornleaf riverweed), a widespread foundation species of eastern North American rivers. Aquatic Botany **139**:65-74.

Emanuel, B. 2019. Ensuring water security for people and nature: A status report from the upper flint river working group. American Rivers.

CH2M Hill. 2018. Shoal Creek Water Reclamation Facility Decommissioning Feasibility Study, Task 1 of the Upper Flint Hydrology Study Project. Clayton County Water Authority

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M. and Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society, **24**(3), pp.706-723.

Wood, J.L., Skaggs, J.W., Conn, C. and Freeman, M.C., 2019. Water velocity regulates macro-consumer herbivory on the benthic macrophyte *Podostemum ceratophyllum* Michx. Freshwater Biology, **64**(11), pp.2037-2045.

Appendix A: *Podostemum* simulation model for Flint River shoals

Objective: Compare ecological outcomes among flow-scenarios in the upper Flint River.

Model components:

1. Daily flows for a scenario are used to simulate daily net change in *Podostemum* biomass for a one or more growing annual cycles. Daily net change in biomass is used simulate biomass standing stock across each annual cycle, from an arbitrary beginning amount (e.g., 1000 mg AFDM/m^2 at the beginning of the first cycle if simulation covers multiple years).

2. Simulated standing stock biomass at the end of each annual cycle is multiplied by the lowest 30-d average proportion of shoal width estimated to maintain flow during that year. We assume that drying for 30-d leads to complete loss of the plant (Pahl 2009), and so the smallest area of shoal that retains flow (i.e., drying for less than 30 d) across the season is the area that can support the simulated standing stock *Podostemum* biomass.

Methods:

1. Use measurements of water velocity in Flint River shoals (during 2001, 2002; Marcinek, UGA, unpublished) to estimate a relation between discharge at the USGS Carsonville gage and proportion of shoal habitat that has water velocity < 0.4 m/s ("low velocity extent").
2. For a flow scenario, project daily flows at the Carsonville gage
3. For each day in the scenario, estimate proportion of shoal habitat with velocity <0.4 m/s using the relation from step 1.
4. Use regression coefficients estimated from Middle Oconee River to translate daily proportion of shoal habitat with velocity <0.4 m/s to a daily *Podostemum* growth rate.
5. Use daily growth rate to estimate daily change in *Podostemum* biomass, over each annual cycle in the simulation period.
6. Finally, use a linear regression to estimate the minimum 30-d average percent wetted channel in Flint River shoal habitat for each annual cycle in the simulation period.
7. Assume that exposure for 30 days eliminates *Podostemum* (Pahl 2009). *Podostemum* biomass in shoal habitat at the end of each annual cycle is estimated by final, annual biomass estimate (from step 5) multiplied by the minimum 30-d average percent wetted channel (step 6).

Sections:

I. Estimating proportion of Flint River shoal habitat with velocity <0.4 m/s in relation to daily flow , using field observations in 2001 and 2002.
II. Overview: estimating *Podostemum* daily growth rate in relation to shoal habitat with velocity <0.4 m/s, using biomass time-series observations in the Middle Oconee River.
III. Estimating the proportion of shoal drying at Sprewell Bluff shoals based on three discharge and drying points
IV. Model code
V. References

I. Estimating proportion of Flint River shoal habitat with velocity <0.4 m/s in relation to daily flow , using field observations in 2001 and 2002.

Data comprise velocity measurements at randomly chosen locations within 17 Flint River shoals, made in conjunction with fish sampling during 2001 and 2002 (Marcinek 2003). Shoals are located between Gay-Flat Shoals Road and Pobiddy Road crossings of the Flint River and were randomly chosen to represent large (>100 m in length) and small (<100 m in length) shoals in the upper and lower halves of the study reach (Marcinek 2003). Water velocity was measured at 60% of the water depth (measured from the surface) with an electronic current meter and top-setting wading rod.

We tested two models (log-log and logistic) to relate the proportion of measurements that were <0.4 m/s (“slow velocity”) to the flow at the Carsonville gage on the day measurements were made. Both models include a random effect for shoal identity (“site[i]”); three shoals were sampled in both years, one shoal in 2001 only, and 13 shoals in 2002 only. Number of velocity measurements per shoal visit ranged from 26 to 80 (median = 59). Note that on 18 of the 20 total visits, flow at the Carsonville gage was < 600 cfs, and that the majority of velocity measurements were <0.4 m/s.

