The Influence of Jennings Randolph Lake and Dam Operations on River Flow and Water Quality in the North Branch Potomac River

A Technical Report Supporting Preparation of a Comprehensive Scoping Plan Considering an Update of the Jennings Randolph Lake Water Control Plan

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Disclaimer

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Acronyms

Abbrev.	Name
°C	degrees Centigrade
AMD	acid mine drainage
AVF	artificially varied flows

BIBI	Basin-wide Index of Biotic Integrity
cfs	cubic feet per second
DO	dissolved oxygen
EASP	Maryland's Environmental Assessment and Standard Program
HUC	Hydrologic Unit Code
ICPRB	Interstate Commission on the Potomac River Basin
JRL	Jennings Randolph Lake
MDDNR	Maryland Department of Natural Resources
MDE	Maryland Department of the Environment
mg/liter	milligrams per liter
mi^2	square mile
min	minute
NBPR	North Branch Potomac River
NPS	National Park Service
NTU	Nephelometric Turbidity Units
NWS	National Weather Service
SpCond	specific conductivity
SRR	Savage River Reservoir
TDS	total dissolved solids
TMDL	total maximum daily load
TSS	total suspended solids
uS/cm	micro-Siemens per centimeter
USACE	U. S. Army Corps of Engineers
USEPA	U. S. Environmental Protection Agency
USGS	U. S. Geological Survey
VADEQ	Virginia Department of Environmental Quality
WQP	Water Quality Portal
WVDEP	West Virginia Department of Environmental Protection
WWTP	wastewater treatment plant

Executive Summary

The watershed of the North Branch Potomac River (NBPR) experienced severe environmental degradation in the 20th century, which intensified the frequent flooding in river and stream valleys caused by the region's rugged topography. A dam across the river mainstem was completed in 1982, creating Jennings Randolph Lake (JRL). The lake has four authorized purposes: control floods, dilute downstream pollution, supply drinking to Washington DC during droughts, and provide recreation. Our analysis of available flow and water quality data found that river and stream environments in the North Branch watershed have improved considerably since the dam was built. This outcome is attributed to many factors, including regulatory enforcement, mine runoff mitigation, wastewater treatment, infrastructure improvements, forest regrowth and the abatement of acid rain. In this report, we analyze some of the current river and stream conditions and examine the changing relevance of lake operations to the first two authorized purposes. The U. S. Army Corps of Engineers (USACE) operates the dam in coordination with the smaller Savage River Reservoir, a regional source of drinking water. Our analysis informs a joint multi-year scoping study with USACE to determine if an update of the Corps' 1997 Water Control Plan for Jennings Randolph Lake could benefit the region at large and the lower river mainstem in particular.

USACE dam operations substantially reduce peak flows and flooding in the lower mainstem of the North Branch Potomac River. During the recent 15-year period (water years 2004 – 2018), USACE's coordinated releases have accomplished the project's primary goal of preventing floods at Luke, MD (Figure 1). Dam operations did not prevent flooding in tributaries to the NBPR or in the mainstem further downstream at Cumberland, MD where the river receives water from Pennsylvania as well as Maryland and West Virginia. Current JRL dam operations play an important role in controlling floods along the river mainstem to at least Keyser, WV and McCoole, MD (Keyser/McCoole).

Dam operations also routinely increase, or augment, flows when river levels are low. Of the 90,203 acre-feet (29.397 billion gallons) usable volume of JRL's conservation pool, 55.44% is allocated to water quality storage and used for low flow augmentation. The purpose is to dilute pollutants, improve aquatic habitat, and flush built-up sediment downstream. JRL dam operators employ a selective withdrawal system with adjustable outflow rates to blend water from different lake depths and optimize water quality released from the lake. In practical terms, the water quality goal is for the lower NBPR mainstem to meet the middle range of water quality standards established by the State of Maryland (USACE 1997b). Quantitative goals and assessment methodologies for aquatic habitats and bottom sediments are lacking, leading to an inability to determine the effectiveness of Corps operations.

Low-flow augmentation appears to have little to no influence on pH or dissolved oxygen in the lower NBPR mainstem. Mine remediation and lime dosers have resolved many low pH problems in the watershed and pH in both the upper and lower NBPR mainstem currently meet Maryland's 6.5 - 8.5 criteria. With a few exceptions in some NBPR tributaries, dissolved oxygen throughout the watershed also meets Maryland and West Virginia criteria of more than 5 mg/liter. Low flow augmentation is not needed to hold either pH or dissolved oxygen to their respective water quality standards in the lower NBPR mainstem. The possible exception is acid mine "blowouts" entering the mainstem which could be diluted by USACE releases if they occur.

Historically, concentrations of dissolved and particulate solids in the NBPR mainstem have been low between JRL and Bloomington, MD and then rise sharply over the next 7.5 miles to Keyser/McCoole. Increases in median concentrations are 41.1% in specific conductivity, 43.1% in total dissolved solids, 276% in turbidity, 62% in total suspended solids, and 116% in total alkalinity. The first four of these constituents exceed desirable levels at Keyser/McCoole despite the JRL low-flow releases. The major pollution source for this river segment was the Verso Luke paper mill which sent its wastewater to the Westernport treatment plant. The paper mill closed on June 30, 2019. Water flowing from Georges Creek is a secondary source. The creek enters at Westernport and comprises roughly a tenth of the total mainstem flow there. The USACE Master Manual for Reservoir Operations has no specific JRL procedure to mitigate the effects of downstream wastewater discharges other than to release relatively clean water and maintain a minimum flow of 120 cfs at the Luke stream gage (USACE 1997b). The closure of the Verso Luke Mill puts into question the need for JRL low-flow augmentation to dilute downstream wastewater.

Organic solids from industrial and municipal sources can build up in the NBPR mainstem below Westernport and at Cumberland during summer low flow periods. Artificially varied flows (AVFs), or short-term high-flow releases from JRL are a specific form of low-flow augmentation used by USACE to flush organic solids that settle on the river bottom. Dam operators have anecdotally confirmed sediment removal by AVFs near Westernport but not Cumberland. Empirical data have not been collected that quantify sediment buildup or transport in relation to flow. Closure of the Verso Luke Mill questions the need for AVFs to flush wastewater-related solids downstream.

Selective releases from JRL's deeper waters in summer presently have the most beneficial and important ecological effects on NBPR aquatic habitats. The proportion of time the downstream mainstem meets Maryland trout stocking guidelines (4 – 20 ºC) has increased significantly since JRL operations began. Diminishing traces of the summer cold water releases can be seen as far as Keyser/McCoole and sometimes beyond. Because of these releases, cold temperature refugia in the NBPR tributaries are connected longer to the mainstem and thus to each other during summer. This allows cold-water species more opportunity to move and avoid local stressors due to mining operations, land clearing, and development. For cold-water fish such as trout, the likely ecological outcome of more mobility and longer periods of active feeding and growth at desirable temperatures is greater survival and reproduction.

The temperature dataset for the NBPR watershed is large and currently being expanded with high frequency temperature data collected by Maryland's Department of Natural Resources, the US Geologic Survey, and the Interstate Commission on the Potomac River Basin. Watershed temperature modeling should be able to demonstrate how stratified releases from JRL can complement natural cooling effects of groundwater, forest cover, and elevation in the watershed's streams and small rivers. Aquatic populations, including natural and stocked trout, would be better connected and sustained if this information is used to enhance cold- and cool-water habitats in the NBPR mainstem. Stable, resilient aquatic populations will further support local recreational economies and eventually help Maryland and West Virginia justify delisting the region's impaired waters.

Outside of its role in modifying downstream water quality, JRL appears to serve as a sink for dissolved solids and to some extent suspended particles entering the lake at Kitzmiller, MD. How these effects are accomplished is not clear because consistent patterns of stratification are not evident in the few depth profiles available for the lake. The limited amount of available lake data precludes any thorough analysis of the lake environment.

Gradual increasing trends in specific conductivity and total dissolved solids are apparent in places in the NBPR watershed. Reversing these trends will require watershed management approaches rather than changes in JRL dam protocols. For example, procedures for operating lime dosers, a potential source of dissolved solids, may need to be reviewed and adjusted. With closure of the Luke mill, turbidity and total suspended solids concentrations in the watershed will not be extreme except in the Georges Creek subwatershed and some isolated locations. They may require targeted and more sophisticated remediation efforts.

A reassessment of the JRL operations as described in the 1997 Water Control Plan and of the lake's current water quality storage allocation (55.44% of the useable conservation pool) is warranted in our opinion. We recommend doing this after additional information has been collected and studied. The available instream data and the management tools used now are insufficient to determine the contemporary role of JRL dam operations in the river's ecosystem. We feel a more holistic and comprehensive vision, or watershed management plan, is required to better describe how the watershed should be managed for multiple purposes going forward.

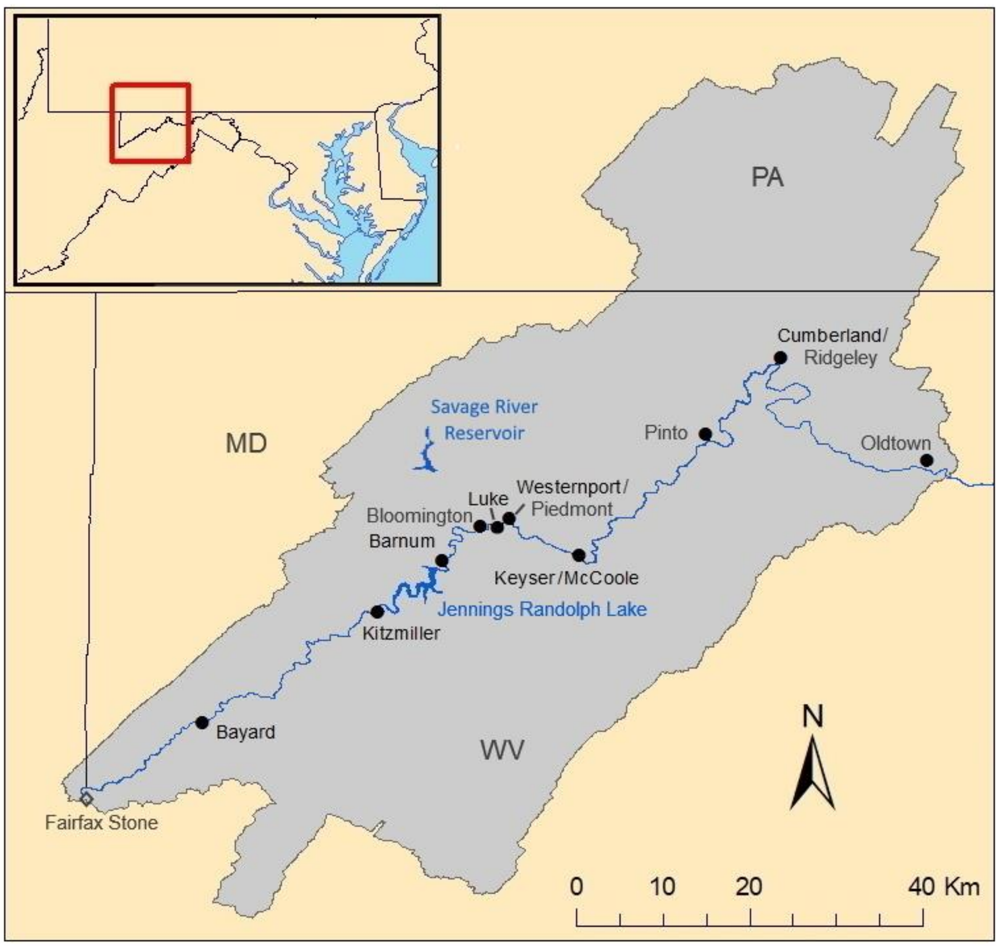

Figure 1. North Branch Potomac River and watershed (HUC8 02070002)
Major towns and cities located on or near the river mainstem are named. The river forms the border between Maryland and West Virginia from near its origin at the Fairfax Stone to its confluence with the South Branch Potomac River.

The Influence of Jennings Randolph Lake and Dam Operations on River Flow and Water Quality in the North Branch Potomac River:

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1 Introduction

The North Branch Potomac River (NBPR) and many of its tributaries are recovering from significant environmental degradation that occurred in the watershed during the 20th century. Water quality in the region was adversely impacted by acid mine drainage, industrial effluents, residential wastewater discharges, and legacy sediment from forest clear-cutting. River and stream environments have improved since the turn of the century, an outcome of regulatory enforcement, mine runoff mitigation, wastewater treatment, some infrastructure improvements, forest regrowth, and the abatement of acid rain. However, in recent Maryland and West Virginia Integrated Reports to the U. S. Environmental Protection Agency (USEPA) many subwatersheds are still identified as impaired to some extent by sediments, nutrients, low pH, fecal coliform, metals (aluminum, iron, manganese), toxics (cyanide), ions (sulfate, chloride), and/or impacts to biological communities (MDE 2017, WVDEP 2016).

Jennings Randolph Lake (JRL), formerly the Bloomington Reservoir, was authorized in 1962 by the 87th United States Congress primarily as means of flood control for the NBPR. It was completed in 1982 and is operated by the United States Army Corps of Engineers (USACE). JRL's original Water Control Plan had four goals: (1) reduce high flows to control downstream flooding, (2) improve downstream water quality by augmenting low flows, (3) supply drinking water to Washington, D. C. and the local region during droughts, and (4) provide in-lake and downstream public recreation.

Dam operations at JRL use various approaches to achieve the specific objectives identified in the JRL Water Control Plan. During high flow events, releases from JRL and nearby Savage River Reservoir (SRR) are both slowed to reduce the risk of flooding in downstream riverside towns, including Bloomington, Luke, Westernport, McCoole, and Cumberland in Maryland and Piedmont, Keyser, and Ridgeley in West Virginia (Figure 1). During low flow periods, JRL drawdowns raise water levels and flows for the purpose of diluting downstream pollution, some of which originates from the above mentioned towns. JRL stratifies thermally and chemically, and a selective withdrawal system with portals at different reservoir depths allows JRL dam operators to influence downstream river temperatures. During severe droughts, water is released from JRL to satisfy the drinking water needs of metropolitan Washington, D. C. The Interstate Commission on the Potomac River Basin (ICPRB) represents the metro area water suppliers and channels requests for releases through the USACE's Water Management and Quality Section. These requests are infrequent, with the last two occurring in 2002 and 2010. Finally, several access roads and recreational facilities support in-lake uses by the public. Pulsed releases, usually in spring, are made specifically for whitewater rafting and kayaking in the mainstem immediately downstream of JRL.

The original JRL Water Control Plan was updated in 1997 (USACE 1997a, USACE 1997b) with some modifications. Most notably, the Plan added a short-term objective to support Maryland and West Virginia natural resource programs that manage NBPR fisheries and a long-term objective to establish a self-sustaining sport fishery (USACE 1997a 4.7). The Corps recently initiated a scoping study to determine if another update of the Plan could benefit the region at large and the lower river mainstem in particular.

This report provides supporting information for that scoping study. The report's first section describes how JRL dam operations change NBPR flow characteristics to control flooding during high water events and augment flows during low water periods. The second section looks at long-term changes in key water quality parameters in the NBPR watershed and river and examines the role that low flow augmentation currently plays in improving downstream water quality. The report is a companion to an in-depth analysis of NBPR environmental conditions supporting aquatic life use, and in particular cold-water fish (Selckmann and Buchanan, in prep.).

2 River Flow

Since its completion in 1982, JRL's highest priority in terms of dam operations has been flood control, and flood damage reduction continues to be listed as a JRL goal in recent USACE annual reports. JRL elevations and releases are regulated by USACE after reviewing both United States Geological Survey (USGS) streamflow data and National Weather Service (NWS) flood stages at three places: Kitzmiller located immediately upstream of JRL (flood stage = 9.0 ft), Luke located below the confluence of NBPR and Savage River (flood stage = 10.5 ft), and Cumberland located about 41 miles downstream of JRL (flood stage = 17.0 ft) (USACE 1997b, Table 7-02). During high water events, JRL and SRR dam releases are limited, reduced, or halted depending on downstream river stage and the operating constraints of each dam. Excess water flowing into the reservoirs is stored for release later when downstream river stages have receded (USACE 1997b). If stages at key downstream locations have reached flood stage and are expected to continue to rise, the JRL outlet gates are usually closed except for a minimum outflow. If the gates are closed, they typically remain closed until downstream gages have crested. Estimated travel times from JRL during high water events are considered when making releases: 0.5 hr to Barnum; 1.0 hr to Luke; 7 hr to Pinto; 12 hr to Cumberland. When the gates are initially opened following a major high water event, releases are made incrementally to ensure the safety of downstream users, avoid streambank and streambed erosion, and minimize impacts to stream biota.

JRL dam operators augment low flows in the NBPR mainstem to improve downstream water quality, the second authorized purpose of the dam. Higher than ambient flows are released during low flow periods to maintain a minimum of 120 cfs at Luke MD. Operators employ a selective withdrawal system to blend water from different lake depths and improve the thermal and chemical characteristics of waters discharged from JRL. They also periodically release pulses of high water, called artificially variable flows (AVF), to flush organic solids that have settled on the riverbed downstream. AVFs have the side benefit of providing whitewater rafting and kayaking opportunities. A "water quality storage" volume comprising 50,009 acre-feet (16,298 billion gallons), or roughly 55.44% of JRL's conservation pool usable storage, is available for water quality control. This percentage was 53.86% in the 1997 Plan, a percentage derived from an earlier, larger estimate of the conservation pool total volume (USACE 1997b). In conjunction with SSR releases, JRL operators are supposed to "use as much of the available water quality storage as needed every year to produce the greatest possible improvement in water quality, both in-lake and downstream" (USACE 1997b 7-08).

To characterize the influence of dam releases on NBPR flows, we examined USGS streamflow data from the Kitzmiller gage upstream of JRL and the Barnum gage a short distance below JRL. Only about 9.5 river miles separate these two gages (Figure 1). Kitzmiller's watershed is 225 mi^2 and Barnum's is just 18% larger at 266 mi^2. Due to their proximity, flows at the Kitzmiller and Barnum stream gages would be similar if JRL had not been built. Comparisons of Kitzmiller and Barnum flow metrics illustrate the immediate effects of JRL operations on river flow. Metrics calculated for other gages on the NBPR mainstem above and below JRL illustrate the normal influence of watershed size as well as the downstream extent of JRL and SRR flow modifications.

2.1 Data Analysis Methods

A suite of metrics (Table 1) was calculated from sub-daily flow data downloaded from the USGS National Water Information System, or NWIS, for seven gages in the North Branch Potomac River watershed (Table 2). The analysis was performed on data for the recent 15-year period of water years 2004 – 2018

(10/1/2003 to 9/30/2018). Discharge measurements at the gages are typically made at 15 or 30-minute intervals. All USGS gage records downloaded in December 2018 had gaps in coverage. The total number of days without flow data during the 15-year study period ranged from 4 (North Branch @ Barnum) to 574 (Savage @ Barton) days. Most gaps occurred in winter months (December - February), when ice formation is capable of interfering with flow measurements. Due to these gaps in coverage, most of the analyses were performed only on non-winter records of the 15 years (March – November).

2.2 Daily Mean Flows

Analysis of daily mean flows during the non-winter 15-year period shows dam operations produce large changes in an array of flow metrics (Figure 2). When the results are normalized to watershed size, average annual 1-day maximum flow rate falls 45% from 23.71 cfs/mi^2 at Kitzmiller to 12.99 cfs/mi^2 at Barnum, and average annual 3-day maximum flow rate falls 30% from 15.72 cfs/mi^2 to 11.05 cfs/mi^2. The average annual 1-day minimum increases 4.1-fold from 0.14 cfs/mi^2 to 0.57 cfs/mi^2, the average annual 3-day minimum increases 3.9-fold from 0.15 cfs/mi^2 to 0.59 cfs/mi^2, and August median increases 2.4-fold from 0.36 cfs/mi^2 to 0.87 cfs/mi^2. The baseflow index is 4.1-fold higher, increasing from 0.08 to 0.33. Rise and fall rates calculated on the daily means are substantially slower at Barnum, which results in a much lower flashiness index. Reversals calculated on the daily means increase sharply, reflecting dam operations. The overall mean and median flows show a gradual decline as watershed size increases but reflect little or no effect of the lake or dam operations.

Additional flow metrics were calculated for Kitzmiller and Barnum to quantify the number of low and high flow pulses and their durations. Low pulses are daily mean flows below the 10th percentile of all daily means in the study period; high pulses are daily mean flows above the 90th percentile. In non-winter months, Kitzmiller experiences low pulses about four times per year on average whereas Barnum experiences them twice per year. Kitzmiller's low pulses are of shorter duration, lasting 7.0 days as compared to Barnum's 9.8 days. Kitzmiller experiences high pulses about six times per year whereas Barnum experiences them just four times per year. Kitzmiller's high pulses of shorter duration, lasting 2.8 days as compared to Barnum's 5.0 days. The average duration of events with daily mean flows above the overall median flow (DH17) was 13.8 days at Kitzmiller and 21.8 days at Barnum.