Code for log-log model:

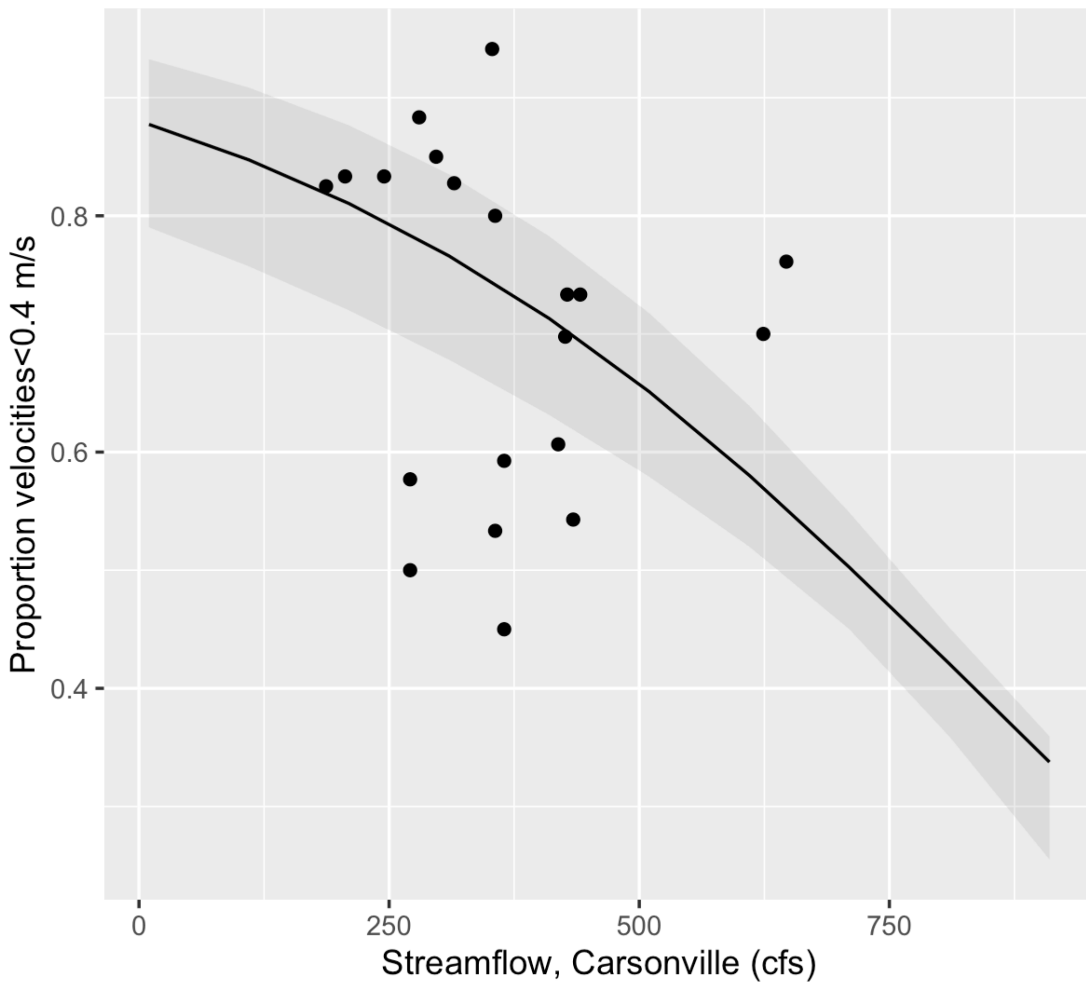
```
slow[i]~dbern(p.slow[i])
p.slow[i]<-exp(-exp(s[i]*100*(q[i]-c)))
s[i]<-s0 + epsilon[site[i]]
```

Code for the logistic model:

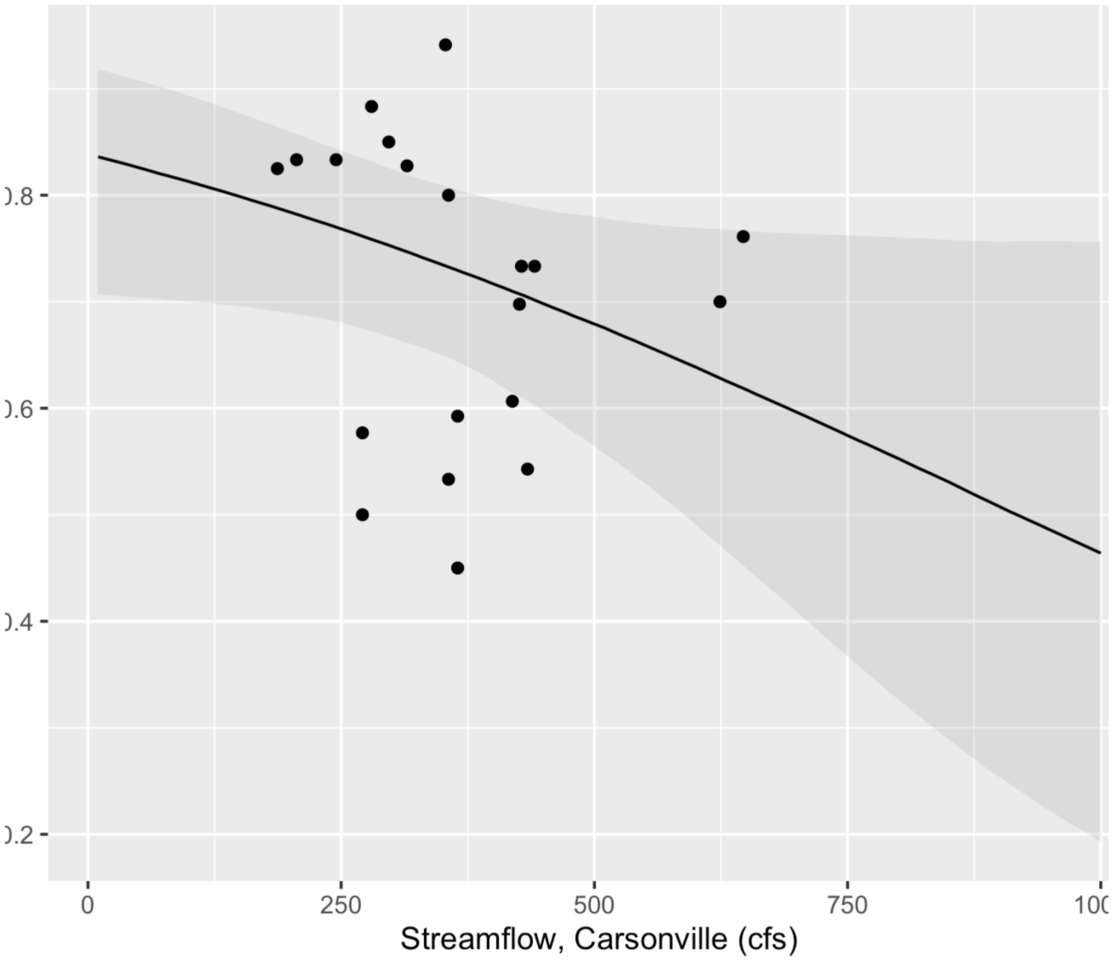
```
slow[i]~dbern(p.low[i])
logit(p.low[i])<-a0.1 + a1.1*q[i] + epsilon[site[i]]
```

Here, ‘slow[i]’ is an individual water velocity measurement at a particular shoal, coded as 1 if <0.4 m/s and 0 otherwise.

Resulting regressions based on 992 velocity measurements at 17 shoals are illustrated below. We used the log-log regression model in the Flint shoal application.



Log-log model of proportion ‘slow velocity’ v. Q at Carsonville. Regression line and 95% credible interval are based on individual velocity measurements; data summarized as proportion of measurements for each shoal visit are plotted as points.



Logistic regression model of proportion ‘slow velocity’ v. Q at Carsonville. Regression line and 95% credible interval are based on individual velocity measurements; data summarized as proportion of measurements for each shoal visit are plotted as points.

II. Overview: estimating *Podostemum* daily growth rate in relation to shoal habitat with velocity <0.4 m/s, using biomass time-series observations in the Middle Oconee River.

Data comprise four time-series of approximately monthly biomass estimates for *Podostemum* growing in four locations in the Middle Oconee River near Athens. Data were collected in 1956-1957 (Nelson and Scott 1962), 1991-1992 (Grubaugh and Wallace 1995), 2007-2008 (Pahl 2009), and 2016-2018 (Conn, unpublished) Time series were assembled into a 4 x 26 matrix of monthly mean biomasses as reported in each study, with missing values for months lacking measurements.

Model code:

```
biomass[i,j]~dlnorm(mu[i,j], tau.biomass)  # i =1 to 4 timeseries, j = 1 to 26 monthly biomasses
   mu[i,j]<-mu[i,(j-1)] + r[i,j]*days[i,(j-1)]           # days = number of days, j-1 to j
   r[i,j]~dnorm(mu.r[i,j], tau.r)                     # r is daily accumulation rate

mu.r[i,j]<-b0 + b1*(exp(mu[i,(j-1)]))+b2*grazing[i,(j-1)]
```

Here, daily growth rate (mu.r[i,j]) is influenced by a density-dependent term (exp(mu[i,(j-1)]), which is the biomass on date j-1 in g AFDM/0.1 m^2), and by the mean proportion of shoal area with velocities < 0.4 m/s, each interval j-1 to j (“grazing[i,(j-1)]”). This (vulnerable to) grazing term was estimated using logistic regression of velocity measurements in relation to streamflow for a range of low-flow conditions (Pahl, unpublished; Conn, unpublished; Rack, unpublished) in areas representing each biomass time-series.

Parameter estimates, mean (95% CI):

b0	0.017 (0.0058 - 0.029)
b1	-0.0003 (-0.0005 to -0.0001)
b2	-0.026 (-0.043 to -0.0066)

III. Estimating the proportion of shoal drying at Sprewell Bluff shoals based on three discharge and drying points.

Estimating how much shoal habitat remains wetted and flowing during low-flow periods is key to understanding low-flow effects on riverweed (*Podostemum*). This is because our model assumes that riverweed can only persist in areas of a shoal that dry for less than 30 days (based on experimental evidence from Pahl 2009). To construct a preliminary relation between streamflow (as recorded at the Carsonville gage) and extent of rock exposure, we used three assumptions for the Sprewell Bluff shoal:

- when flow = 0 at Carsonville, the entire shoal lacks flow (although there may be wet areas)
- when flow = 200 cfs at Carsonville, 50% of the shoal is wetted and flowing (based on photos)
- when flow = 1000 cfs at Carsonville, the entire shoal is wetted and flowing.

For each simulated annual cycle, we interpolated the proportion of the shoal estimated to retain flow during the lowest 30-d average flow during that cycle.

This portion of the simulation model would be substantively improved with additional data on wetted area in upper Flint River shoals in relation to streamflow.

IV. Model code written in the software R and using packages rjags and R2jags.

This model:
(1) Uses four time-series of Middle Oconee River biomass measurements and estimates of extent of low to estimate effect of low velocity on *Podostemum* growth rate;
(2) uses 2001 & 2002 water velocity data from 17 Flint River shoals to relate proportion of shoal velocity measurements that are <0.4 m/s ("low-velocity extent") to discharge (q);
(3) calculates "low-velocity extent" in Flint River shoal habitat for each day using a daily flow time-series, and finally
(4), computes the *Podostemum* growth rate given that day's "low-velocity extent" using regression coefficients from a regression model for the four time-series of Middle Oconee River biomass
measurements.