By the time the NBPR mainstem reaches Cumberland, its watershed size has grown to 877 mi^2 and several large tributaries have joined the river. Regulated flows from Savage River subwatershed (106 mi^2) enter the NBPR immediately above Luke. Sizes of the major subwatersheds between Luke and Cumberland are Georges Creek (74.1 mi^2), New Creek (53.5 mi^2), and Wills Creek (252.8 mi^2). Their unregulated flows differ from the regulated JRL and Savage Reservoir flows. By Cumberland, the normalized 1-day maximum has increased slightly, indicating a diminished influence of JRL operations to control flooding at Cumberland. The 1- and 3-day minima are substantially lower than Barnum, indicating JRL operations are also losing their effectiveness to augment low flows at Cumberland. After being strongly modified by JRL operations, the flashiness index has increased again at Cumberland while the baseflow index and the number of reversals have resumed decreasing.

2.3 Sub-daily Flow Rates

The rise and fall rates of change in sub-daily flows, or the individual flow measurements taken every 15 or 30 minutes, were also examined for the non-winter 2004 – 2018 water year period. Steyer, located furthest upstream on the NBPR mainstem, tended to have the fastest sub-daily rise and fall rates,

Table 1. Flow metrics

Calculations were performed in Microsoft Excel 2016 on non-winter (March – November) flow records for the 15-year study period from 10/1/2003 to 9/30/2018 (Water Years 2004 – 2018).

Metric Name	Description	Units
1-Day Maximum	The average of each year's highest daily mean flow (cfs) during the study period divided by watershed area (mi^2).	cfs/mi^2
3-Day Maximum	The average of each year's highest 3-day moving average of daily mean flow (cfs) during the study period divided by watershed area (mi^2).	cfs/mi^2
Mean	The average of all the annual means of daily mean flows (cfs) during the study period divided by watershed area (mi^2). The average of each year's mean daily flows is calculated, and then the means of each year are averaged.	cfs/mi^2
Median	The median of all the daily mean flows (cfs) during the study period divided by watershed area (mi^2).	cfs/mi^2
August Median	The median of the August median flow for each year in the study period divided by watershed area (mi^2).	cfs/mi^2
Base Flow Index	The median of each year's 7-day minimum flow (cfs) divided by the mean annual flow (cfs).	ratio (unitless)
1-Day Minimum	The average of each year's minimum daily mean flow (cfs) during the study period divided by watershed area (mi^2).	cfs/mi^2
3-Day Minimum	The average of each year's lowest 3-day moving average of daily flow (cfs) during the study period divided by watershed area (mi^2).	cfs/mi^2
Number of Reversals	The average number of times in a year that daily mean flow switches from rising to falling and vice versa.	#/year
Rise Rate (Daily Mean)	The average of all positive differences in daily mean flow during "rising periods," or consecutive days for which change in daily flow is positive, in a year.	cfs/mi2/day
Fall Rate (Daily Mean)	The average of all negative differences in daily mean flow during "falling periods," or consecutive days for which change in daily flow is negative, in a year.	cfs/mi2/day
Flashiness	(Richards-Baker Index) Sum of the absolute values of day-to-day changes in the daily mean flow divided by the sum of the daily mean flows.	ratio (unitless)
High Pulse Duration	The median of the annual average number of consecutive days per year that daily flow is above the 90th percentile of the 15-year period of record.	days/year
High Pulse Count	The median of the annual average of each year's number of times the daily mean flow is above the 90th percentile of all flows for the study period.	#/year
Low Pulse Duration	The median of the annual average number of consecutive days per year that daily flow is below the 10th percentile of the study period.	days/year
Low Pulse Count	The median of the annual average of each year's number of times the daily mean flow is below the 10th percentile of all flows for the study period.	#/year
High Flow Duration DH17	The average duration of flow events with flows above the median flow for the entire study period.	days

Table 2. U.S. Geological Survey flow gages in the North Branch Potomac River
Data were downloaded from https://waterdata.usgs.gov/nwis for the water years 2004 – 2018 (10/1/2003 – 9/30/2018).

Gage Number	Location	Description
01595000	Steyer, MD	North Branch Potomac River. Drainage area 73.1 mi^2. Data record often interrupted in mid-winter, resulting in 452 (8.2%) missing days.
01595500	Kitzmiller	North Branch Potomac River. Drainage area 225 mi^2. Data record often interrupted in mid-winter, resulting in 427 (7.8%) missing days.
01595800	Barnum	North Branch Potomac River. Drainage area 266 mi^2. Data record mostly complete. Only 4 (<0.1%) missing days.
01598500	Luke	North Branch Potomac River. Drainage area 406 mi^2. Data record has 34 (0.6%) missing days.
01601500	Cumberland	North Branch Potomac River. Drainage area 877 mi^2. Data record has 140 (2.6%) missing days, most are in mid-winter.
01596500	Savage-Barton	Savage River. Drainage area 49.1 mi^2. Data record often interrupted in mid-winter, resulting in 574 (10.5%) missing days.
01597500	Savage-Bloomington	Savage River. Drainage area 106 mi^2. Data record has 37 (0.6%) missing days.

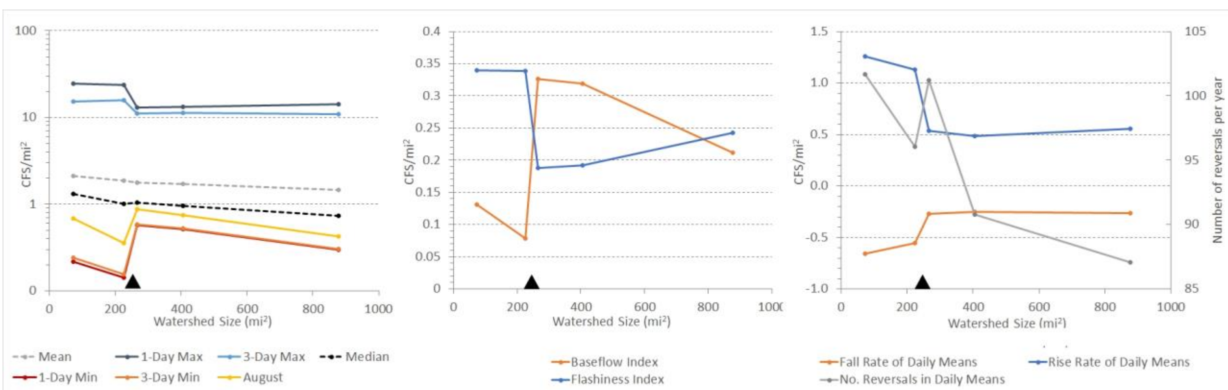


Figure 2. Flow metrics for North Branch Potomac River mainstem, March – November, water years 2004 – 2018
Dots (from left to right) indicate the USGS streamflow gages on the mainstem at Steyer, Kitzmiller, Barnum, Luke and Cumberland. Solid triangle (▲): location of Jennings Randolph Lake. Watershed sizes at USGS gages in NBPR mainstem: Steyer MD, 73 mi^2; Kitzmiller, 225 mi^2; Barnum 266 mi^2; Luke, 406 mi^2; Cumberland, 877 mi^2.

reflecting the influence of its smaller watershed (Figure 3). The NBPR at Cumberland, located furthest downstream, tended to have the slowest sub-daily rise and fall rates. Sub-daily rise rates were overall faster than fall rates at Steyer, Kitzmiller and Cumberland but were nearly identical at Barnum and Luke, reflecting the influence of JRL and SSR operations. This effect can be seen in Figure 3 where distributions of Barnum and Luke's rise rates almost exactly match the distributions of their fall rates. It indicates the relatively abrupt, prescribed changes in dam release rates which result in similarly fast increases and decreases in downstream water level.

Table 3 shows the frequencies of three categories of change: fall rates faster than -0.0002 cfs/mi^2/min, rise rates faster than +0.0002 cfs/mi^2/min, and little or no change in sub-daily flows. In addition to its high reversal rate (see Figure 2), Steyer had the second highest combined frequencies of sub-daily rising

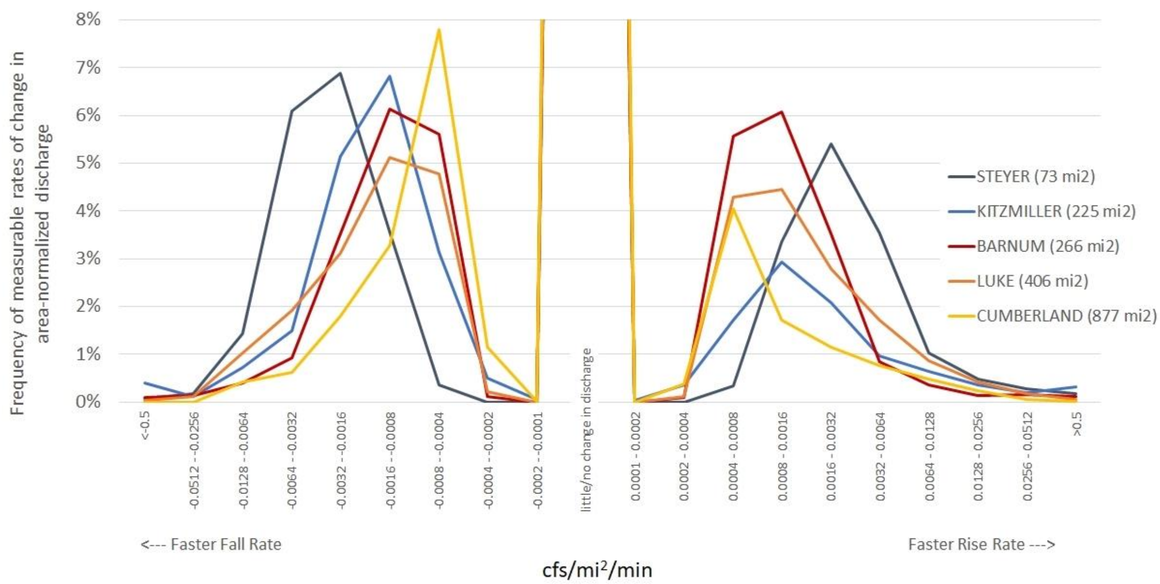


Figure 3. Changes in sub-daily (15- and 30-minute) discharge measurements at the North Branch Potomac River gages normalized to watershed area

Rise and fall rates greater than +/- 0.0002 cfs/mi^2/min occurs in 33.65% of Steyer discharge measurements, 28.36% of Kitzmiller measurements, 34.05% of Barnum measurements, 31.74% of Luke measurements and 24.02% of Cumberland measurements. See also Table 3.

Table 3. Frequency of sub-daily rise and fall rates

The frequencies of fall rates (≤ -0.0002 cfs/mi^2/min), rise rates (≥ +0.0002 cfs/mi^2/min) were calculated on sub-daily flow measurements normalized to watershed size, for water years 2004 – 2018. The threshold 0.0001 cfs/mi^2/min is equivalent to a change over 30 minutes of 0.44 cfs at Steyer, 1.35 cfs at Kitzmiller, 1.60 cfs at Barnum, 2.44 cfs at Luke, 5.26 cfs at Cumberland, 0.29 cfs at Savage Barton and 0.64 cfs at Savage Bloomington.

	NBPR @ Steyer	NBPR @ Kitzmiller	NBPR @ Barnum	NBPR @ Luke	NBPR @ Cumberland	Savage @ Barton	Savage @ Bloomington
Fall rates	19.02%	18.64%	17.15%	16.81%	15.17%	14.49%	6.21%
Little/no change	66.35%	71.75%	65.96%	68.27%	75.99%	74.23%	88.60%
Rise rates	14.62%	9.61%	16.89%	14.92%	8.83%	11.28%	5.19%

and falling water levels (33.65%). This contrasts with Savage at Barton, where rising and fall levels occur in just 25.77% of measurements. Savage at Barton has a watershed size similar to Steyer's, but different upstream land cover and water uses. Comparisons of Kitzmiller and Barnum show these two gages experience similar frequencies of water levels falling faster than -0.0002 cfs/mi^2/min, but Barnum experiences almost twice as many instances of water levels rising faster than +0.0002 cfs/mi^2/min. This effect is seen downstream at Luke and but has disappeared by Cumberland. Dam operations at Savage have a different effect on sub-daily rising and falling rates than dam operations at JRL, likely due to different release protocols. Rising and falling rates there only occur 11.4% of the time and flow rates do not change in 88.6% of the sub-daily flow measurements.

The maximum and minimum flows measured on each Julian day were identified for Kitzmiller and Barnum for the 15-year analysis period and their watershed-normalized discharges compared. Figure 4 shows the suppression of peak levels during high water events and augmentation of low flow levels in summer and fall. Appendix A contains each water year's hydrograph of sub-daily flows at the Kitzmiller and Barnum gages. The stepped hydrograph at Barnum is clearly different from the natural, skewed shapes of rising and falling flows at Kitzmiller. Changes in release rates at JRL are seen as sudden up or down changes in the hydrographs.

During the 15-year analysis period, NBPR above JRL at Kitzmiller exceeded its NWS flood stage in five high water events while NBPR below JRL at Luke avoided flood stage (10.5 ft) the entire period. Dam operations did not prevent flooding further downstream at Cumberland, where levels exceeded the flood stage there (17 ft) in an estimated seven high water events during the same period.

Flow levels at Luke drop slightly below the prescribed 120 cfs minimum flow on two days in November 2010 (water year 2011). Otherwise, dam operations succeeded in meeting this objective as well.

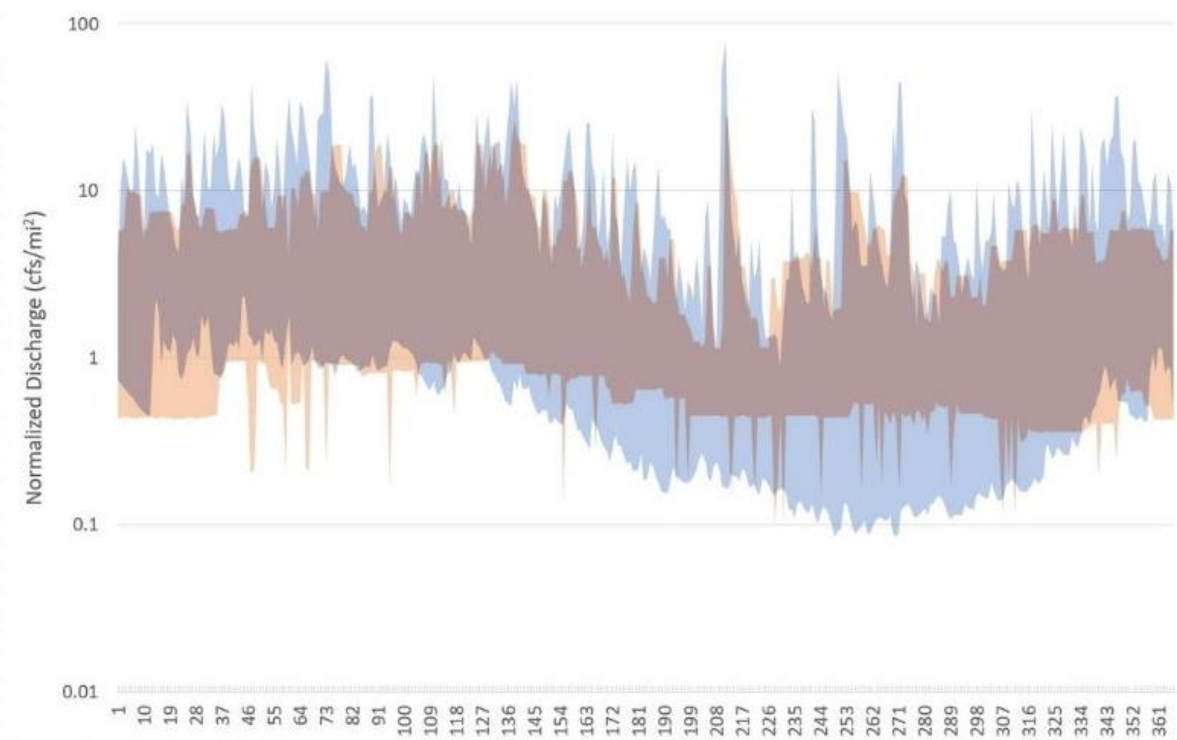


Figure 4. Range of daily mean flow rates at Kitzmiller (blue) and Barnum (orange) USGS streamflow gages by day of year, for water years 2004 – 2018
Flow rates are normalized to watershed size (mi^2) to make them directly comparable.

2.4 Artificially Varied Flows

AVFs are a specific form of low-flow augmentation where releases from JRL are increased rapidly from low pre-release levels to meet a combined target flow from JRL and Savage of 1,000 cfs at Luke, MD. AVF flows are held at the high flow level for a continuous period typically lasting 24 - 48 hours (Table 4).

The original purpose of AVFs was to flush organic solids that settle to the river bottom during low flow periods, usually July, August, and September. The paper mill in Luke has historically been the primary source of the organic solids. USACE also uses high flows to provide temporary opportunities for whitewater recreation below JRL. AVFs were not an original objective of the JRL Water Control Plan but were written into the updated Master Manual for Reservoir Regulation, Appendix A (USACE 1997b). Whitewater recreation was added as a project purpose by the Water Resources Development Act of 1988. JRL releases specifically for whitewater recreation are of a shorter duration than AVFs.

In addition to the prescribed AVFs for flushing settled organic solids during low-flow periods, other large and relatively fast releases are clearly seen in the sub-daily Barnum hydrographs for water years 2004 - 2018 (Appendix A). A total of 309 releases of more than 1,000 cfs in a one-hour period occurred in March, April, May, June, July, August, September, and November during the 22 years. Some appear related to heavy rain events; others do not. The greatest number of these releases occurred in 2011 (65) and 2018 (52); the least in 2005 (5), 2006 (4), and 2016 (6). The average number per year is 20.6. If a lower threshold of 800 cfs increase per hour is considered, the average number per year rises to 30.9.

Table 4. Artificially varied flows (AVFs) for water quality control, 2008 - 2018 (from USACE)

*, the scheduled AVF was cancelled and a whitewater release was made instead.

	August			September		
Year	Duration (Hours)	Flow Target CFS	PreRelease CFS	Duration (Hours)	Flow Target CFS	PreRelease CFS
2018	8	Cancelled*	-		Cancelled	
2017	8	Cancelled*	275		Cancelled*	
2016	27	1000	200	28	850	180
2015	30	1000	225	31	1000	200
2014	29	1000	200	29	1000	200
2013	32	1000	265	31	1000	270
2012	29	1000	150	29	1000	150
2011		Cancelled*		30	1000	400
2010	30	850	125	-	-	-
2009	27	1000	175	-	-	-
2008	26	1000	225	-	-	-

3 Water Quality

Improvement of downstream water quality is the authorized purpose listed second in the JRL Manual of Operations after flood control. Reservoir water is of higher quality than downstream water which receives industrial and municipal discharges and acid mine drainage (AMD) runoff from tributaries. JRL operations intentionally increase reservoir releases during low flow periods, when downstream flows are not enough to dilute and flush out the pollutants. Several features of JRL allow its releases to affect downstream water quality. 1) The reservoir provides a large storage sink where precipitates of AMD contaminants and heavy metals from upstream tributary sources can settle to the bottom. 2) Chemical interactions within the lake are thought to buffer against low pH and other AMD contaminants (although see pH and Alkalinity sections below). 3) The reservoir's natural thermal stratification and its release portals that draw from different lake depths allow dam operators to make cool water releases in summer. 4) Over half of the reservoir volume is allocated to "water quality storage" and intended to increase downstream water levels and dilute downstream pollutants during low flow periods.

In practical terms, the goal for downstream water quality is to meet the middle range of water quality standards established by the State of Maryland for Jennings Randolph in-lake and downstream use. Table 7-04 in USACE 1997b lists the applicable water quality criteria at that time for Maryland's 1 – P designated use category which includes water contact recreation, protection of aquatic life, and public water supply. Fecal coliform and other pathogenic or harmful organisms cannot constitute a public health hazard as determined by Maryland Department of the Environment; dissolved oxygen (DO) cannot be less than 5 mg/liter; maximum temperatures outside an identified mixing zone cannot be higher than 90 ^{o}F (32 ^{o}C); pH must be between 6.5 and 8.5; and turbidity cannot exceed levels detrimental to aquatic life. Turbidity in surface water resulting from any industrial or municipal discharge cannot exceed 150 NTUs at any time or 50 NTUs as a monthly average. There were no criteria for sediment buildup on the riverbed, but it was a concern.