One can estimate proportion of shoal habitat with velocity <0.4 in relation to stream flow with a log-log model (as in model below) or with a logit model (see Appendix A).

```
model {
## estimate regression coefficients, growth v. time<0.4m/s, using Middle Oconee data;
## note biomasses are scaled to g AFDM/0.1 m2
for (i in 1:nseries){
   biomass[i,1]~ dlnorm(mu[i,1], tau.biomass) ## starting biomass, each time series
   mu[i,1]<-a0[i] #have 4 values, 1 for each time-series

   for (j in 2:26){
   biomass[i,j]~dlnorm(mu[i,j], tau.biomass)
   mu[i,j]<-mu[i,(j-1)] + r[i,j]*days[i,(j-1)]
   r[i,j]~dnorm(mu.r[i,j], tau.r) # r is daily accumulation rate

   ## density and grazing - 2 terms
  mu.r[i,j]<-b0 + b1*(exp(mu[i,(j-1)]))+b2*grazing[i,(j-1)]
    }}

# priors
for (i in 1:4){
a0[i] ~ dnorm(5, 0.01) #log scale

}
b0 ~ dnorm(0, 0.01) # mean daily growth rate
b1 ~ dnorm(0, 0.001) #adjustment for biomass
b2 ~ dnorm(0, 0.001)  #adjustment for low velocities

tau.biomass<-1 / sigma.biomass^2
sigma.biomass~dunif(0,10)

tau.r<-1 / sigma.r^2
sigma.r~dunif(0,1)
```

```
#### estimate time <0.4m/s for flint time series, log-log relation
for (i in 1:nobs){
  slow[i]~dbern(p.slow[i])
  p.slow[i]<-exp(-exp(s[i]*100*(q[i]-c)))
  s[i]<-s0 + epsilon[site[i]]
}

s0 ~ dnorm(0, 0.001)
c  ~ dunif(2,9)
for (i in 1:17){
 epsilon[i]~dnorm(0, tau.site)
}
  tau.site<-1 / sigma.site^2
  sigma.site~dunif(0,10)

## estimate prop of shoal with velocity <0.4, each day, 184 d growing season in this case

for (i in 1:184){
p.low.est[i]<-(exp(-exp(s0*100*(obs.q[i]-c))))
}

## estimate biomass each day using exponential growth rate;
  flint.biomass[1]<-100 #biomass, g AFDM/0.1 m2; starting value
  for (i in 1:183){
  flint.r[i]<-b0 + b1*(flint.biomass[i])+b2*p.low.est[i]
  flint.biomass[i+1]<-flint.biomass[i]*exp(flint.r[i])
}}

inits <- function(){list(a0 =c(3,4,1,4), b0 =0.02, b1=-0.0003, b2=-0.02, s0=0, c=6, sigma.site=1,
             sigma.biomass = 1, sigma.r = 0.1)}
```

Data to run this code:

- nseries = 4
- biomass = a 4 x 26 matrix of monthly biomass estimates from the Middle Oconee River, scaled to g AFDM/0.1 m^2
- grazing = a 4 x 25 matrix of interval-specific, estimated mean proportion of the study area (for each Middle Oconee River data set) with velocity < 0.4 m/s
- days = a 4 x 25 matrix of the number of days between each ~ monthly Middle Oconee River biomass measurement
- nobs= 992
- slow = 992 observed velocities in Flint River shoals, coded as 1 if < 0.4 m/s, and 0 otherwise
- q= 992 observed streamflow values for the Flint River at Carsonville divided by 100, corresponding to ‘slow’ observations
- site = 992 coded site locales, corresponding to ‘slow’ observations
- obs.q = *n* daily flows for the Flint River at Carsonville divided by 100, for the simulation period

V. References

Grubaugh, J.W. and Wallace, J.B., 1995. Functional structure and production of the benthic community in a Piedmont river: 1956-1957 and 1991-1992. *Limnology and Oceanography*, *40*(3), pp.490-501.

Marcinek, P.A. 2003. Variation of fish assemblages and species abundances in the upper Flint River shoals, Georgia. MS thesis, University of Georgia, Athens, GA.

Nelson, D.J. and Scott, D.C., 1962. Role of detritus in the productivity of a rock-outcrop community in a Piedmont stream. *Limnology and Oceanography*, *7*(3), pp.396-413.

Pahl, J. P. 2009. Effects of flow alteration on the aquatic macrophyte *Podostemum ceratophyllum* (riverweed); local recovery potential and regional monitoring strategy. MS thesis, University of Georgia, Athens, GA.

Appendix B: *Project Overview*

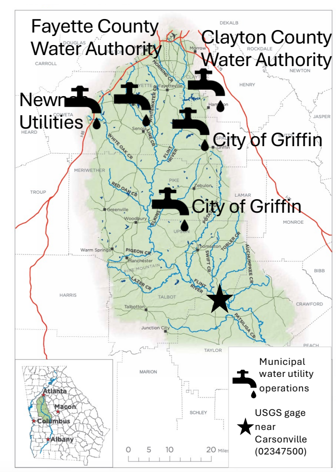
Evaluating options for improving drought resilience of the upper Flint River

This work was funded by the Regional Water Planning Seed Grant Fund (EPD) and conducted by the UGA River Basin Center and American Rivers, in collaboration with the Upper Flint Regional Water Planning Council and Upper Flint River Working Group.