3.1 Data Analysis Methods

Data for the analyses came primarily from federal, state and other datasets available through the national Water Quality Portal (WQP). Data for the Maryland and West Virginia portions of NBPR hydrologic unit (HUC8 02070002) were downloaded from the WQP on February 26, 2019. Contributors included the USGS, Maryland Department of the Environment (MDE), Maryland Department of Natural Resources (MDDNR), National Park Service (NPS), and West Virginia Division of Environmental Protection (WVDEP). Sample dates ranged from July 1945 to February 2019, with a few results submitted by USGS Maryland for 1906 and 1907. Data was available only through 2017 for most parameters. In August 2019, WVDEP shared with the Commission their ambient water quality monitoring data for the North Branch watershed. This dataset was significantly larger and longer than WVDEP data available in the WQP download. WVDEP records in the WQP download were removed and the WVDEP and WQP datasets merged. Analyses for this report were performed on the merged dataset. Water quality data collected by the US Army Corps of Engineers (USACE), Baltimore District in JRL for three years, between 6/10/2015 and 7/19/2017, were included in the download. Lake data for 2011 – 2017 were also obtained directly from Baltimore District staff.

High frequency temperature measurements collected by MDE at nine sites during 2013 – 2014 were included in the WQP downloaded. Hourly temperature, pH, and specific conductivity measurements collected at Barnum below the JRL dam between 10/1/2012 and 12/31/2018 were obtained directly from the USGS Water Data for the Nation website.

Different station names assigned by various monitoring agencies for the same location were resolved by mapping sample locations according to their given latitudes and longitudes and grouping locations close to each other and in the same river or stream. In the NBPR mainstem between JRL and the Savage River confluence, USGS, MDE, and/or MDDNR made measurements at two locations which we identify as "Barnum" (39.445133 latitude, -79.1108 longitude) and "Bloomington" (39.4789722 latitude, -79.0637778 longitude). This river reach has no large tributaries and the locations are for practical purposes comparable, so we often combined them in analyses. Similarly, the Kitzmiller site on NBPR mainstem above JRL had three or four slightly different station locations and were combined and identified as "Kitzmiller." For analysis purposes, seven regional groups of sites were established:

- NBPR mainstem (Mainstem)
- tributaries to the NBPR located above JRL (Upstream)
- Savage River and its tributaries (Savage)
- Georges Creek and its tributaries (George)
- New Creek and its tributaries (New)
- Patterson Creek and its tributaries (Patterson)
- Evitts and Wills creeks and their tributaries in Maryland, and the various small tributaries to the NBPR located downstream of the JRL and not included in Savage, George, or Patterson/New groups (Downstream)

These groups are illustrated in Figure 5. Samples were not generally collected evenly over time and across each subwatershed. The Mainstem group was further divided to investigate change in the various water quality constituents along the mainstem.

Pair-wise comparisons were sometimes done to characterize differences between a parameter's values at two locations. In pair-wise comparisons, data collected on the same date at the two sample locations are matched. This prevents inadvertent bias or weighting caused when more samples are collected at one of the locations in a different period. If there is little difference between the two locations in the pair-wise comparisons, the matched data points will fall close to a 1-to-1 relationship line when graphed. If large differences occur but the matched points generally align with the 1-to-1 relationship, the results imply that conditions at the two locations are not closely linked and, *on average*, are the same. If many points fall either above or below the 1-to-1 line, the two locations are reliably different.

Only a few stations were monitored consistently over time in the NBPR watershed. Trends at these stations are for the most part obvious in time series of the raw data, and formal trend analysis is not necessary. Most stations in the watershed were visited sporadically or randomly, and time series for the six regional groups should be examined carefully with this in mind. Apparent spikes (or dips) in the time series graphs usually indicate the results for intermittently visited stations that had comparatively high (or low) parameter values. The time series, however, help show overall changes on a regional basis.

3.2 Jennings Randolph Lake Water Quality

Data were available from USACE for several parameters measured at five stations in JRL and two stations in the river immediately upstream of the lake on nine occasions between April 2011 and July 2017. Depth profiles at each station were graphed and examined (Appendix B). Temperatures showed the normal seasonal pattern of warmer temperatures at the surface and a gradual decline with depth.

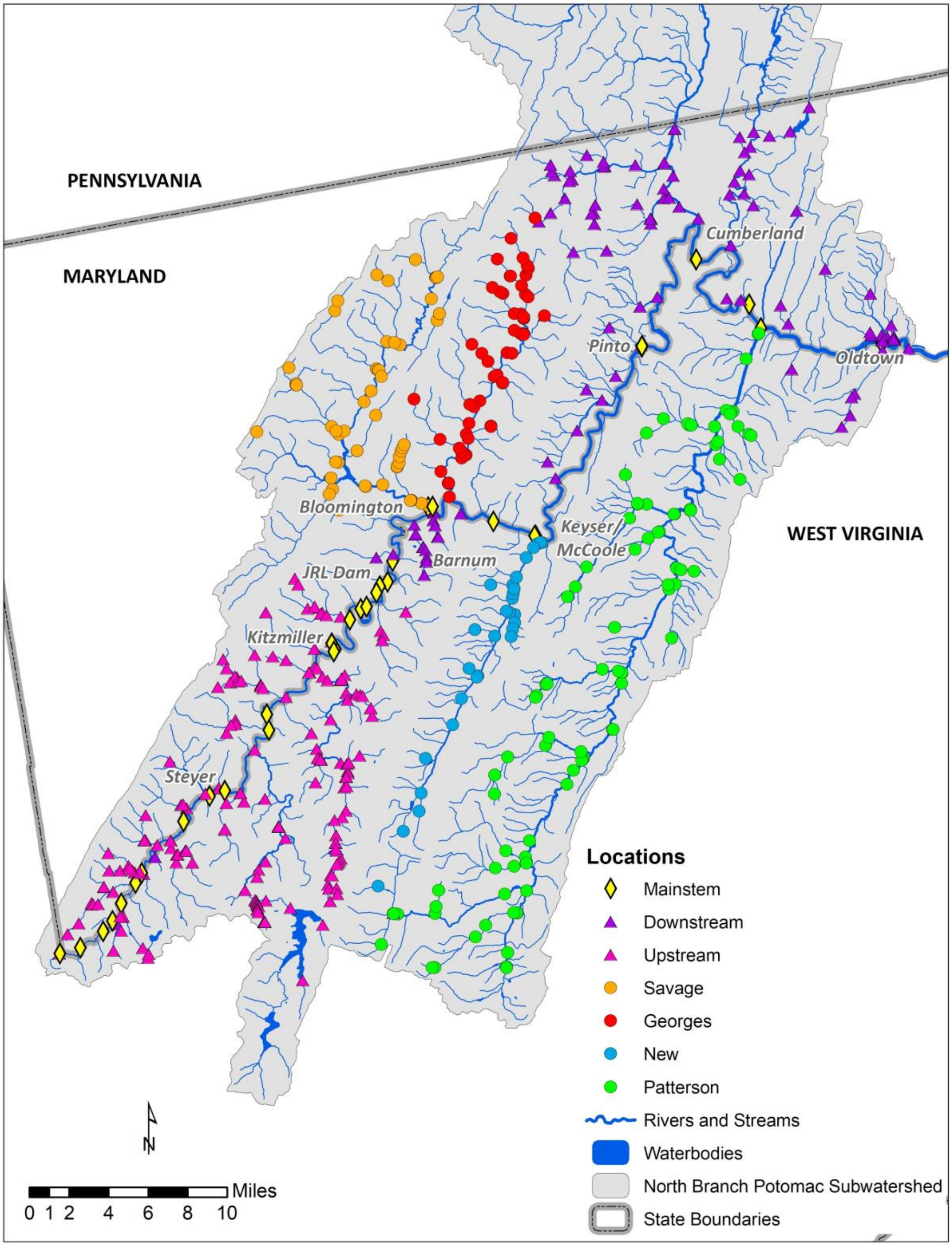


Figure 5. North Branch Potomac River water quality sampling stations in Maryland and West Virginia
Sites visited at least once between July 1945 and February 2019.

DO showed unusual profiles of *increasing* concentration with depth. Concentrations throughout the lake were typically supportive of aquatic life. Specific conductivity (SpCond) levels fluctuated with depth but did not change hugely except on two occasions when levels decreased consistently with depth (June and July 2015). Pulses of high SpCond levels entering the lake were sometimes apparent. pH showed various profiles, sometimes increasing with depth and other times decreasing. The changes in pH with depth, however, were usually very small. Overall, the limited amount of available reservoir data precluded any thorough analysis of the reservoir environment. Comparisons of water quality parameters at Kitzmiller above JRL and Barnum and/or Bloomington a short distance below JRL provided better insights into the reservoir's effect on downstream water quality.

3.3 River and Stream Water Quality

3.3.1 pH

pH values in the NBPR watershed have improved (increased) from mid-20th century lows and now meet Maryland and West Virginia water quality standards in many locations. In the upper NBPR mainstem, pH values were less than 5.0 (acidic) in the 1960s and have risen to values that are now above 6.5 (Figure 6). At Kitzmiller above JRL and at Barnum and Bloomington below JRL, mainstem pH values were less than 5.0 in the 1960s and now are consistently above 7.0 (Figure 6, 7). The Barnum and Bloomington sites jointly indicate a pattern of pH recovery nearly identical to that at Kitzmiller. In the NBPR mainstem from Keyser/McCoole to Oldtown, pH values below 6 were occasionally seen in the 1980s and earlier, but pH values have been above 6.5 since the mid-1990s (Figure 7, 8). To investigate the influence of JRL operations on NBPR mainstem pH, we did a pair-wise comparison of pH measurements collected on the same date at Kitzmiller upstream of JRL and the combined Barnum/Bloomington sites downstream of JRL. The data were collected during monthly site visits by Maryland (MDDNR, MDE) and the USGS between 1979 and 2017 ($n = 374$). The resulting linear regression is highly correlated ($R^2 = 0.81$) and tracks the 1:1 line, indicating pH values in the mainstem above and below JRL are very similar (Figure 9). In recent years (2000 – 2017), median pH below JRL was 0.2 units *lower* than at Kitzmiller above JRL and thus slightly more acidic. Results indicate JRL may have little if any "buffering capacity."

The numerous tributaries to the NBPR mainstem in the Upstream subwatershed show a wide range of pH values (Figure 10) reflecting the influence of AMD that still occurs in places throughout this region. The overall trend in pH is upward and values are approaching Maryland's surface water quality standards. pH values in the Savage River, George's Creek, and Downstream subwatersheds also show overall increases over time, but with much less variation (Figures 11, 12, and 13, respectively). Low values are found in specific tributaries, noted on the graphs, and examination of satellite imagery shows some of the hot spots are clearly associated with mining. The Patterson and New creeks, both of which are relatively unaffected by mining operations, have pH values that have averaged between 7.0 and 8.0 since the 1970s, with few sites falling below 6.5 (Figure 14).

The pH data collected hourly at Barnum since 10/1/2012 show pH values there do not exceed the Maryland pH criteria of $\geq$ 5.5 and $\leq$ 8.5. A daily signal is found when the data are plotted by time of day (Figure 15), indicating photosynthesis in the river is occurring in all months. pH rises in weakly buffered waters when periphyton and vascular plants take up carbon dioxide during light-driven day-time photosynthesis. pH falls at night as plant and animal respiration returns carbon dioxide to the water. The daily pH cycle is typically strongest in summer when the sun's angle of incidence is higher and temperatures are warmer. At Barnum, the average daily change in pH was minimal – less than 0.3 units.

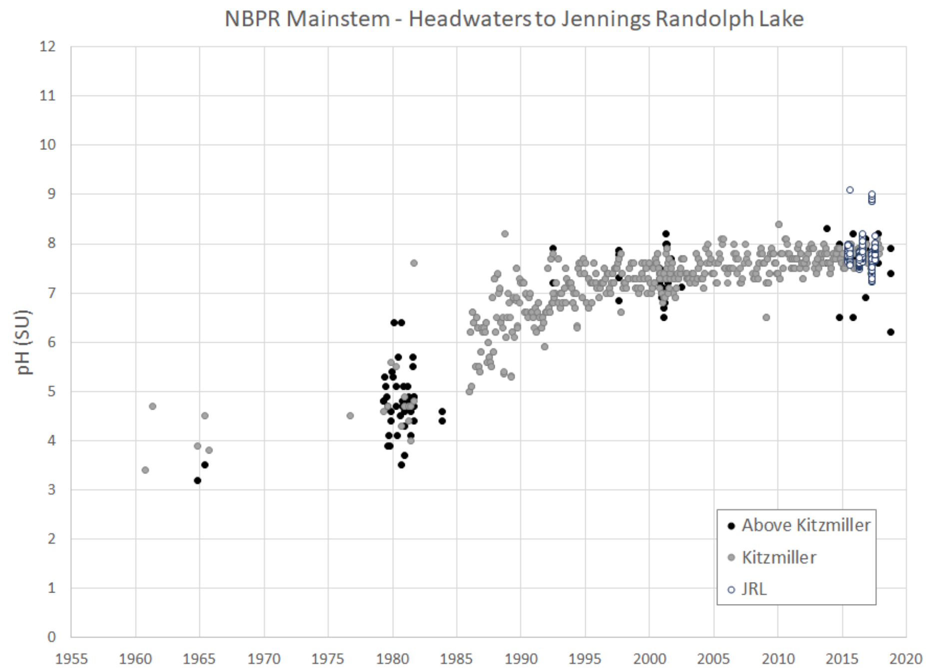


Figure 6. Time series of pH in the upper North Branch Potomac River mainstem

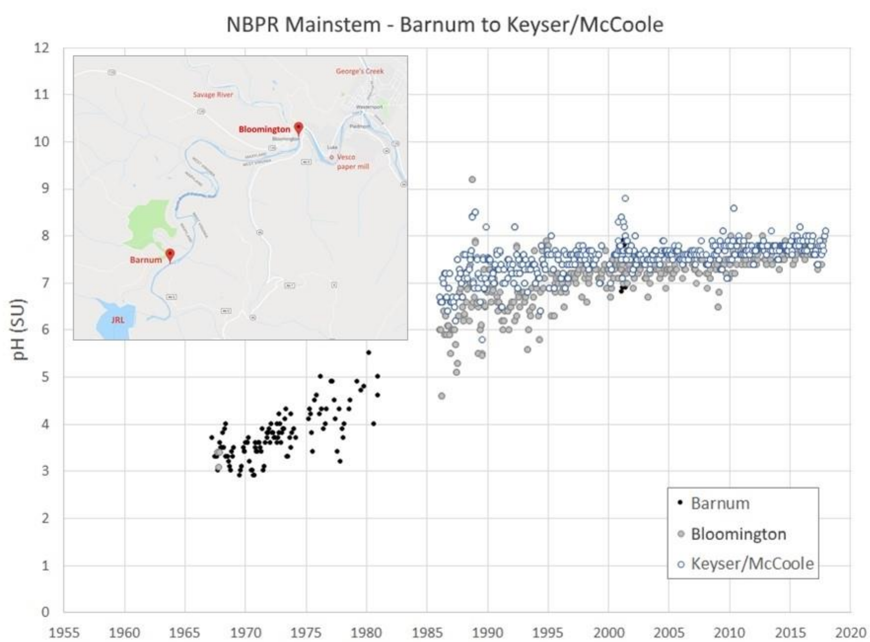


Figure 7. Time series of pH in the middle North Branch Potomac River mainstem

Inset shows Barnum and Bloomington (MDDNR) sites relative to Savage River, Verso Corp. Paper Mill, and George's Creek.

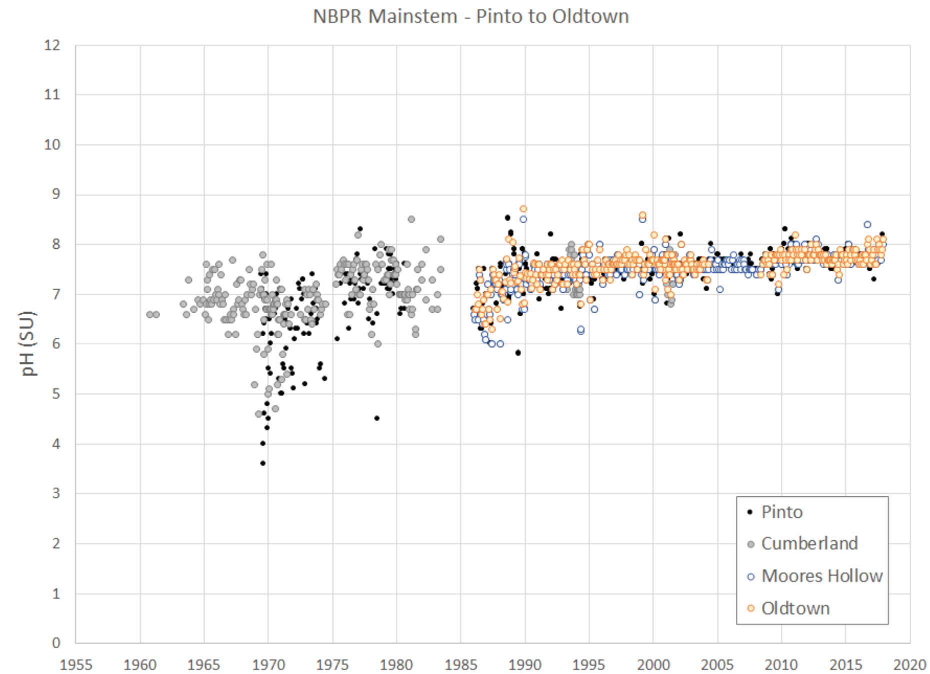


Figure 8. Time series of pH in the lower North Branch Potomac River mainstem

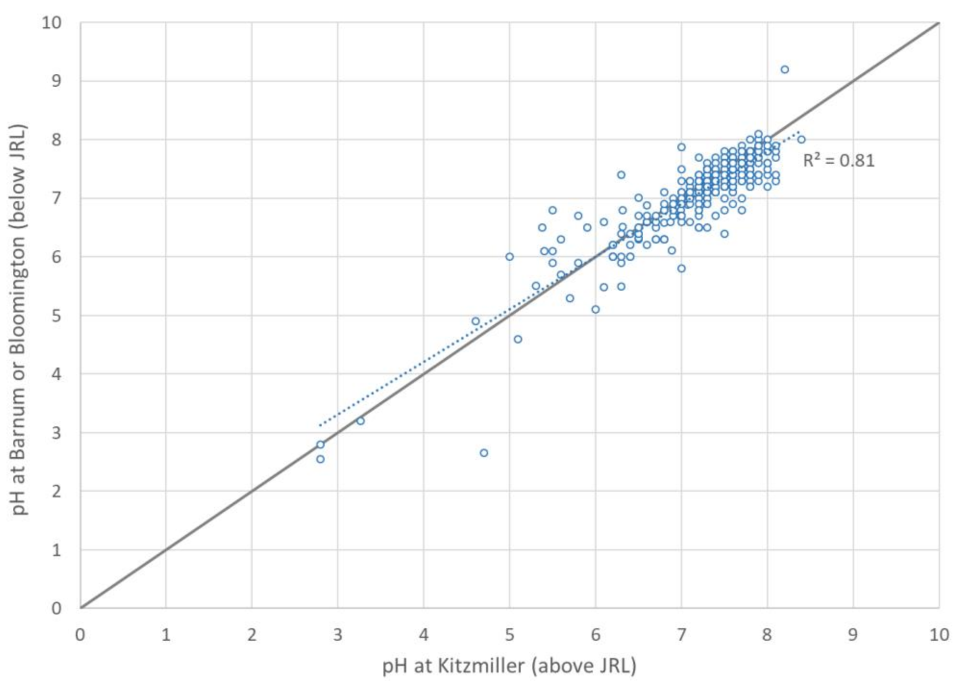


Figure 9. Regression between Kitzmiller and Barnum/Bloomington pH data collected on the same day, 1986 – 2017 (n = 374)

Solid line: 1-to-1 relationship if data show no difference. Dashed line: linear regression ($p < 0.05$). The overlap of the regression line and the 1:1 line indicates JRL, located between the two sites, currently has little overall effect on river pH.