Objectives

- Simulate short- and long-term drought management actions on river flows using EPD's Basin Environmental Assessment Model (BEAM)
- Evaluate how alternative drought-response management actions could mitigate ecosystem effects.
- Predict the ecological consequences of droughts of different severity and duration

Upper Flint Basin



*Modified and reprinted from American Rivers 2013

Simulated Management Actions

Improved infiltration across the basin

Photo credit:

Low-flow operations and responses

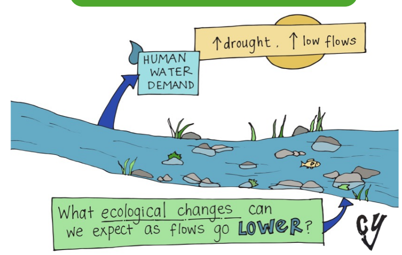


Illustration credit: Carol Yang

*Not an active project.

Quarry storage to augment river flows

Combining management actions showed the greatest opportunity to support streamflow for aquatic ecosystems and water security for public utilities during drought and low flow periods

Overview:

The Upper Flint River system provides drinking water for more than 400,000 residents of south Metro-Atlanta and central Georgia. Due to a lack of impoundments along the river's mainstem, it also supports shoal ecosystems that are important ecologically and enjoyed recreationally. In this project, we assessed the impacts of short- and long-term drought management actions on the river ecosystem and water resources, building on recommendations from the Upper Flint Regional Water Plan (2023) and actions proposed by the Upper Flint River Working Group (American Rivers 2019).

Flint River at Sprewell Bluff State Park. Photo taken on June 10, 2022.

Approach:

We simulated management actions in EPD's Basin Environmental Assessment Model (BEAM). The Flint BEAM simulates daily river flows and provides location-specific data for water withdrawals, discharges, and reservoirs in the basin. Water is routed based on the permit limits for withdrawals and discharges and monthly average demand for municipal utilities, agricultural, and industrial permits.

Photo credit: Alan Cressler
Flint River shoal at Sprewell Bluff State Park when river flows were less than 100 cfs. Photo taken on October 23, 2016.

Evaluation:

We compared each management action individually and then combined to the baseline scenario (permitted withdrawal and discharge limits as of 2018 and the water demand set to 2011 levels) to assess the relative impact.

Ecological impacts were based on relationships developed between low velocity conditions and riverweed, a native aquatic plant that grows extensively in shoals. We compared reservoir storage at or below drought level 2 for municipal water utilities.

Outcomes:

We found that combining management actions reduced the occurrence and duration of days below 100 cfs and 200 cfs near Sprewell Bluff Park. While changing utility operations during summer was the only way to keep more water in the river, augmenting flows from potential quarry storage at the top of the basin reduced the impact on reservoir levels during low flow periods.

Scan QR code or click here to see project document

UNIVERSITY OF GEORGIA River Basin Center

AMERICAN RIVERS

This work was funded by a Regional Water Planning Seed Grant through the Georgia Environmental Protection Division

Appendix C: *Guidance for evaluating ecological indicators in water planning*

Developed as part of the EPD Seed Grant: Evaluating Options for Improving Drought Resilience of the Upper Flint River System

Prepared by: Laura Rack, Seth Wenger, and Mary Freeman
May 2025

Introduction

Freshwater species are adapted to, and depend on, the full range of flows that a river system naturally experiences across seasons and among years to complete their life cycles and sustain populations. For this reason, managers and stakeholders need information on flow levels that support a range of ecosystem functions when assessing future water availability for river ecosystems.

Evaluating water availability to support river ecosystems requires a different approach than is currently used to evaluate gaps in water availability for other demands in Georgia's water planning process. During each 5-year cycle in Georgia's water planning process, planners compare a forecast of future water demand to current water availability. Gaps are expressed as the proportion of time during a model period (80 years) that a demand is not met, or that streamflow falls below the wastewater assimilation threshold. Ecological indicators, or attainment of functional flows, can be assessed using the same framework of current and future flow projections, however evaluation requires shifting from averaging over the entire model period to examining the occurrence and severity of ecologically stressful events.

Evaluating and Interpreting Ecological Indicators

The ecological outcome of an exceptional flow condition (such as an extreme low flow) will partly depend on how low (magnitude), how long (duration), and how often (frequency) stressful events occur. Therefore, it is most useful to evaluate flow thresholds (magnitudes) in the context of how long and how often they are exceeded with respect to current and future conditions.