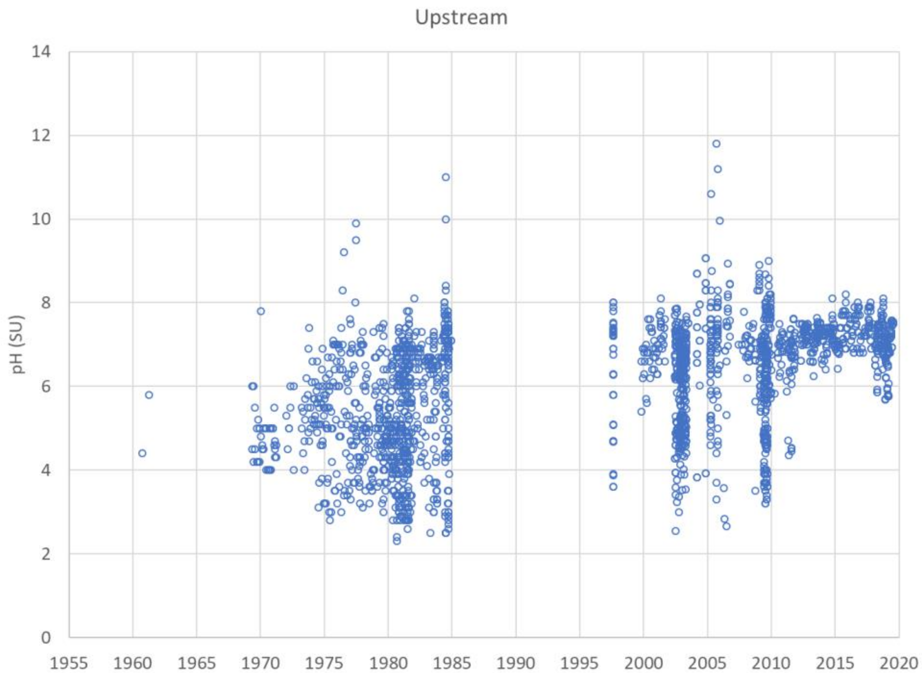


Figure 10. Time series of pH in the Upstream subwatershed
These are North Branch Potomac River tributaries located upstream of Jennings Randolph Lake.

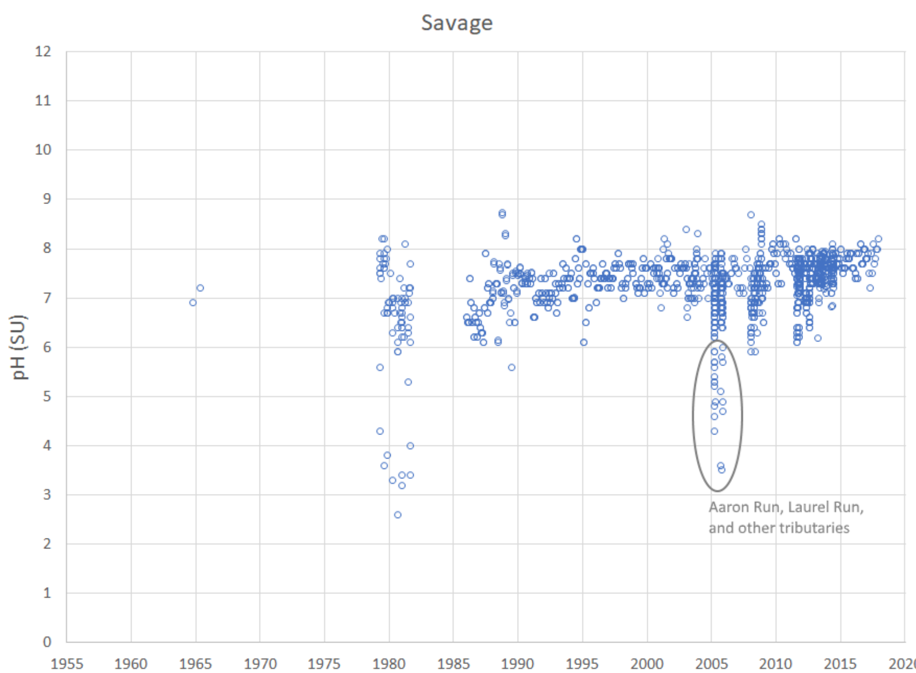


Figure 11. Time series of pH in the Savage River subwatershed

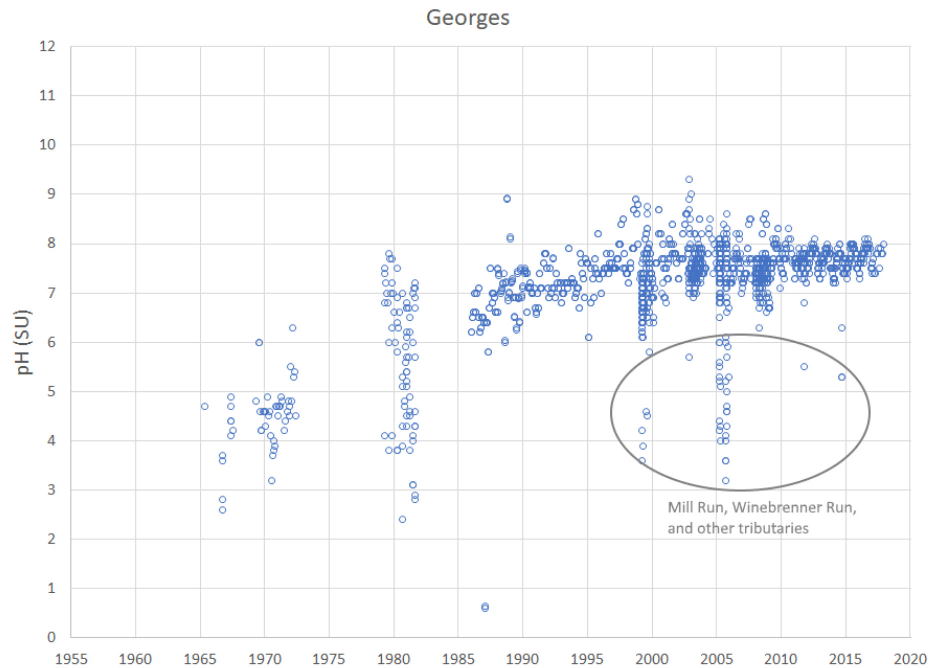


Figure 12. Time series of pH in the George's Creek subwatershed

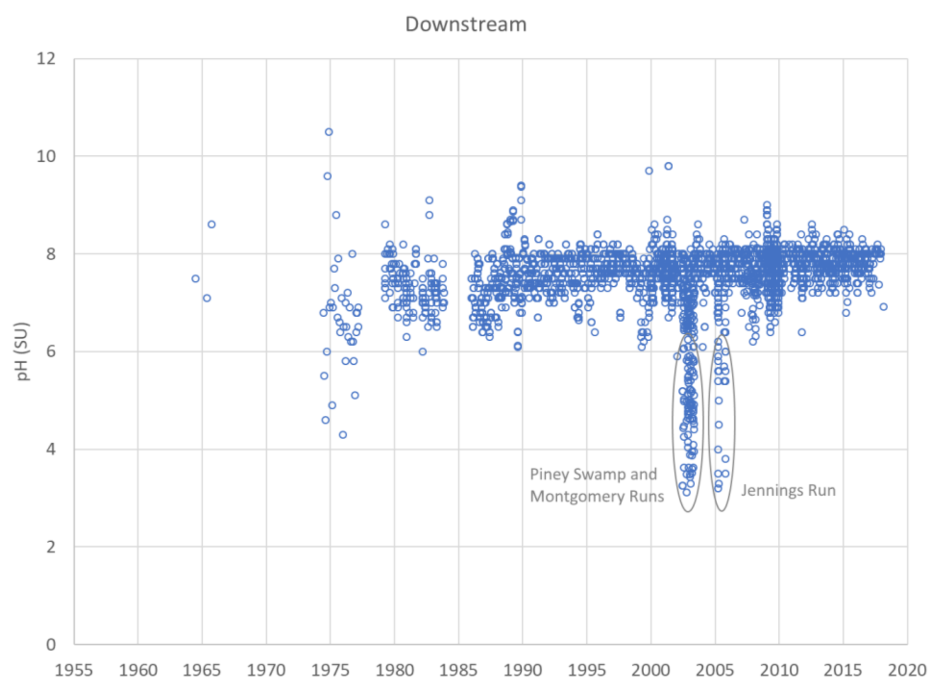


Figure 13. Time series of pH in the Downstream subwatershed

These are North Branch Potomac River tributaries located below JRL and not including the Savage, Georges, New, and Patterson subwatersheds. Data are primarily from Wills and Evitts creeks.

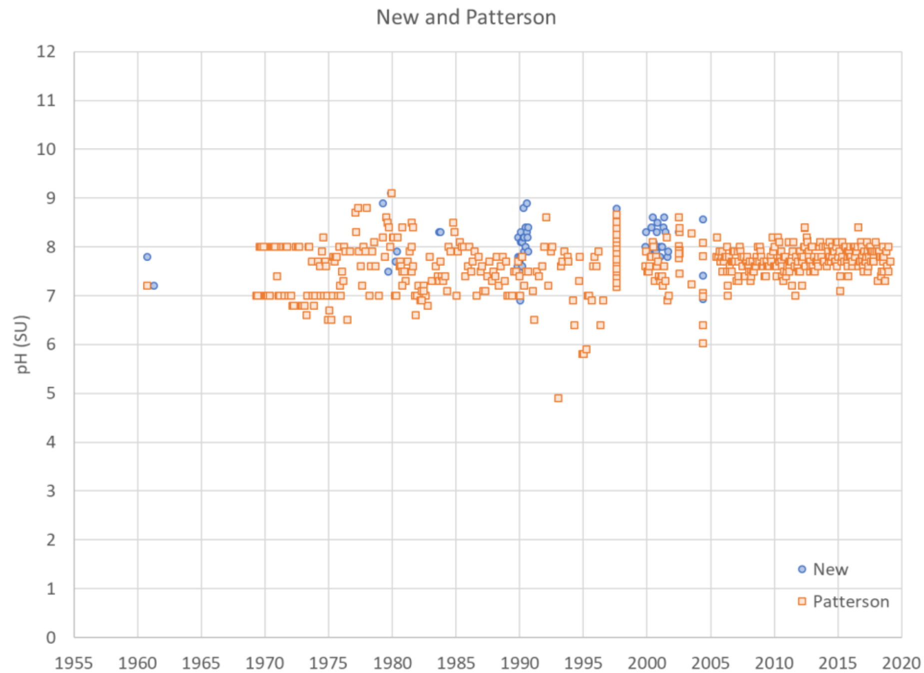


Figure 14. Time series of pH in the Patterson and New creek subwatersheds

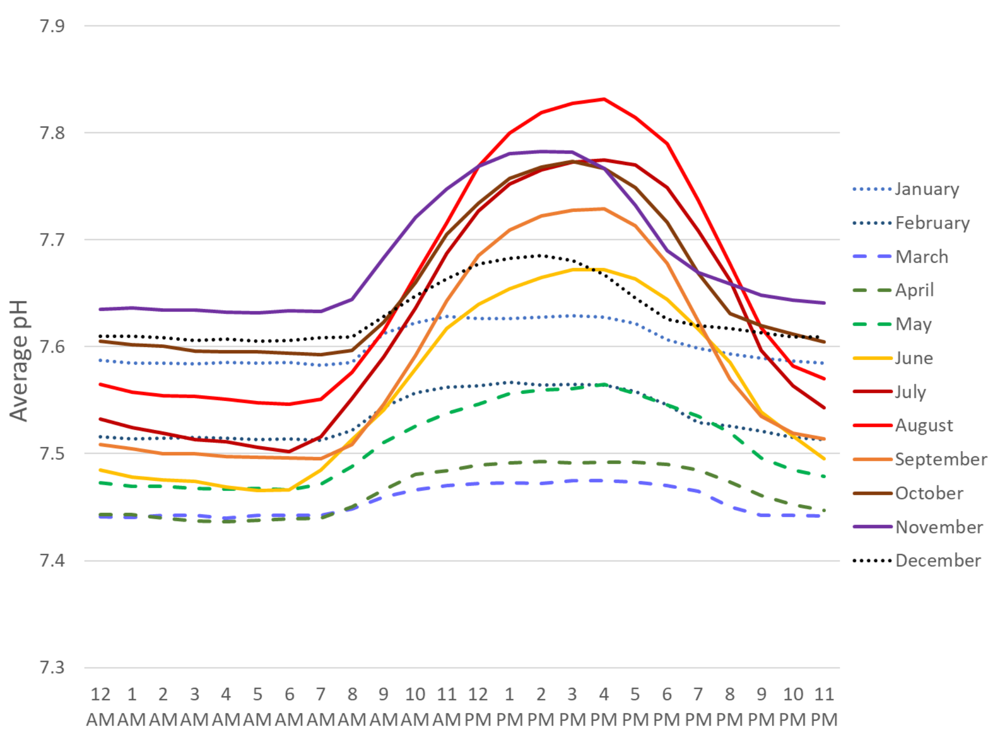


Figure 15. The average of hourly pH measurements at the streamflow gage at Barnum, by month, 10/1/2012 – 12/31/2018

3.3.2 Temperature

NBPR mainstem temperatures below the JRL dam at the combined Barnum/Bloomington site were typically warmer than those above the lake at Kitzmiller in the late 1970s (Figure 16). This was likely a result of solar warming at the lake surface and a greater capacity of the lake's large volume to store heat. Comparatively cooler downstream temperatures began appearing seasonally in the 1980s after the dam was completed and became operational, and consistent patterns emerged in the mid-1990s. Between 1996 and 2017, downstream temperatures, measured primarily at Bloomington and occasionally at Barnum, were on average more than 5°C cooler in July and August, during peak summer temperatures (Figure 17). Downstream temperatures were on average 0.8 - 3.2°C cooler in April, May, and June leading up to summer and 2.8°C cooler in September moving out of summer. The reverse situation usually occurred in fall and winter (October – February) when temperatures were cooler upstream compared to downstream. Up- and downstream temperatures are about the same in March.

Temperature is an important habitat variable, especially for cold-water species such as Brook Trout (*Salvelinus fontinalis*). To examine some of the potential benefits of the JRL dam's deep water releases, we compared upstream (Kitzmiller) and downstream (Barnum/Bloomington) frequencies of temperatures between 4°C and 18°C, a temperature range within which Brook Trout are actively feeding and growing (e.g., Chadwick and McCormick 2017). Measurements were made during monthly site visits, mostly during daytime, over the 22-year period of 1996 -2017. We also looked at frequencies in the 4°C - 20°C range which is Maryland's stocking guideline for trout of several species (COMAR Section 26.08.02.03-3). The results, shown in Figure 18, indicate JRL cold-water releases increase the likelihood of temperatures meeting the stocking guidelines in the NBPR mainstem below JRL during summer and even winter. Summer temperatures frequently exceeded 18°C (upper graph), but they almost always stayed below the stocking guidelines 20°C threshold (lower graph). Relatively warmer waters are discharged from JRL in winter, extending the period of preferred temperatures into winter. (In winter, denser 4°C waters stratify below cooler, less dense waters at the surface. Dam releases blending waters from multiple depths will therefore tend to be warmer than ambient water temperatures.) Upstream of JRL at Kitzmiller, temperatures meet the trout stocking range 100% of the time in April and October but percentages fall in summer to 26.1% of the time in July.

Using the Maryland trout stocking guidelines, we analyzed monthly temperatures for 1996 – 2017 at additional long-term monitoring sites in the NBPR watershed (Table 5). The cooling effect of JRL releases is gradually lost with distance downstream. At Keyser/McCoole, frequencies of temperature measurements meeting the stocking guidelines were 89% in June, 58% in July, 42% in August, and 85% in September. Further downstream at Pinto, they were 61% in June, 24% in July, 16% in August, and 77% in September (Figure 19). Routine temperature measurements in Savage River and Wills Creek, both relatively large subwatersheds, indicate these NBPR tributaries stay cooler than the mainstem in many summers and offer temperature refugia for trout (Figure 20). Savage River near the NBPR confluence achieved the Maryland trout stocking guideline throughout the summer except once in August 2006. Wills Creek near the NBPR confluence achieved frequencies of 76% in June, 47% in July, 62% in August, and 96% in September.

An aggregation of the 1996 – 2017 data by subwatershed found that well over half of daytime summer temperatures were in the 4°C - 20°C range, except in Patterson. The lowest summer-time achievement rates occurred in July and August in the Downstream group (58%), in July in Georges Creek (53%), in August in Savage River (99%), and in July in the Upstream group (58%). (Insufficient data were available to evaluate New Creek summer temperatures for 1996 – 2017.) The very cool temperatures in Savage might reflect greater contributions of colder ground water in summer, overall higher elevations, and/or a greater amount of forest cover compared to the other subwatersheds. In Patterson Creek, only 31% of temperature records achieved the 4°C - 20°C range in June, 0% in July, 21% in August, and 53% in September. Located on the eastern edge of the NBPR watershed, in a more agricultural landscape and at somewhat lower elevations, this is the NBPR's warmest subwatershed.

Water temperature varies throughout the day in response to changes in solar radiation and air temperature. USGS has collected high frequency (hourly, 15 minute) temperature readings at three gages in the NBPR watershed since October 1, 2012. (Table 6). As part of their Western Maryland Shale Baseline project, the Environmental Assessment and Standard Program (EASP) of MDE positioned temperature loggers at nine locations in the NBPR watershed between August 2013 and October 2014 (excluding November and December of 2013). Temperature measurements were recorded hourly in streams and rivers ranging from 1st to 5th Strahler Stream Order. Recently, MDDNR installed a temperature logger in the lower Savage River near the Aaron Run confluence and another at Keyser/McCoole in NBPR mainstem. These loggers are currently functioning, and their data can be accessed through the Storm Central Water Log operated by YSI Inc. / Xylem Inc. ICPRB also installed loggers in the summer of 2019 in the NBPR mainstem between Keyser/McCoole and Cumberland. These recent data were not analyzed at the time of this report's completion.

Analysis of high frequency (hourly) summer temperature readings generally confirms the findings of the long-term monthly day-time temperature readings (Table 7). In the mainstem at Kitzmiller above JRL, Maryland 2013 – 2014 logger deployments show maximum daily temperatures in June, July and August exceeded 20°C on most days. In 1st – 3rd order NBPR tributaries, however, temperatures tended to stay cooler and were less likely to exceed the 20°C threshold. This was especially true for streams in predominantly forested watersheds, like Savage. In the 6-year USGS datasets, the sites downstream of JRL (Barnum) and Savage (Bloomington) dams were able to maintain temperatures below 20°C throughout the summer with very few exceptions. At Barton, upstream of Savage reservoir, temperatures exceeded 20°C on roughly half of the days.

Table 5. Selected stations with long-term temperature records (1996 – 2017) collected during the daytime and at least monthly

ICPRB Group	Location	Lat	Long	Description
Downstream	Wills Creek	39.6619	-78.7803	USGS gaging station 01601500 at Wills Creek near Cumberland MD
Mainstem	NBPR (Kitzmiller)	39.3894	-79.1794	USGS gaging station 01595500 at Kitzmiller MD above Jennings Randolph Lake
Mainstem	NBPR (Bloomington)	39.4792	-79.0680	Bloomington MD just upstream of confluence with Savage River
Mainstem	NBPR (Keyser/McCoole)	39.4449	-78.9718	MD Route 220 bridge between Keyser WV and McCoole MD
Mainstem	NBPR (Pinto)	39.5668	-78.8389	USGS gage station near Western Maryland Railroad at Pinto, MD
Savage	Savage River	39.4806	-79.0681	Savage River at MD135 bridge near Bloomington, MD

Table 6. Stations with high frequency temperature measurements

MDE, Maryland Department of the Environment; DNR, Maryland Department of Natural Resources; USGS, U.S. Geological Survey.

Sub-watershed	Agency	Identification	Lat/Long	Start	End	Freq.	Count
Georges	MDE	MDE_EASP-GEOR-201-D (Koontz Run)	39.58256, -78.99127	8/8/2013 12 am	11/24/2014 9 am	Hourly	9,563
Mainstem	DNR	North Branch Potomac River (near Keyser)	39.44499 -78.97260	5/13/2019 12:30 am	ongoing	15-min	TBD
Mainstem	MDE	MDE_EASP-PRUN-401-D (NBP0689, Kitzmiller)	39.389265, -79.17948	8/8/2013 12 am	11/24/2014 9 am	Hourly	9,886
Mainstem	USGS	USGS 01595800 NBPR @ Barnum	39.445111, -79.110806	10/01/2012 1 am	ongoing	Hourly	TBD
Savage	DNR	Lower Savage River (near Aaron Run)	39.48616, -79.08295	5/13/2019 12:30 am	ongoing	15-min	TBD
Savage	MDE	MDE_EASP-SAVA-102-D (Blue Lick)	39.646804, -79.06725	10/9/2013 10 am	11/24/2014 9 am	Hourly	8,402
Savage	MDE	MDE_EASP-SAVA-103-D (Pine Swamp Run)	39.52902, -79.125414	8/14/2013 6 pm	11/24/2014 9 am	Hourly	8,526
Savage	MDE	MDE_EASP-SAVA-203-D (Mud Lick)	39.64297, -79.02176	8/9/2013 10 am	10/21/2014 9 am	Hourly	9,051
Savage	MDE	MDE_EASP-SAVA-302-D (Savage @ Mt. Aetna Rd)	39.643194, -79.020028	9/10/2013 1 pm	10/21/2014 9 am	Hourly	8,280
Savage	USGS	USGS 01596500 Savage @ Barton	39.570056, -79.101944	10/01/2012 1 am	ongoing	Hourly	TBD
Savage	USGS	USGS 01597500 Savage @ Bloomington	39.502750, -79.123972	10/01/2012 1 am	ongoing	Hourly	TBD
Upstream	MDE	MDE_EASP-PRUN-201-D (Short Run)	39.37607 -79.20747	8/8/2013 1 pm	11/24/2014 9 am	Hourly	8,290
Upstream	MDE	MDE_EASP-PRUN-202-D (Laurel Run)	39.34881, -79.28555	8/8/2013 2 pm	11/24/2014 9 am	Hourly	8,572
Upstream	MDE	MDE_EASP-PRUN-301-D (Nydegger Run)	39.297528, -79.350167	8/8/2013 2 pm	10/21/2014 9 am	Hourly	8,997

Table 7. Percent of days with summer maximum daily temperatures not exceeding 20°C, by month, calculated from high frequency (hourly or shorter) temperature measurements

MDE: May, June and July data are for 2013 only; August, September, and October data are for 2013 and 2014. USGS: October 2012 – December 2018. See Table 6 for site locations and data details. ICPRB Group, data analysis grouping; SSO, Strahler Order according to the USGS National Hydrography Dataset Plus (NHD Plus) high resolution stream layer (8/13/2018); Dominant Land Cover, dominant land cover upstream of location according to the National Land Cover Data (2011), where 41 indicates deciduous forest, 42 evergreen forest, 21 developed or open spaces, and 81 pasture and hay.

ICPRB Group	Maryland Identifier (Station Name)	SSO	Dominant Land Cover	May	June	July	Aug.	Sept.	Oct.
Georges	MDE_EASP-GEOR-201-D (Koontz Run)	2nd	41	100.0%	86.7%	48.4%	81.8%	79.6%	100%
Mainstem	MDE_EASP-PRUN-401-D (Kitzmiller)	5th	81, 21, 41	71.0%	3.3%	3.2%	5.5%	43.3%	95.2%
Mainstem	USGS 01595800 NBPR @ Barnum	5th	41, 21	100.0%	100.0%	100.0%	100.0%	96.6%	97.6%
Savage	MDE_EASP-SAVA-102-D (Blue Lick)	1st	41, 42	100.0%	100.0%	100.0%	100.0%	100.0%	100%
Savage	MDE_EASP-SAVA-103-D (Pine Swamp Run)	1st	41	100.0%	100.0%	100.0%	100.0%	100.0%	100%
Savage	MDE_EASP-SAVA-203-D (Mud Lick)	3rd	41, 42	100.0%	80.0%	29.0%	72.2%	85.0%	100%
Savage	MDE_EASP-SAVA-302-D (Mt. Aetna Rd)	3rd	41, 81, 42	100.0%	73.3%	29.0%	38.7%	82.4%	100%
Savage	USGS 01596500 Savage @ Barton	4th	41, 42, 81	98.8%	82.0%	38.8%	53.8%	73.3%	100.0%
Savage	USGS 01597500 Savage @ Bloomington	5th	41, 21	100.0%	100.0%	98.4%	99.5%	100.0%	100.0%
Upstream	MDE_EASP-PRUN-201-D (Short Run)	2nd	41	100.0%	100.0%	ND	100.0%	88.3%	100%
Upstream	MDE_EASP-PRUN-202-D (Laurel Run)	3rd	41	100.0%	100.0%	96.8%	100.0%	96.7%	100%
Upstream	MDE_EASP-PRUN-301-D (Nydegger Run)	3rd	41, 21, 81	90.3%	86.7%	45.2%	95.4%	86.7%	100%

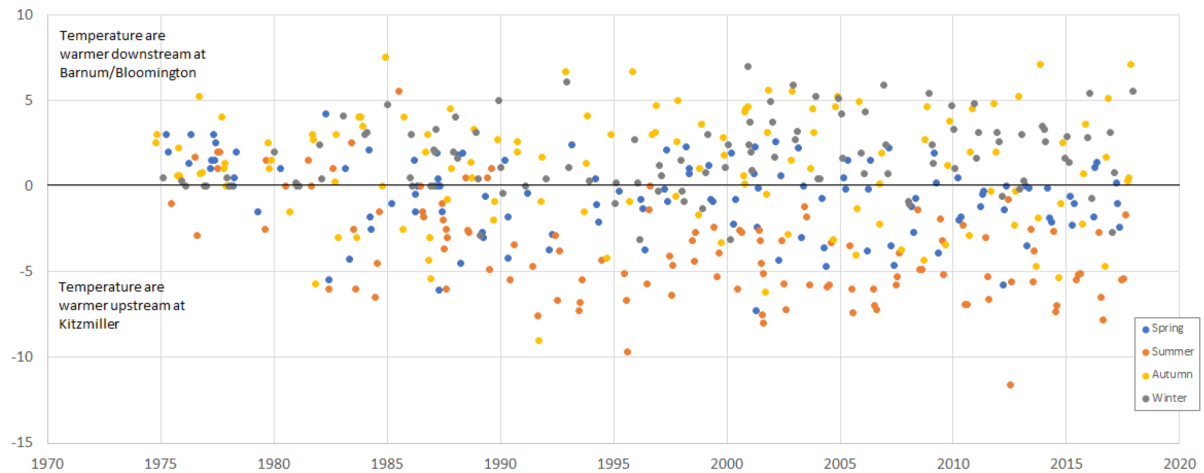


Figure 16. Pair-wise comparison of temperatures collected upstream (Kitzmiller) and downstream of Jennings Randolph Lake (Barnum or Bloomington)

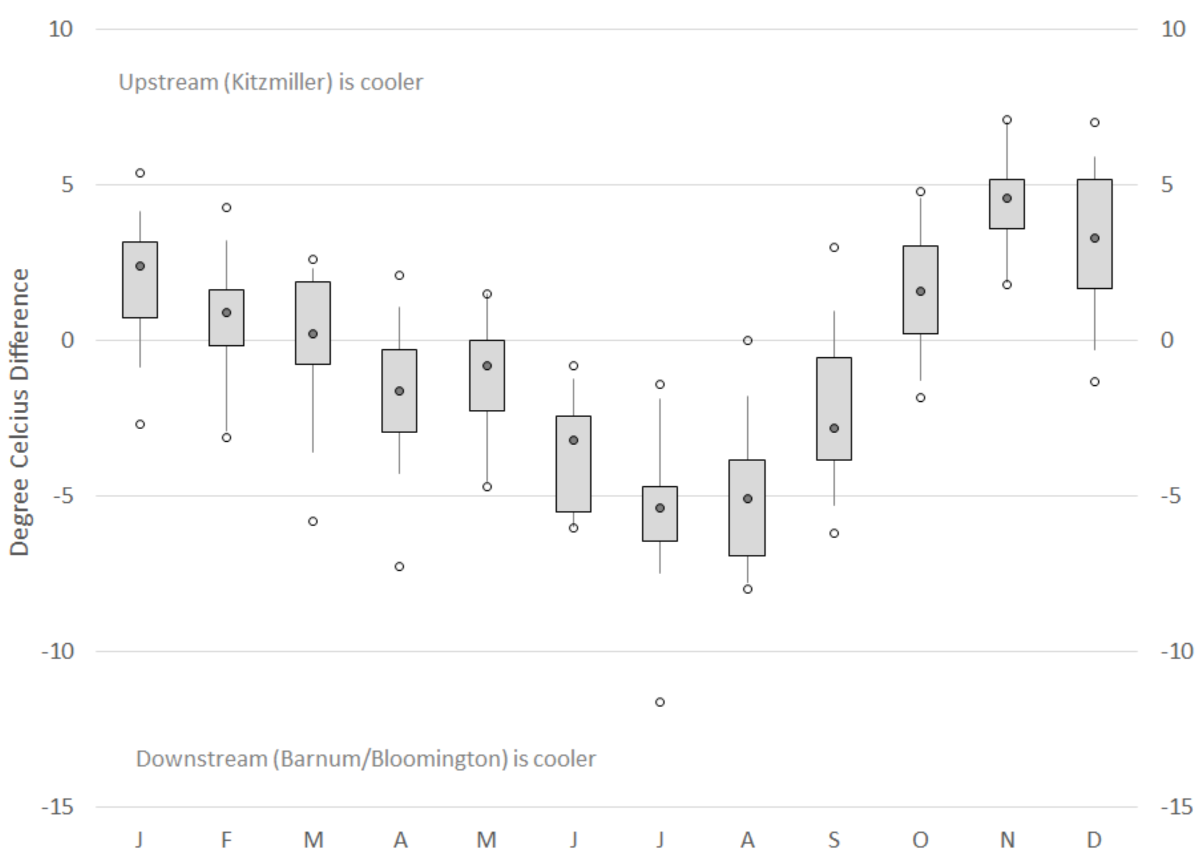


Figure 17. Difference in temperatures up- and downstream of Jennings Randolph Lake
Difference between temperatures observed upstream of Jennings Randolph Lake at Kitzmiller and downstream at Bloomington or Barnum on the same date, by month, for the 1996 – 2017 period. Box-and-whiskers indicate 5th, 25th, median, 75th, and 95th percentiles; open circles, minimum and maximum differences.

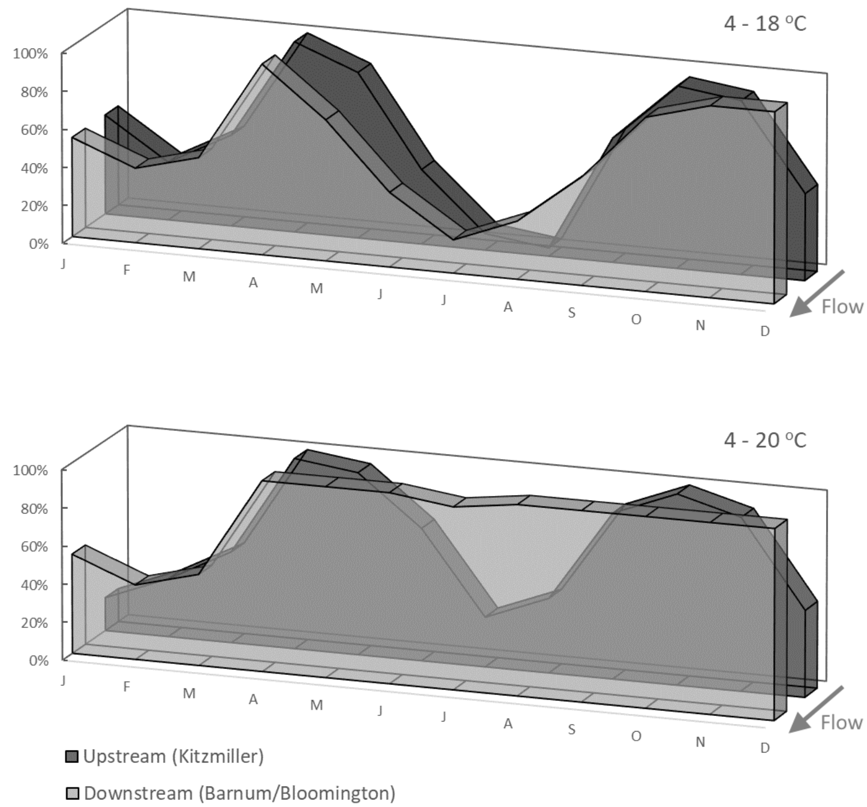


Figure 18. Monthly frequencies of 4 – 18 °C and 4 – 20 °C temperatures up- and downstream of Jennings Randolph Lake

Temperatures between 4 °C and 18 °C, when Brook Trout are actively feeding and growing (upper graph), and between 4 °C and 20 °C, Maryland's guidelines for stocking trout (lower graph), in the North Branch Potomac River mainstem immediately upstream of Jennings Randolph Lake (Kitzmiller) and downstream of the lake (Barnum and Bloomington). Temperatures were typically measured in daytime during monthly site visits.

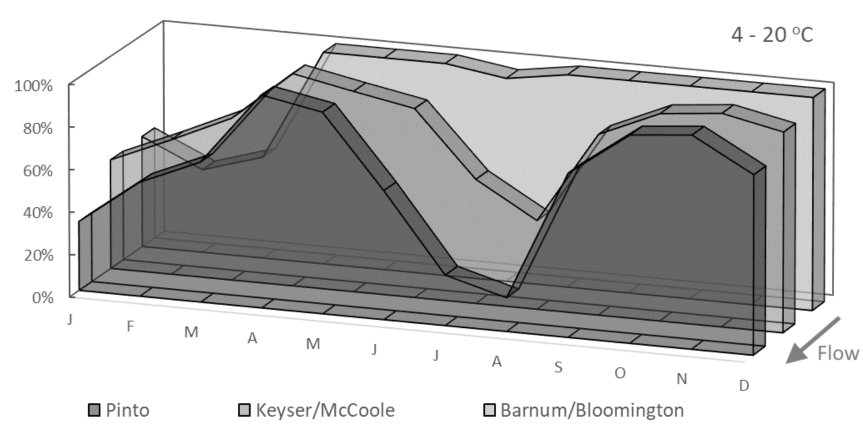


Figure 19. Monthly frequencies of 4 – 20 °C temperatures between Barnum and Pinto

Temperatures between 4 °C and 20 °C (Maryland's guidelines for stocking trout) in the North Branch Potomac River mainstem at Barnum/Bloomington (also shown in Figure 13), Keyser/McCoole, and Pinto MD. Data from monthly site visits.

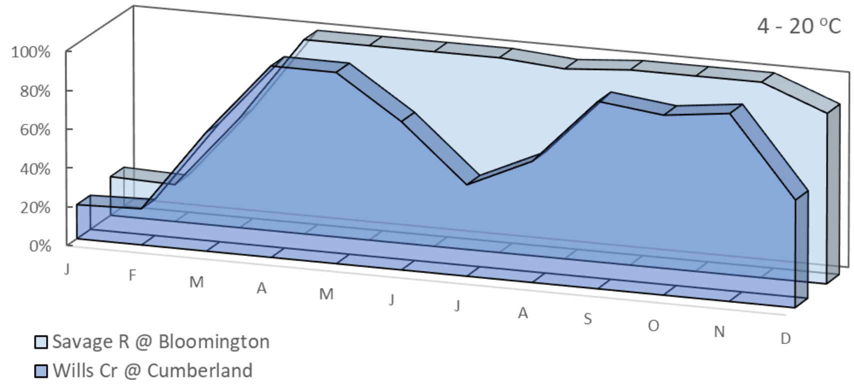


Figure 20. Monthly frequencies of 4 – 20 °C temperatures in two large tributaries, Savage River and Wills Creek
Maryland's guidelines for stocking trout are temperatures between 4 °C and 20 °C. Each station is located just upstream of its river's confluence with the NBPR mainstem. Data are from monthly site visits.

3.3.3 Specific Conductivity

Maryland and West Virginia do not have water quality standards for surface water specific conductivity, however values over 300 - 500 µS/cm are considered detrimental to aquatic life (USEPA 2011, WVDEP 2018, MDE 2009, Hill et al. 2017). Concentrations of SpCond concentrations have been highly variable over time in the NBPR watershed. In the NBPR mainstem upstream of JRL, SpCond exceeded 500 µS/cm and often reached values greater than 1,000 µS/cm throughout the time series (Figure 21). Below Kitzmiller, SpCond often exceeded 500 µS/cm in the free-flowing river before JRL was built (data collected primarily at Barnum). After the lake was completed, SpCond rarely exceeded 500 µS/cm in this stretch (data now collected at Bloomington) (Figure 22). Further downstream, SpCond concentrations in the mainstem at Keyser/McCoole frequently exceeded 500 µS/cm, but apparently did not exceed 1,000 µS/cm (Figure 22). Below Keyser/McCoole, SpCond has been less than about 800 µS/cm since ~1985, however many samples exceed 500 µS/cm (Figure 23). Since 2000, the frequency of SpCond greater than 500 µS/cm in the mainstem has been 39% at Kitzmiller, 3% at Bloomington, 45% at Keyser/McCoole, 45% at Pinto, 37% at Moores Hollow Road, and 37% at Oldtown. Concentrations appear to be increasing slightly over time.

SpCond was highly variable in the Upstream subwatershed (Figure 24). In the Savage River subwatershed, Aaron Run and Mud Lick Run had values that often exceeded 500 µS/cm, however samples in the rest of the subwatershed were less than 250 µS/cm (Figure 25). Few data were available for the Georges Creek subwatershed upstream of its confluence with NBPR, but concentrations were high overall and increasing at its confluence with NBPR (Figure 26). They were low in the Patterson and New subwatersheds, staying below 100 mg/liter for the most part. They were variable and generally high in the Downstream subwatershed (Figure 27). Between 2000 and 2017, median concentrations of SpCond at the tributary mouths were lower than in the NBPR mainstem, except for Georges Creek (Table 8).

Pair-wise comparisons of SpCond at Kitzmiller and Barnum/Bloomington reveal a curvilinear relationship between the two locations (Figure 28). Below ~400 µS/cm, there is a very rough 1-to-1 relationship between the two but Barnum/Bloomington concentrations level off when Kitzmiller concentrations exceed 500 µS/cm. SpCond entering the lake can reach values greater than 1,000 µS/cm while values below the lake typically do not exceed 500 µS/cm, suggesting the lake serves as a SpCond sink to some extent. Median SpCond concentrations at Keyser/McCoole were significantly higher (41%) than Barnum/Bloomington (Mann-Whitney, $p < 0.01$), indicating one or more sources enters the river between the two locations. Comparisons between the other mainstem stations show no significant changes between Keyser/McCoole and Pinto, followed by a gradual decline to Oldtown. Potential sources of SpCond entering between Barnum/Bloomington and Keyser/McCoole include Savage River, Georges Creek, and industries and municipal facilities between Bloomington and Keyser/McCoole.

Table 8. Specific conductivity (µS/cm) at six North Branch Potomac River mainstem locations, tributary mouths, and subwatersheds, 2000 – 2018

*Values greater than 500 µS/cm are considered harmful to aquatic life. Some stations in the subwatersheds are sampled more often or at different times than others. ND, ten or fewer data points; *, excludes tributary mouth stations but includes "hotspots."*

Stations/groups	n	Median	Range	% Greater Than 500 µS/cm
Mainstem Stations				
Kitzmiller	*213*	442	(81 – 1,293)	39%
Bloomington	*213*	343	(119 – 585)	3%
Keyser/McCoole	*209*	484	(130 – 849)	45%
Pinto	*213*	475	(167 – 849)	45%
Moores Hollow Rd	*211*	432	(186 – 715)	37%
Oldtown	*165*	411	(172 – 744)	37%
Tributary Mouths				
Savage@Bloomington	*212*	128	(49 – 233)	0%
Georges@Westernport	*556*	898	(203 – 2,170)	92%
New@Keyser	*19*	246	(151 – 412)	(too few)
Wills@Cumberland	*403*	214	(87 – 1,270)	25%
Patterson@NBPR	*15*	203	(112 – 363)	(too few)
Subwatersheds*				
Upstream	*770*	343	(35 – 5,860)	31%
Savage	*237*	393	(24 – 2,809)	47%
Georges	*ND*			
New	*169*	262	(50 – 748)	10%
Downstream	*684*	519	(32 – 4,804)	53%
Patterson	*852*	220	(64 – 885)	<1%

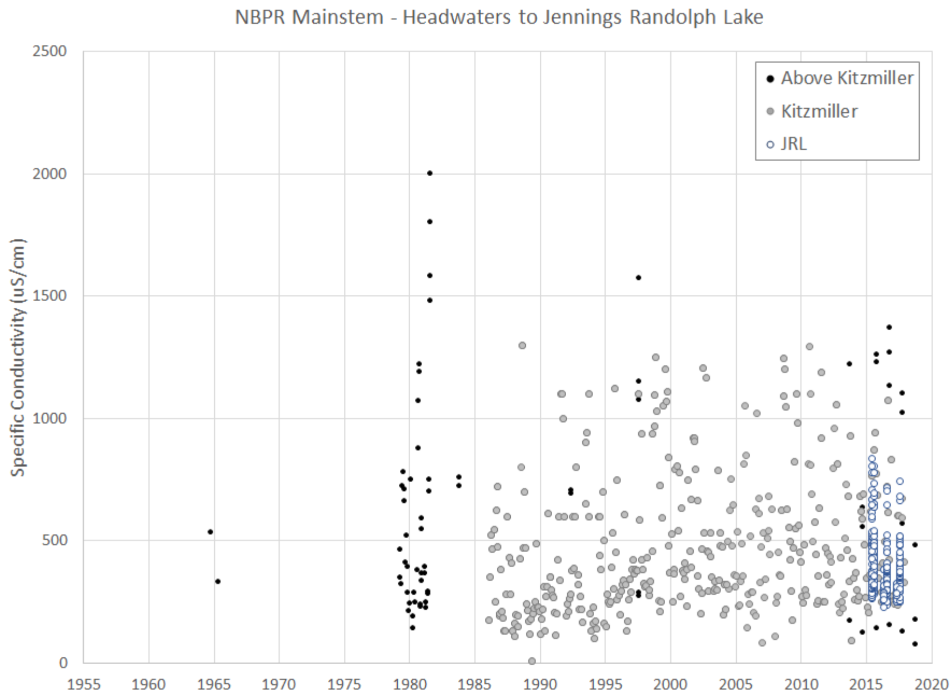


Figure 21. Time series of specific conductivity in the upper North Branch Potomac River mainstem