For example, supporting survival of aquatic organisms is a key streamflow function that will be affected when flow falls below a 'dry-season threshold.' To evaluate whether future flows during the dry season are likely to compromise organism survival, it would be useful to compare the annual frequency and duration of flow events below the dry season threshold (e.g., during June-October) for the current and future scenarios. We show an example of this evaluation process below for the Upper Flint Regional Water Council.

Deciding how much change is too much may depend on a variety of factors, including risk tolerance (e.g., of utilities and resource managers), the availability of current or future options to minimize the change, and the ecological function of the flow being evaluated (e.g., flows necessary for survival across many groups of organisms versus seasonal connectivity to floodplain habitats for a subset of organisms). If the consequences of crossing a flow threshold in a future scenario are too great, the next step is to investigate management alternatives to prevent this outcome.

<u>Example for the Upper Flint River Water Council</u>

In the 2023 Upper Flint Regional Water Plan, the Council requested that metrics for recreation and ecological indicators be evaluated, based on flows levels provided in "Guidance on Drought Resilience for People and Nature in the Upper Flint River Basin" (Upper Flint River Working Group 2021). The streamflow metrics were evaluated at the Carsonville gage (Flint River at US 19, near Carsonville, USGS gage 02347500; USGS 2025) and comprised two flow levels: 100 cfs, representing a drying threshold where the river shoals were "more rocks than water," and 600 cfs, which is a generally accepted minimum flow for floating a kayak or canoe down Flint River shoals. This "paddling flow" is similar to a flow level (500 cfs) estimated to sustain swift-water habitat in Flint River shoal ecosystems and can be used to evaluate outcomes for both recreation and shoal ecosystems.

The metrics were evaluated in the Regional Water Plan (RWP) as the total proportion of the 80-year model period during which flow at the Carsonville gage was below metric thresholds for the baseline demand (average demand from 2010-2018) and the baseline drought demand (2011; RWP, pages 3.6-3.10). The baselines were compared with future water availability to meet these metrics based on data from agricultural demand forecasts through 2060; results showed minimal differences between current and future conditions for either metric, since most agricultural growth was projected to occur downstream of the Carsonville gage.

Table 3-5: Surface Water Availability Streamflow Results

Carsonville Flow Summary	Streamflow Metric *cfs*	Scenario	
		Baseline	Baseline Drought
% Time Below Streamflow Metric	100	0.91%	1.02%
	600	23.6%	23.9%
**% Time is calculated as a proportion of the full model period (1939-2018).*			

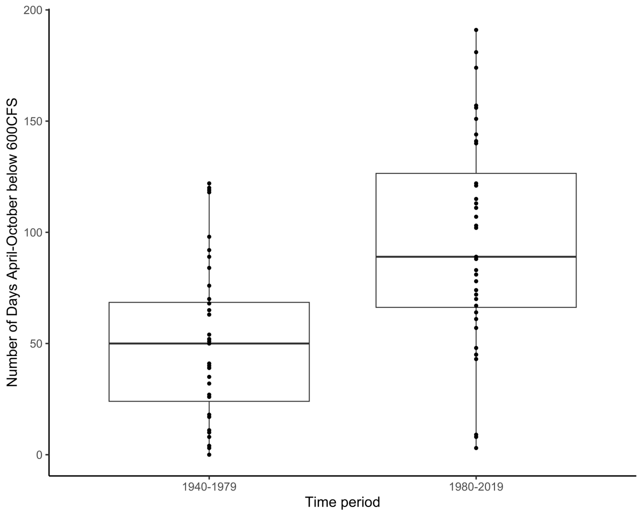
*Results table from the 2023 Upper Flint RWP.

Interpreting these metrics as percent of total time exceeded presents a challenge. For example, 1% of time below 100 cfs ("more rocks than water" condition) could reflect annual events of 3-4 days each year of the 80-year period, or events lasting over a month once every 10 years. The ecological consequences of these scenarios could be substantially different, depending on an organism's ability to withstand stagnant water or emersion. Similarly, the effect of flows below the river-recreation threshold may depend on whether those low flows occur as one "poor boating" year out of every four or represent three months of lost recreation during the period of highest demand every year. Thus, to interpret the ecological consequences or the impact on recreation of flows under a given scenario, it is relevant to consider the seasonality, duration and frequency of individual flow excursions below ecological and recreational thresholds. Recreational paddling (best-supported when flows exceed 600 cfs) is concentrated between April and October, which overlaps with the seasonally low flows that impact shoal habitat for aquatic organisms (Flint River flows are generally higher in winter and spring and lowest during summer and fall). Extreme low flows that lead to riverbed drying ("more rocks than water" condition; 100 cfs) are most likely to occur and overlap with potentially stressful, elevated water temperatures from June to October.