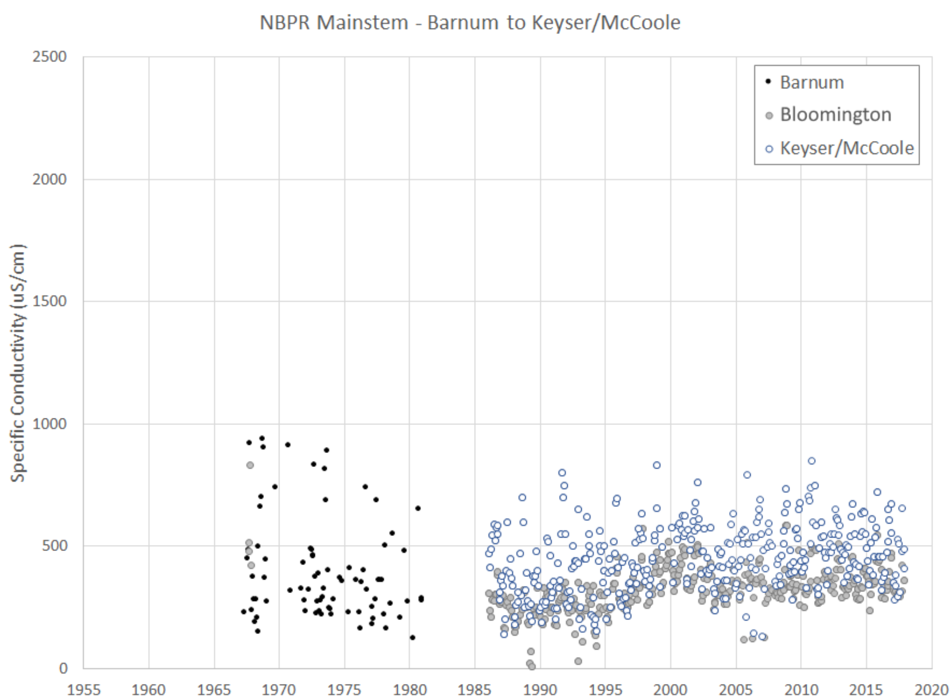


Figure 22. Time series of specific conductivity in the lower North Branch Potomac River mainstem, Barnum to Keyser/McCoole

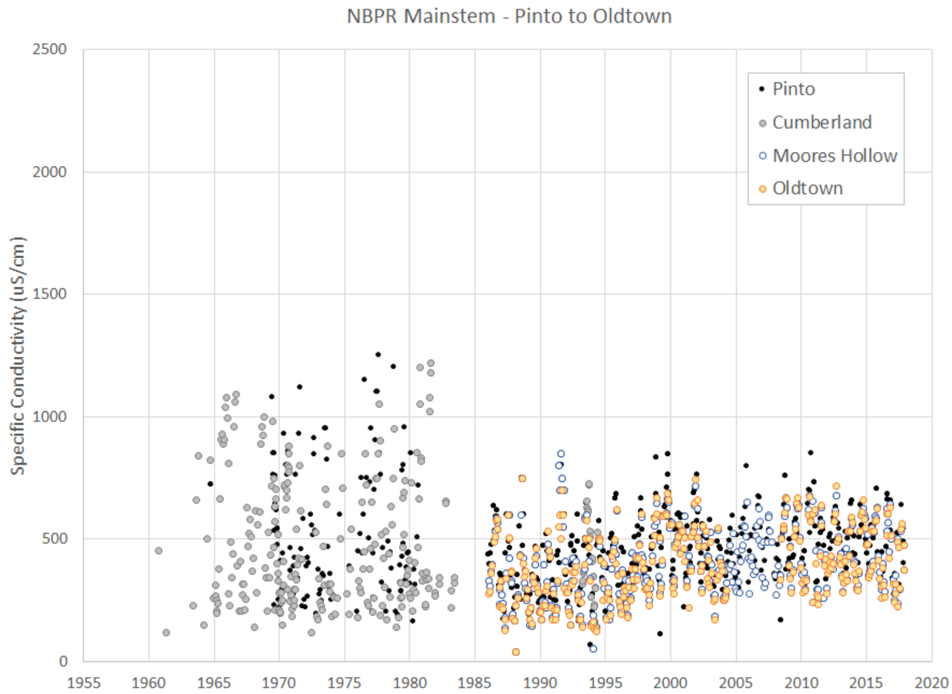


Figure 23. Time series of specific conductivity in the lower North Branch Potomac River mainstem, Pinto to Oldtown

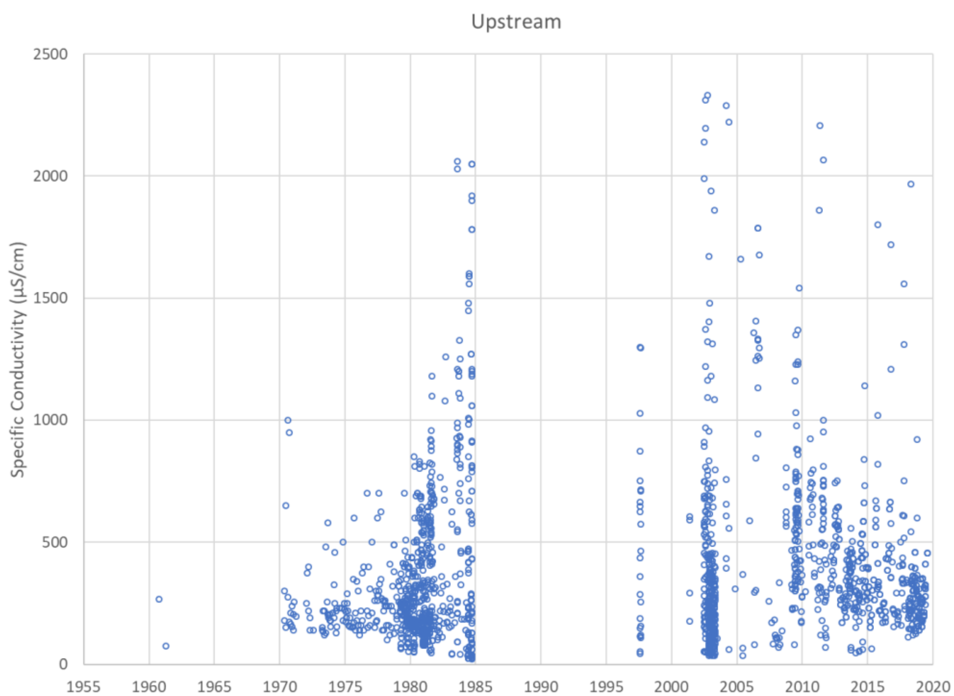


Figure 24. Time series of specific conductivity in the Upstream subwatershed

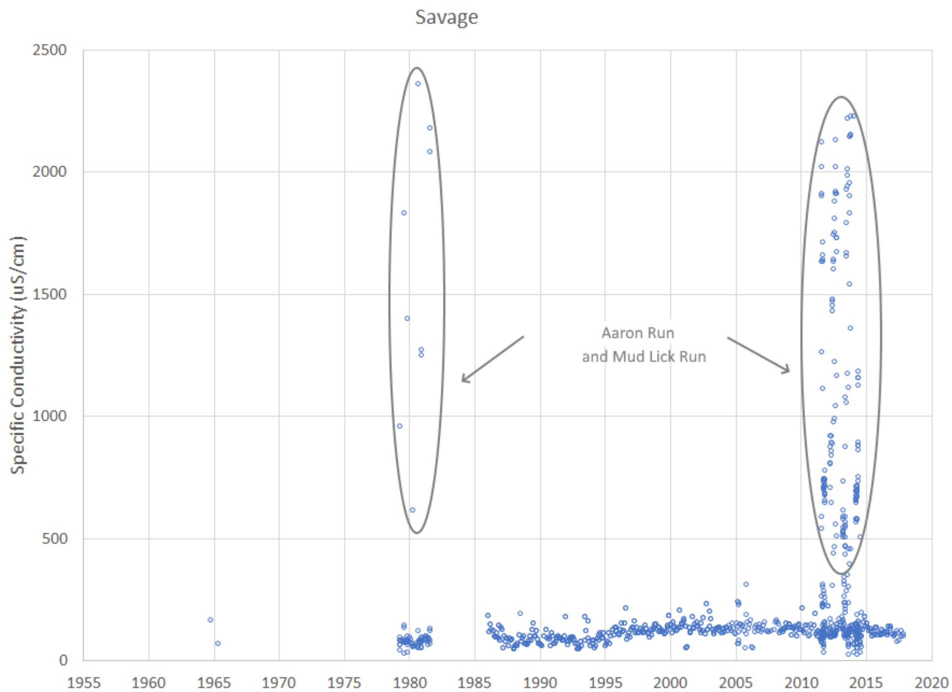


Figure 25. Time series of specific conductivity in the Savage River subwatershed

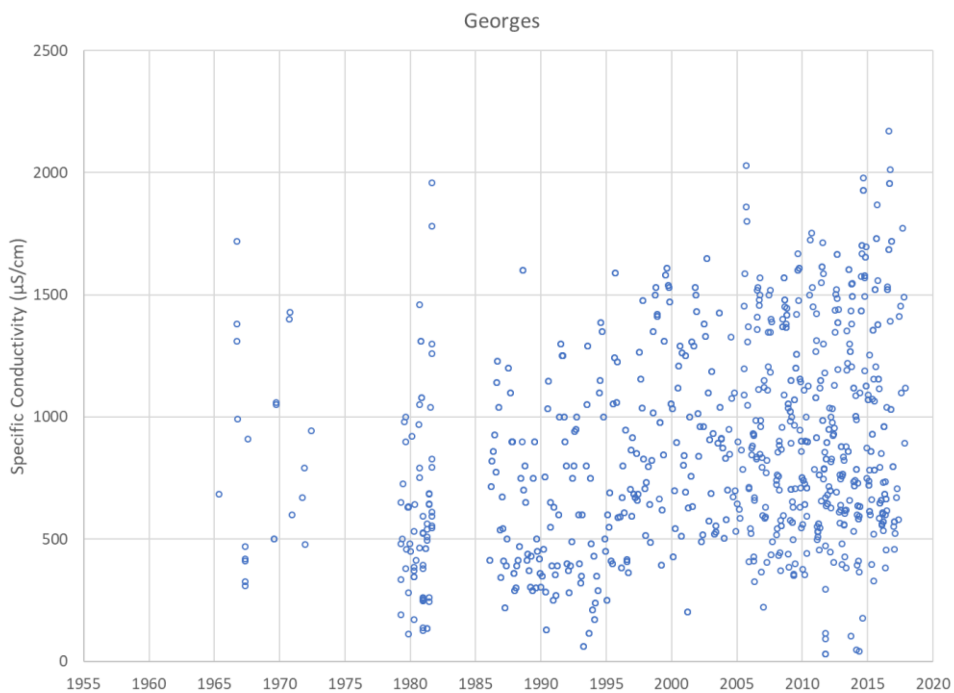


Figure 26. Time series of specific conductivity in Georges Creek subwatershed
Most samples collected near the confluence with the North Branch Potomac River mainstem.

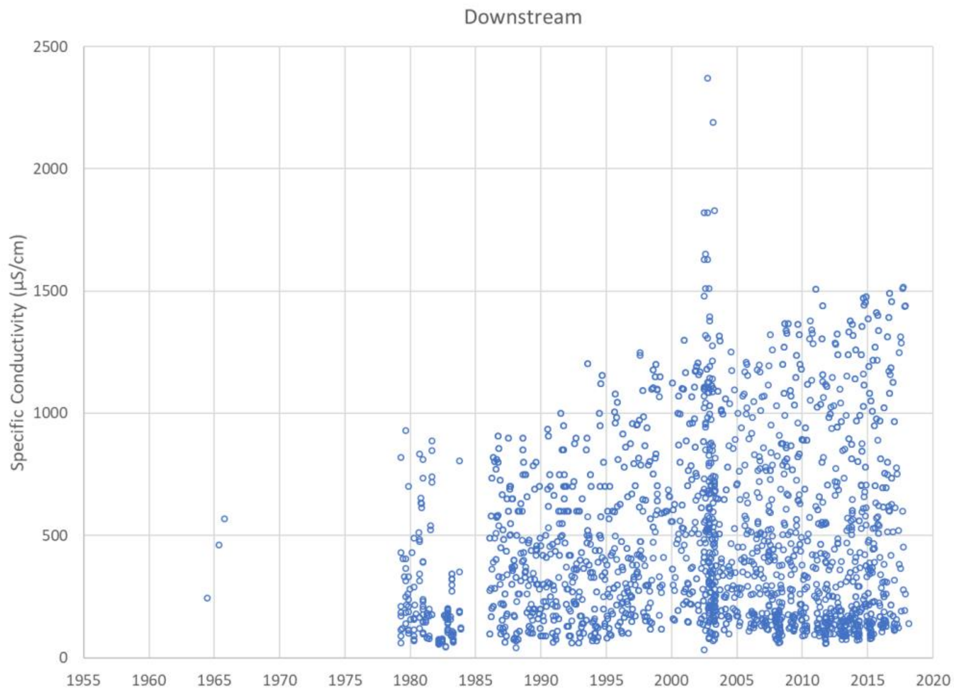


Figure 27. Time series of specific conductivity concentrations in Downstream subwatershed
Excludes Savage, Georges, New, and Patterson. Data are primarily from Wills and Evitts creeks.

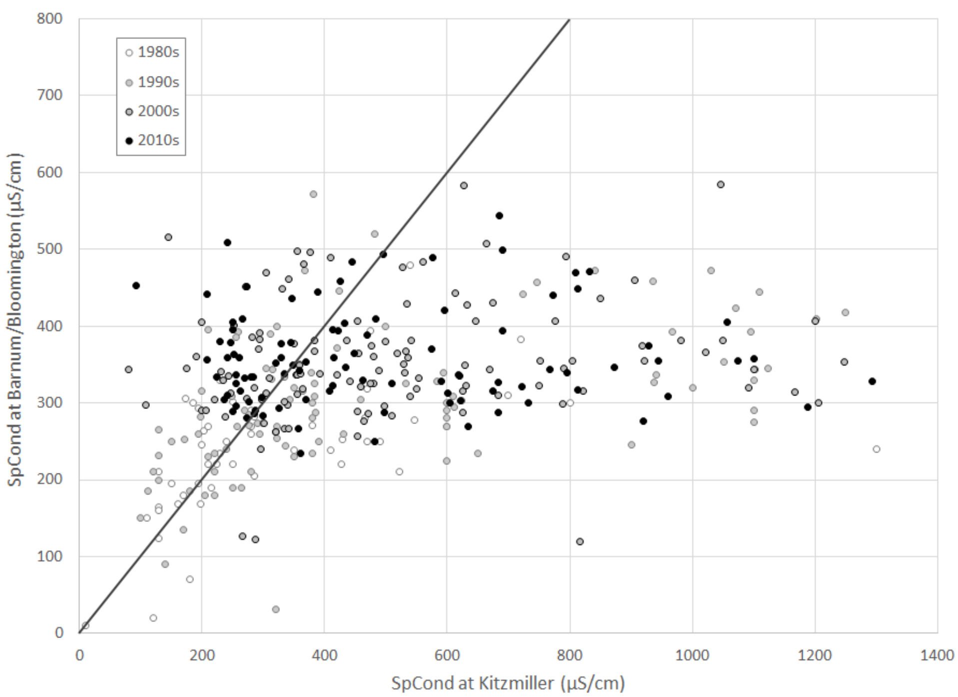


Figure 28. Pair-wide comparison of specific conductivity (SpCond) collected routinely at Kitzmiller above Jennings Randolph Lake and at Barnum or Bloomington below the lake (n = 361)
Solid line: 1-to-1 relationship if data show no difference. Points below and to the right of the line: Kitzmiller value is larger than Barnum/Bloomington; points above and to the left: Barnum/Bloomington value is larger.

3.3.4 Total Dissolved Solids

Total dissolved solids (TDS) are the sum of all salts, minerals, metals, cations and anions dissolved in water. TDS measurements, expressed as mg/liter, are obtained by weighing the residue left after a water sample has been passed through a standard glass filter and dried. The relationship between SpCond and TDS is usually close, and the relationship was evident in the NBPR data in comparisons of the two parameters collected during the same sampling event. Figure 29 shows their relationships at four mainstem locations: Kitzmiller, Barnum, Bloomington, and Keyser/McCoole. Divergence in the regression lines can be due to several factors including changes in the chemical makeup of water. EPA's 1997 stream monitoring guidelines for volunteers (adopted by the West Virginia Save Our Streams program, www.dep.wv.gov/sos) and Maryland's biological stressor identification procedures (MDE 2009) use an upper threshold of 500 mg/liter to identify TDS levels stressful to aquatic life. Virginia uses the lower threshold of 350 mg/liter (Hill et al. 2017).

Pair-wise comparisons of mainstem measurements above JRL at Kitzmiller and below JRL at Barnum/Bloomington on the same date show the same curvi-linear relationship evident in Figure 28 for SpCond. Below ~250 mg/liter TDS, there appears to be a rough correspondence between values above and below the lake. However, when Kitzmiller concentrations exceed 250 mg/liter, Barnum/Bloomington concentrations diverge from that 1-to-1 relationship and level off (Figure 30). TDS entering the lake can reach values as high as 1,100 mg/liter while values below JRL typically do not exceed 400 mg/liter. Like SpCond, the TDS results indicate the lake serves as a sink to some extent for dissolved salts, minerals, metals, cations, and anions entering the lake from upstream sources.

Time series of TDS in the NBPR subwatersheds are very similar to those for SpCond shown in Figures 24 – 27. Like SpCond, TDS was highly variable in the Upstream subwatershed. Its concentrations ranging from 16 – 2,990 mg/liter. The Downstream subwatershed, dominated by Wills and Evitts creeks entering near Cumberland, ranging from 0 – 1,174 mg/liter. Like SpCond, TDS in this subwatershed shows an upward trend with increasing frequencies of high values. Few data were available for Georges subwatershed upstream of Westernport, and values ranged from 14.6 - 1,830 mg/liter. Few data were available for the New and Patterson subwatersheds; however, all are below 260 mg/liter. Excluding two hotspots (Aaron Run, Mud Lick), TDS concentrations in the Savage subwatershed typically remained below 190 mg/liter and show no trend.

The overall median TDS concentration at Kitzmiller since 2000 was 284 mg/liter. The median drops 23% to 218 mg/liter at Barnum/Bloomington, indicating JRL's role as a TDS sink. In the 7.5 miles between Bloomington and Keyser/McCoole, TDS climbs 43% to a median concentration of 312 mg/liter and a range of 0.2 - 604 mg/liter. From there, mainstem TDS concentrations show a gradual decline with distance. Median concentrations were 312 mg/liter at Pinto, 260 mg/liter at Moores Hollow Rd., and 251 mg/liter at Oldtown. Georges Creek is partly responsible for the jump in TDS between Barnum/Bloomington and Keyser/McCoole. The median concentration at its mouth (MDDNR GEO0009) was 686 mg/liter. Since flow coming in from Georges Creek is only about a tenth of the NBPR flow at Keyser/McCoole, the creek is only partly responsible for the rise in TDS.

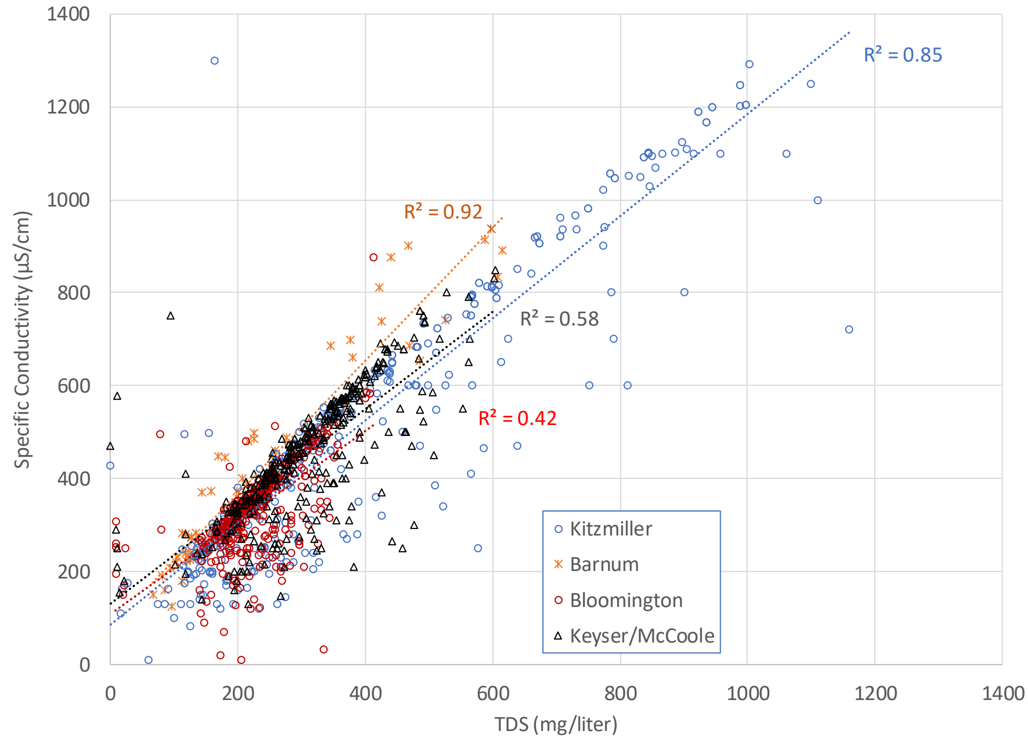


Figure 29. Relationships between specific conductivity (µS/cm) and total dissolved solids (mg/liter)

Figure 30. Pair-wise comparison of total dissolved solids in North Branch Potomac River mainstem above the Jennings Randolph Lake at Kitzmiller and below the lake at Barnum or Bloomington
Solid line: 1-to-1 relationship if data showed no difference. Compare to Figure 28 (specific conductivity).

3.3.5 Dissolved Oxygen

Concern for low DO during summer low flow periods was a justification for implementing AVFs during late summer (ACOE 1997b). Warm temperatures decrease the maximum amount of oxygen that water can hold (saturation) while also increasing the aquatic community's metabolic requirements for oxygen and the oxidation rates of inorganic chemicals such as ammonia and nitrite. Low flows exacerbate these conditions because they often minimize exposure of surface waters to atmospheric oxygen and diffusion of oxygen into the water. DO can become particularly low in river sediments where it threatens fish egg survival and harms macroinvertebrate communities.

Percent DO saturation of waters above and below JRL was somewhat variable prior to about 1996 but is now very stable and high, typically staying above 90% (Figures 31 and 32). A pair-wise comparison of Kitzmiller and Barnum/Bloomington shows percent DO saturation generally tracked the 1-to-1 line after 1996, indicating little if any difference between the two (Figure 33). When Kitzmiller percentages did fall below 90%, Barnum/Bloomington percentages were able to remain high, causing the relationship to diverge from the 1-to-1 line. Two particularly large differences occurred in April and August of 2008. A slight upward trend in percent DO saturation was observed at both Kitzmiller and Barnum/Bloomington after 1996.

In the combined WVDEP and downloaded WQP databases, only nine of a total 6,279 sampling events between 2000 and 2017 had DO concentrations less than the Maryland and West Virginia water quality standard of 5 mg/liter (Table 9). Otherwise, rivers and creeks in the NBPR watershed did not appear to experience impairment due to low DO. DO in the water column along the length of the NBPR mainstem currently meets Maryland and West Virginia standards (Figure 34). DO could be low in sediments that have settled on the riverbed, however we had no data to confirm this.

Table 9. Sampling events with dissolved oxygen less than 5 mg/liter
Measurements made between 2000 and 2017 in the North Branch Potomac watershed.

Date	Location	Subwatershed	Latitude	Longitude	DO (mg/liter)
9/10/2008	Georges Creek	Georges	39.59146	-78.9486	4.1
6/12/2007	Staggs Run	Patterson	39.39275	-78.8557	1.5
9/10/2007	Plum Run	Patterson	39.54431	-78.7436	4.5
8/28/2007	Thorn Run	Patterson	39.21169	-79.0363	4.5
8/28/2007	Un. Trib. Patterson Cr North Fork	Patterson	39.18714	-79.1301	5.0
9/12/2012	Aaron Run	Savage	39.51933	-79.0866	3.4
7/15/2009	Abrams Creek	Upstream	39.20937	-79.2264	4.0
11/11/2002	Abrams Creek	Upstream	39.22819	-79.2214	4.0
9/21/2005	Lostland Run	Upstream	39.39552	-79.2560	4.6

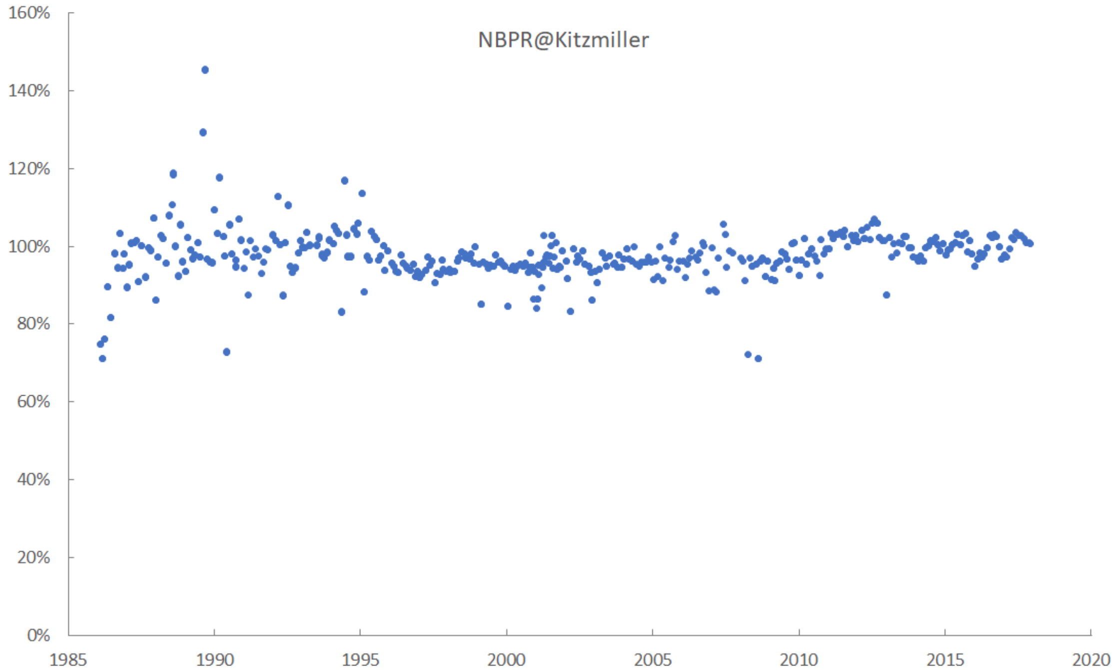


Figure 31. Time series of percent dissolved oxygen saturation at Kitzmiller, upstream of Jennings Randolph Lake

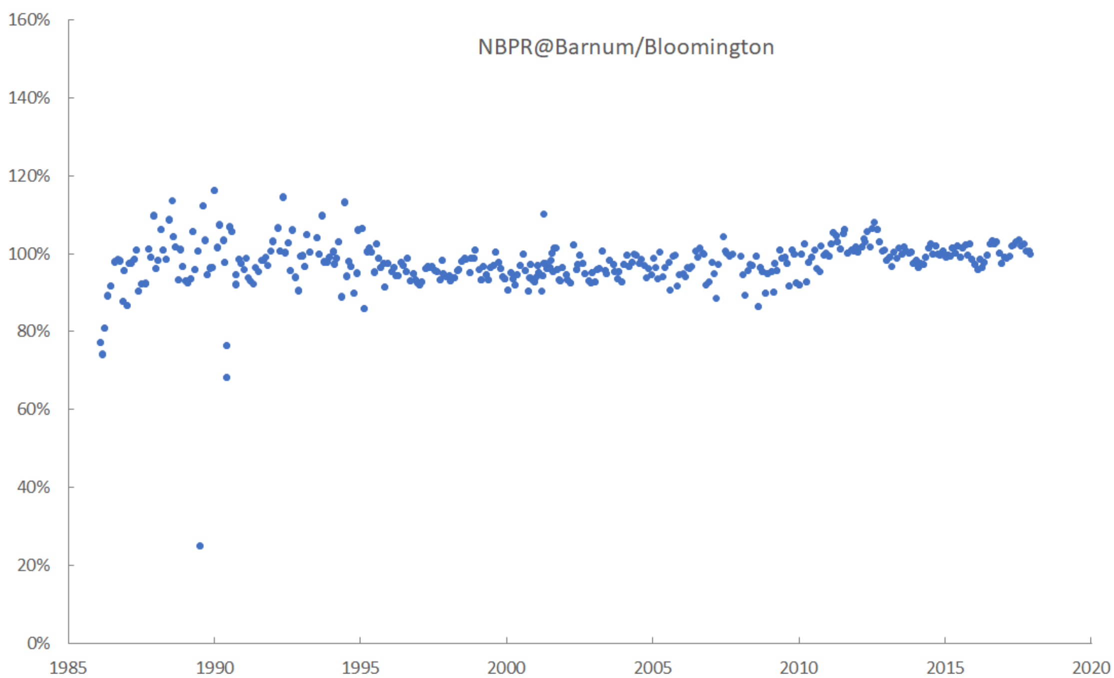


Figure 32. Time series of percent dissolved oxygen saturation at Barnum/Bloomington, below Jennings Randolph Lake

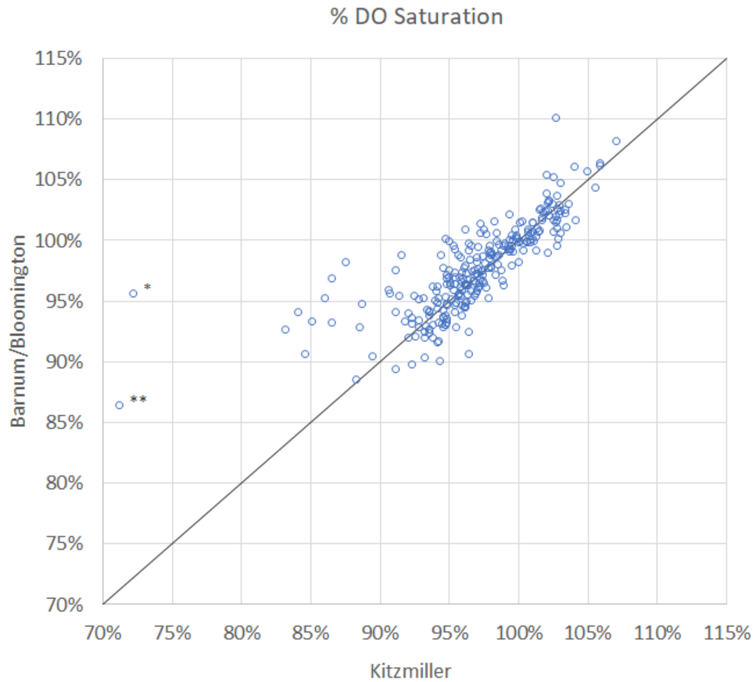


*Figure 33. Pair-wise comparison of percent dissolved oxygen saturation at Kitzmiller and Barnum/Bloomington Data collected 1996 – 2017. Line: 1-to-1 relationship if data show no difference. Outliers: *, April 2008; **, August 2008.*

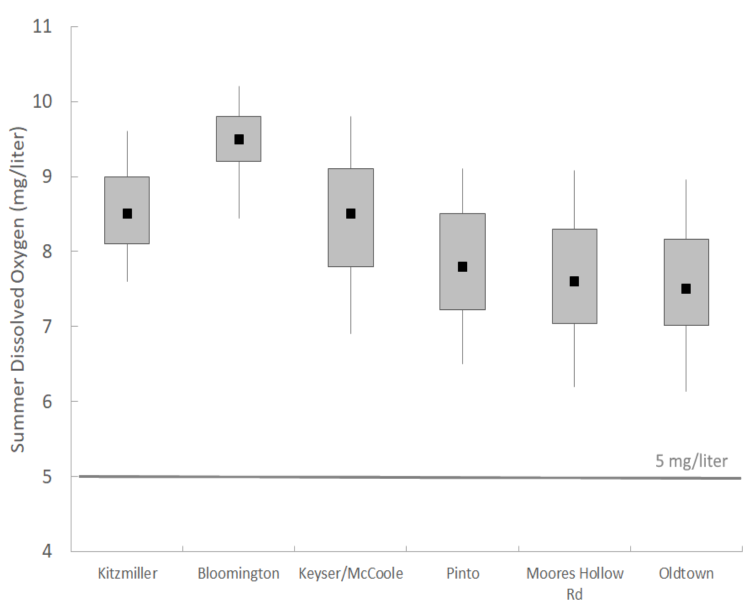


Figure 34. Dissolved oxygen in summer (June – September) in the North Branch Potomac River mainstem Data from 2000 – 2017. Box and whiskers show the 5th, 25th, median, 75th, and 95th percentiles. All concentrations were above 5 mg/liter, the Maryland and West Virginia water quality criteria.

3.3.6 Turbidity

Turbidity is often measured as the intensity of light deflected 90° as the beam passes through a water sample. The reported value is obtained after subtracting the deflected beam intensity for a standard reference (typically a filtered "blank"). The reported value indicates the amount of light scattered by the sample's particulate matter. Readings vary depending on light source (wavelength), light beam angle, and other factors (see https://or.water.usgs.gov/grapher/fnu.html). The amount of light absorbed by sample water is assumed to be minimal; however, true color, that is the color of water which is due to dissolved substances that absorb light, will cause turbidity readings to be lower than they would be otherwise (USEPA 1993). We limited our analysis to readings taken in the field and expressed as NTUs, which are made with white light (400 – 800 nm) and a nephelometer. These values comprised the majority of records downloaded from the WQP or obtained from WVDEP. Maryland and West Virginia have discharge criteria but no instream standards for turbidity, so a value of 50 NTUs was used as a threshold for evaluation purposes.

Pair-wise comparisons of mainstem measurements above JRL at Kitzmiller and below JRL at Bloomington on the same date show turbidity at Kitzmiller is more often higher than Bloomington (Figure 35 A). Between 2000 and 2017, median concentrations were 2.0 NTU at Kitzmiller and 1.7 NTU at Bloomington (Table 10). The lake appears to be a weak sink for particles, reducing turbidity by roughly 15%. Mainstem turbidity concentrations are lowest at Bloomington and then rise sharply as the river passes Luke and Westernport. Pair-wise comparisons of turbidities at Bloomington and Keyser/McCoole, show turbidity at Keyser/McCoole is almost always much higher (Figure 35 B) and the median increases 3.8-fold (276%) from 1.7 to 6.4 NTU (Table 10). The change, which occurs over 7.5 miles, suggests a large influx of turbidity to the mainstem below Bloomington and before the river reaches Keyser/McCoole. Mainstem turbidities gradually fall as NBPR flows from Keyser/McCoole past Pinto MD and Moores Hollow Rd. At Oldtown MD, the median turbidity is 3.5 NTU.

Hypothetical sources of turbidity to the mainstem between Bloomington and Keyser/McCoole include the Savage River tributary, the Georges Creek tributary, and effluent or runoff from various industries and the municipalities along this stretch of the mainstem. Figure 36 shows pair-wise comparisons of the NBPR mainstem at Keyser/McCoole with Savage River and with Georges Creek. Turbidity readings at the mouth of Savage River (MDDNR site SAV0000) are almost always significantly lower than those at Keyser/McCoole. Given that the Savage River flow is roughly 28% of NBPR mainstem flow, Savage inputs will almost always dilute the mainstem turbidity concentration to some degree and not increase it (Figure 36 A). Readings near the mouth of Georges Creek (MDDNR site GEO0009, USGS site 0159900) are somewhat higher than at Keyser/McCoole 5.5 miles downstream, so this tributary is a possible source of turbidity to the mainstem (Figure 36 B). It is not the sole source, however, because flow from Georges Creek is only about a tenth of that in the mainstem at Keyser/McCoole. Another source is the Westernport Wastewater Treatment Plant (WWTP). Operated by the Upper Potomac River Commission (UPRC), the plan processes municipal waste from surrounding towns. It also processed industrial waste from Verso Luke Mill until the mill's recent closure in June 2019. The WWTP discharges to the NBPR mainstem (Figure 37), and its Maryland discharge permit (05DP0230) allows a daily turbidity maximum of 300 NTU and monthly average of 150 NTU. These levels are significantly higher than the usual Maryland discharge standards which says discharges "may not exceed 150 units [NTU] at any time or 50 units [NTU] as a monthly average" (COMAR §26.08.02). Kaolin clays[1] used at the paper mill were a likely

[1] A white fine silicate clay with the chemical composition $Al_2Si_2O5(OH)_4$ that can be colored orange-red by iron oxide. At the paper mill, kaolin is applied as a coating to create paper with different levels of gloss.

contributor to turbidity discharged by the Westernport WWTP. Other sources of turbidity could have included direct discharges from the Verso Luke Mill (state discharge permit 05DP0300) and unregulated runoff from the CSX rail line and industrial activities on the Maryland or West Virginia riverbanks.

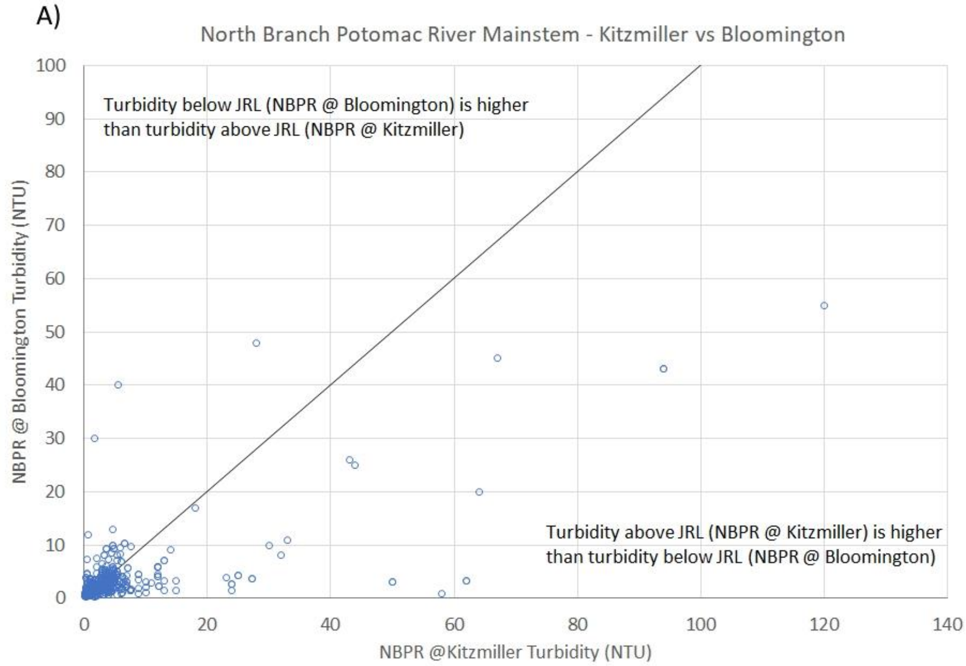
In the streams and small rivers of NBPR subwatersheds, instream turbidity values in the 2000 – 2017 period varied more than in the mainstem, with levels ranging well over the maximum concentrations in the mainstem (Table 10). The Georges subwatershed has the highest median concentrations, but all tributaries experience instances of very high turbidity. A cursory examination of where these high values occur show that they are mostly associated with areas disturbed by historic or active mining operations.