One can use the record for the Carsonville gage to evaluate the historic annual occurrences of seasonal flows below the thresholds for recreational boating (and shoal habitat) and river drying. Because we did not have the forecasted demand data available to compare historic and future scenarios, we split the historical record at the Carsonville gage into two 40-year periods to illustrate how one could evaluate changes in recreation and ecological metrics between time periods. In the context of water planning, one would compare the agreed-upon baseline or current conditions to a future scenario.

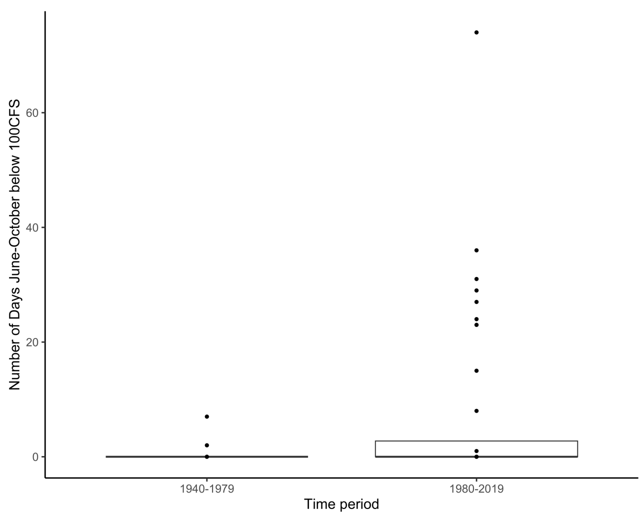
River flows recorded at the Carsonville gage were below 600 cfs and 100 cfs more often and for more days in the years 1980-2019 than in the earlier period, 1940-1979. These changes could be consequential. In the 1980-2019 period, the time that the river was below the paddling threshold almost doubled compared to the prior 40-year period, with nearly half of the years having unsuitable recreational flows for much or most of the season (Figure 1). Flows below 100 cfs rarely occurred between 1940-1979, but in the period 1980-2019 they occurred in about 25% of years and for up to 74 days (Figure 2).

Observing a shift like this in the summer and fall baseflow thresholds would raise a flag that river flows are trending lower for longer during the months evaluated. If these trends were to appear for a water planning scenario, it would be relevant to consider potential causes or evaluate alternative management actions that could mitigate the occurrence or duration of these events.



	1940-1979	1980-2019
# YEARS	40	40
% OF TIME BELOW 600 (APRIL-OCTOBER)	23.4	44.8
# YEARS WITH OCCURRENCE OF FLOWS BELOW: 600 CFS	38	40
MEDIAN # DAYS APRIL-OCTOBER WITH FLOWS BELOW: 600 CFS	50	89
MAX # DAYS APRIL-OCTOBER WITH FLOWS BELOW: 600 CFS	122	191

Figure 1. Boxplot of the annual number of days between April and October that flows were below 600 cfs at the Carsonville gage on the Flint River. In the boxes, 25 percent of the data fall below the lower line, the middle line is the median, and 75 percent of the data are below the upper black line. This type of figure helps visualize the spread of the occurrence and duration of events below the 600 cfs threshold. The table summarizes the total percent of time and the median number of days each year, and the maximum number of days in one year, below 600 cfs during the recreational season.



	1940-1979	1980-2019
# YEARS	40	40
% OF TIME BELOW 100 (JUNE-OCTOBER)	0.15	4.8
# YEARS WITH OCCURRENCE OF FLOWS BELOW: 100 cfs	2	11
MAX # DAYS JUNE-OCTOBER WITH FLOWS BELOW: 100 cfs	7	74

Figure 2. Boxplot of the annual number of days between June and October that flows were below 100 cfs at the Carsonville gage on the Flint River. In the boxes, 25 percent of the data fall below the lower line, the middle line is the median, and 75 percent of the data are below the upper black line. This type of figure helps visualize the spread of the occurrence and duration of events below the 100 cfs “more rocks than water” threshold. The table summarizes the total percent of time, the number of years with occurrence (i.e., at least one day), and the maximum number of days in a single year with flows below 100 cfs during each time period.