Table 10. Turbidity (NTU) six North Branch Potomac River mainstem locations, tributary mouths, and subwatersheds, 2000 – 2017

*Some stations in the subwatersheds are sampled more often or at different times than others. % 50+, percent of samples greater than or equal to 50 NTU; ND, little or no data; *, below detection limit*

Stations/groups	n	Median	Range	% 50+
NBPR Mainstem Stations				
Kitzmiller	*211*	2.0	(0.2 – 94)	1.4%
Bloomington	*211*	1.7	(0.3 – 43)	0.0%
Keyser/McCoole	*207*	6.4	(1.8 – 139)	1.0%
Pinto	*212*	5.2	(1.1 – 144)	1.9%
Moores Hollow Rd	*210*	3.4	(0.9 – 203)	1.9%
Oldtown	*165*	3.5	(1.0 – 174)	1.8%
Tributary Mouths				
Savage@Bloomington	*222*	1.7	(0.3 – 750)	1.5%
Georges@Westernport	*240*	11.0	(0.4 – 377)	8.3%
New@Keyser	*ND*			
Wills@Cumberland	*209*	2.2	(0.1 – 456)	3.3%
Patterson@NBPR	*ND*			
Subwatersheds				
Upstream	*232*	4.6	(* – 536)	1.7%
Savage River	*430*	4.7	(* - 300)	4.0%
Georges Creek	*249*	8.1	(* - 711)	8.8%
New Creek	*ND*			
Patterson Creek	*39*	3.7	(0.9 – 230)	7.7%
Downstream	*779*	4.2	(* - 864)	3.5%

A)



B)

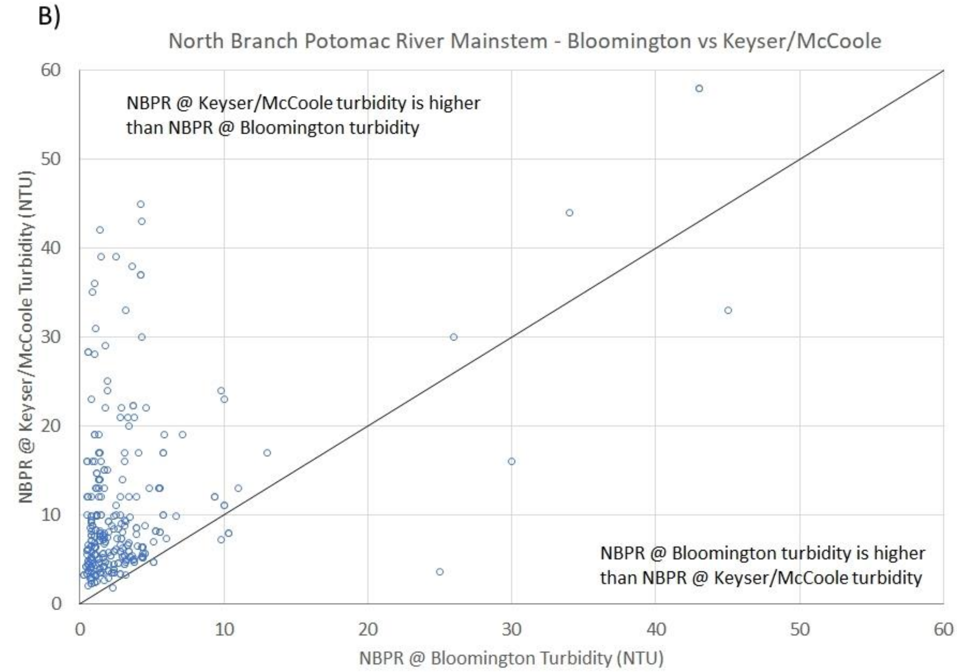
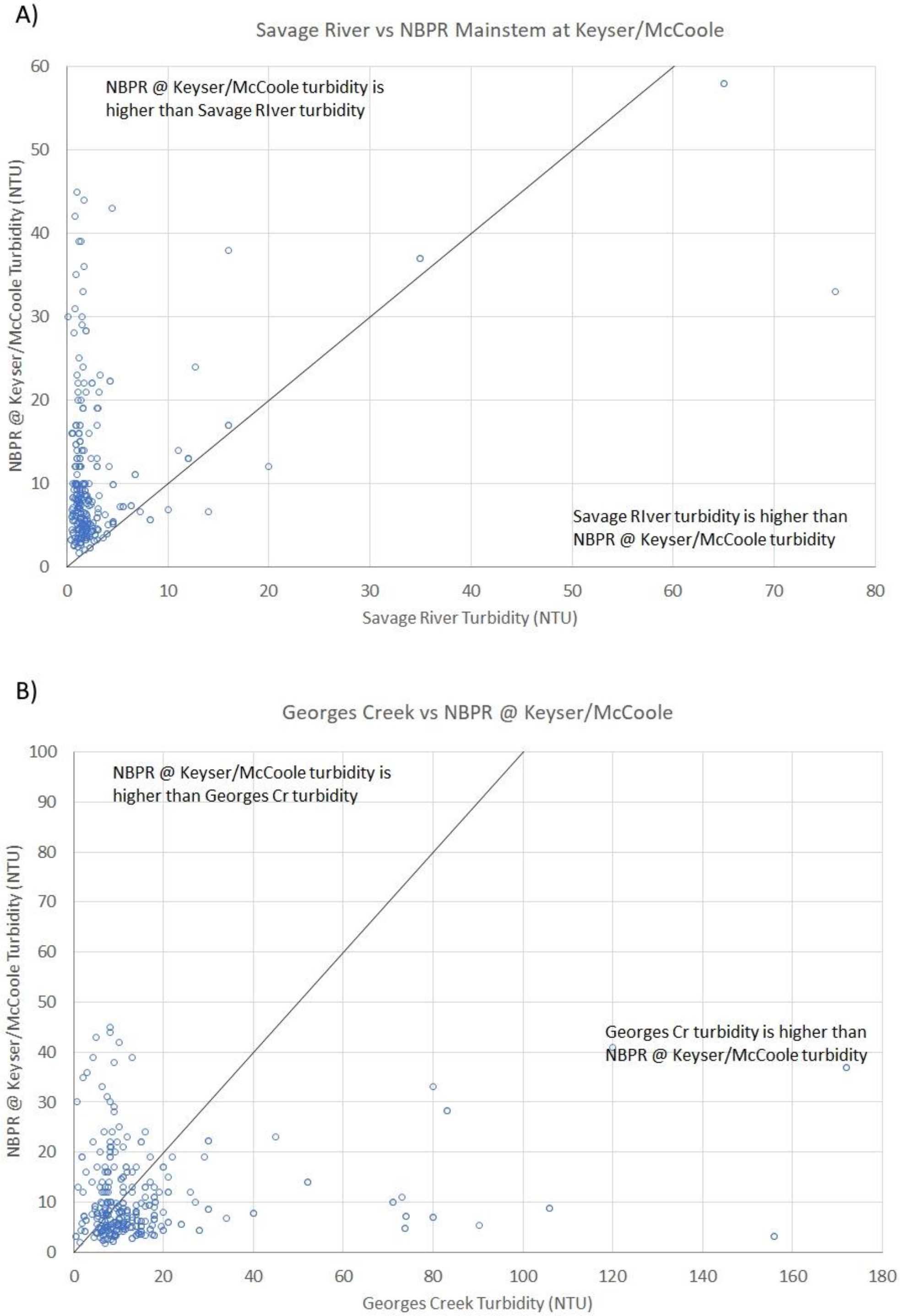


Figure 35. Pair-wise comparisons of turbidity in the North Branch Potomac River mainstem: A) Kitzmiller (above Jennings Randolph Lake) vs Bloomington (below lake) and B) Bloomington vs Keyser McCoole

Solid line: 1-to-1 relationship if data show no difference.

A)



B)

Figure 36. Pair-wise comparisons of turbidity in the North Branch Potomac River mainstem versus A) Savage River and B) Georges Creek near their confluences with the mainstem
Solid line: 1-to-1 relationship if data show no difference.

Figure 37. Effluent from Westernport waste water treatment plant
Left: photo by Dave Harp (obtained from [Bay Journal 2016 article] by Rona Kobell "Cloud lingers over MD paper mill's impact on Potomac.") Right: Google map satellite image of Westernport wastewater treatment plant operated by the Upper Potomac River Commission which processes Verso Luke Mill and municipal waste. Arrow indicates river discharge points (latitude 39.478560, longitude -79.039992).

3.3.7 Total Suspended Solids

Total suspended solids (TSS) is a direct measure of the amount of particles suspended in the water. It is the residue collected on a glass filter after a known sample volume passes through the filter and it consists of both organic and inorganic particles greater than about 1 or 2 microns, the usual pore size of the filter. TSS results are typically like those for turbidity, which is an indirect measure of suspended particles, but the relationship is not as close as the one between SpCond and TDS. Maryland and West Virginia have discharge criteria but no instream standards specific to TSS, so a background concentration of 27 mg/liter calculated from the NBPR data (see below) was used to evaluate TSS.

TSS measurements in the Upstream subwatershed and the NBPR mainstem above Kitzmiller were not collected consistently over time and space during the 2000 – 2017 period. Concentrations were highly variable, ranging from 0.5 – 1,073 mg/liter. By the time Upstream flows reached Kitzmiller, where NBPR enters JRL, the median concentration was 4.0 and had a range of 0.2 – 126 mg/liter (Table 11). Pair-wise comparisons of TSS entering JRL at Kitzmiller and downstream of JRL at Barnum/Bloomington show TSS concentrations tend to be lower immediately below JRL. Passage through JRL reduces TSS an average 25% and distributions of the values were significantly different (Mann-Whitney, $p < 0.001$). This complements the finding above that turbidity drops 15% after passage through JRL.

TSS concentrations show a large and significant increase as NBPR flows by Luke and Westernport/ Piedmont to Keyser/McCoole (Mann-Whitney, $p < 0.001$). Median concentrations jump 67% over the course of 7.5 miles, from 3.6 to 6.0 mg/liter. The range of values at Barnum/Bloomington was 0.3 – 42 mg/liter while the range at Keyser/McCoole was considerably larger at 1.2 – 230 mg/liter. The source of this TSS is not Savage River, which had a median TSS concentrations 3.2 mg/liter near its mouth (MDDNR SAV000). The median TSS concentration at Georges Creek mouth (MDDNR GEO0000, GEO0009) in Westernport MD, was 16 mg/liter, or 2.7-fold higher than Keyser/McCoole, and thus this tributary is a likely source. However, flow from Georges Creek comprises only about a tenth of the flow at

Keyser/McCoole, so it cannot be solely responsible for the TSS increase in this stretch of the river. Like turbidity, the TSS results indicate a large source of suspended particulates to the NBPR mainstem between Barnum/Bloomington and Keyser/McCoole that is not from a tributary. Median TSS concentrations in the NBPR mainstem below Keyser/McCoole, at Pinto, Moores Hollow Rd, and Oldtown were relatively stable at 6.0 mg/liter and had similar ranges (Table 11).

TSS concentrations in streams and small rivers of the Savage subwatershed were the lowest of all NBPR subwatersheds (Table 11). In lieu of state water quality criteria for TSS, the 95th percentile of values in the minimally disturbed Savage subwatershed, i.e., 27 mg/liter, was used as an upper threshold for background TSS concentrations in the NBPR watershed. The Downstream subwatershed also had an overall low median TSS concentration but experienced a larger range of values. Braddock Run at Rt 40 and Wills Creek in Cumberland, both of which are near the confluence with NBPR, were primarily responsible for the higher values. Of the remaining four subwatersheds – Upstream, Georges, New, and Patterson – all had higher medians and New had the fewest instances of exceeding the proposed 27 mg/liter background concentration.

Table 11. Total suspended solids (TSS, mg/liter) six North Branch Potomac River mainstem locations, major tributary mouths, and subwatersheds, 2000 – 2017
*Some stations in the subwatersheds are sampled more often or at different times than others. % 27+ mg/liter indicates the percent of values greater than 27 mg/liter (background); *, excludes tributary mouth stations; **, one value of 1,000 mg/liter removed as outlier.*

Stations/groups	n	Median	Range	% 27+ mg/liter
NBPR Mainstem Stations				
Kitzmiller	*219*	4.0	(0.2 – 126)	4.6%
Barnum/Bloomington	*220*	3.6	(0.5 – 42)	0.5%
Keyser/McCoole	*219*	6.0	(1.2 – 230)	5.0%
Pinto	*221*	6.0	(0.8 – 202)	4.5%
Moores Hollow Rd	*208*	6.0	(0.7 – 240)	5.3%
Oldtown	*167*	6.0	(0.5 – 204)	7.8%
Tributary Mouths				
Savage@Bloomington	*227*	3.2	(0.3 – 111**)	3.1%
Georges@Westernport	*512*	16.0	(0.8 – 1,104)	27.0%
New@Keyser	*28*	3.4	(0.3 – 79)	7.1%
Wills@Cumberland	*399*	5.5	(0.6 – 755)	17.3%
Patterson@NBPR	*55*	2.6	(0.4 – 55)	4.8%
Subwatersheds*				
Upstream	*460*	6.0	(0.5 – 1,073)	6.1%
Savage River	*177*	2.8	(0.3 – 167)	5.0%
Georges Creek	*160*	7.0	(0.3 – 117)	15.6%
New Creek	*39*	6.5	(2 – 28)	2.6%
Patterson Creek	*255*	15.0	(2 – 254)	13.7%
Downstream	*756*	4.4	(0.3 – 604)	6.5%

3.3.8 Total Alkalinity

Alkalinity is the ability of water to buffer, or neutralize, changes in hydrogen (H^+) ion concentration. It is expressed as mg/liter of calcium carbonate ($CaCO_3$) even though buffering can be accomplished by other dissociated anions such as phosphate, silicate, borate, hydroxide, and dissolved ammonia. Alkalinity anions are technically a component of TDS and their natural sources are weathering of rocks and soils. Neither Maryland nor West Virginia have alkalinity criteria; however, alkalinities greater than 20 mg $CaCO_3$/liter are generally thought to provide enough buffering to maintain stable pH levels and protect aquatic life. River water typically contains 100 – 250 mg $CaCO_3$/liter of alkalinity (Wetzel 2001).

Of the alkalinity records extracted from the WQP, 124 had values of 0.0 mg $CaCO_3$/liter and no recorded detection limits. We included them in the analysis despite the likelihood that their actual values were above zero. Another 72 had a detection limit (usually 1 mg $CaCO_3$/liter) but no measured value so we used half their given detection limit as the estimated value. All of the zero and half detection limit values occurred before the year 2000.

Alkalinity has not been consistently collected over time or space in the NBPR watershed. Despite the data gaps, the results show concentrations trending upward everywhere in the watershed since the early 1980s, except in the Savage River subwatershed which has maintained low but slowly increasing levels since at least 1985 (Figures 38 – 41). Presently, the Downstream subwatershed has the highest concentrations overall (Figure 41).

In the NBPR mainstem during 2000 - 2017, median concentrations of alkalinity were 26 mg $CaCO_3$/liter at Kitzmiller above JRL and 19 mg $CaCO_3$/liter below JRL at Bloomington (Table 12). The percent of values greater than 20 mg $CaCO_3$/liter also dropped from 69.0% at Kitzmiller to 41.2% at Bloomington, indicating a loss of buffering capacity. The lake appears to allow precipitates of carbonate and the other bases to settle and become trapped after entering the lake. Further downstream, in the short distance between Bloomington and Keyser/McCoole, median concentrations increase 2.2-fold and then continue rising more slowly as the mainstem flows passed Pinto, Moores Hollow Rd and Oldtown. Percentages of concentrations above 20 mg $CaCO_3$/liter are very high between Keyser/McCoole and Oldtown. Overall the mainstem below Keyser/McCoole is well buffered against pH swings.

Table 12. Total alkalinity (mg $CaCO_3$/liter) at six North Branch Potomac River mainstem locations, tributary mouths, and subwatersheds, 2000 – 2017

*Values greater than 20 mg $CaCO_3$/liter are considered sufficient to neutralize increases in hydrogen (H^+) ion concentrations. Some stations in the subwatersheds are sampled more often or at different times than others. ND, less than 10 data points; *, excludes tributary mouth stations.*

Stations/groups	n	Median	Range	% Greater Than 20 mg $CaCO_3$/liter
Mainstem Stations				
Kitzmiller	*210*	26	(9 – 69)	69.0%
Bloomington	*211*	19	(8 – 46)	41.2%
Keyser/McCoole	*208*	41	(18 – 78)	95.7%
Pinto	*212*	46	(19 – 79)	99.5%
Moores Hollow Rd	*209*	55	(4 – 86)	99.0%
Oldtown	*165*	55	(26 – 87)	100.0%
Tributary Mouths				
Savage@Bloomington	*211*	14	(3.5 – 35)	17.1%
Georges@Westernport	*213*	40	(0.8 – 203)	95.8%
New@Keyser	*ND*			
Wills@Cumberland	*208*	38	(14 – 157)	87.5%
Patterson@NBPR	*ND*			
Subwatersheds*				
Upstream	*305*	8	(1 – 796)	23.6%
Savage	*11*	17	(4 – 52)	27.3%
Georges	*ND*			
New	*15*	49	(7 – 167)	66.7%
Downstream	*509*	61	(5 – 252)	84.7%
Patterson	*59*	77	(14 – 138)	91.5%

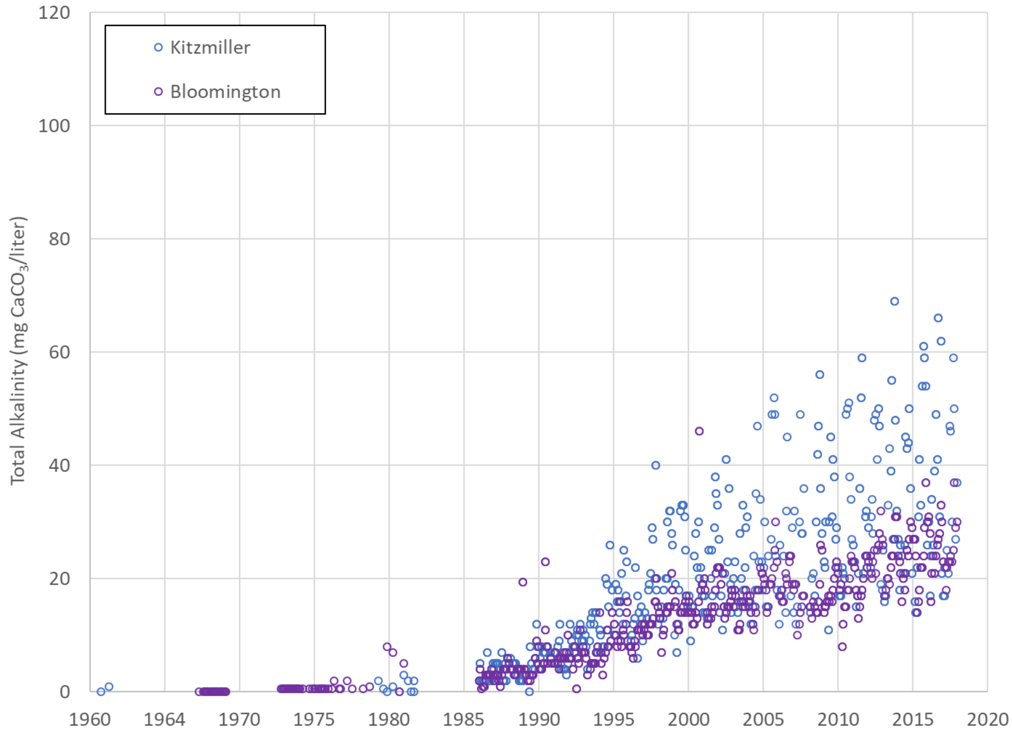


Figure 38. Time series of total alkalinity at Kitzmiller and Bloomington on NBPR mainstem

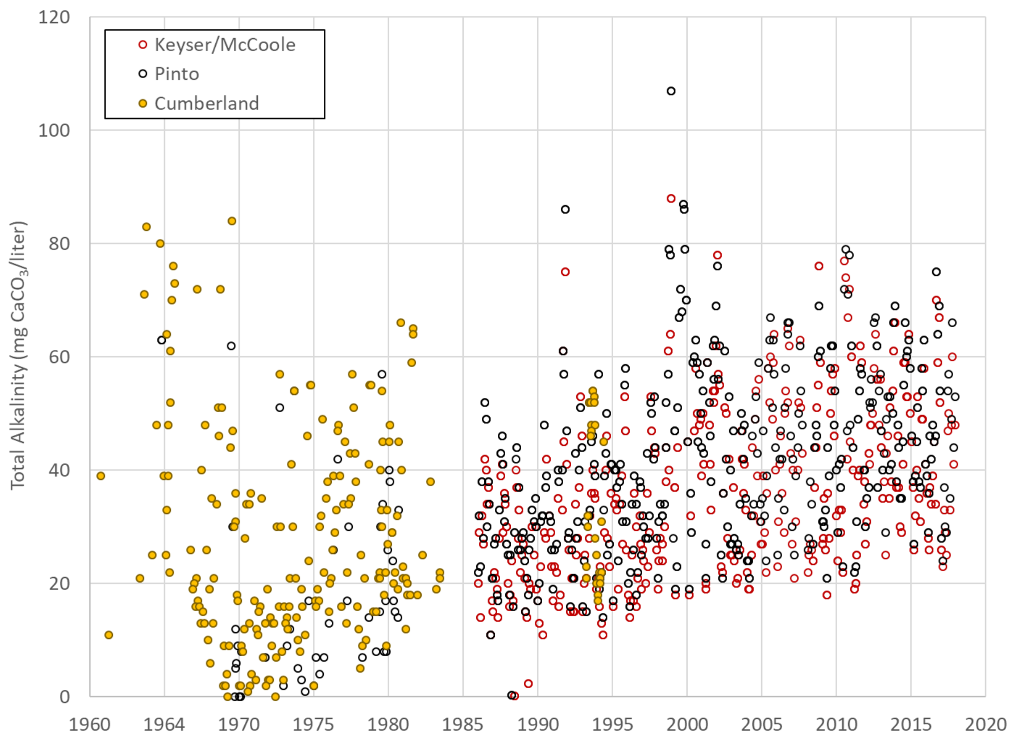


Figure 39. Time series of total alkalinity at Keyser/McCoole, Pinto, and Cumberland on NBPR mainstem

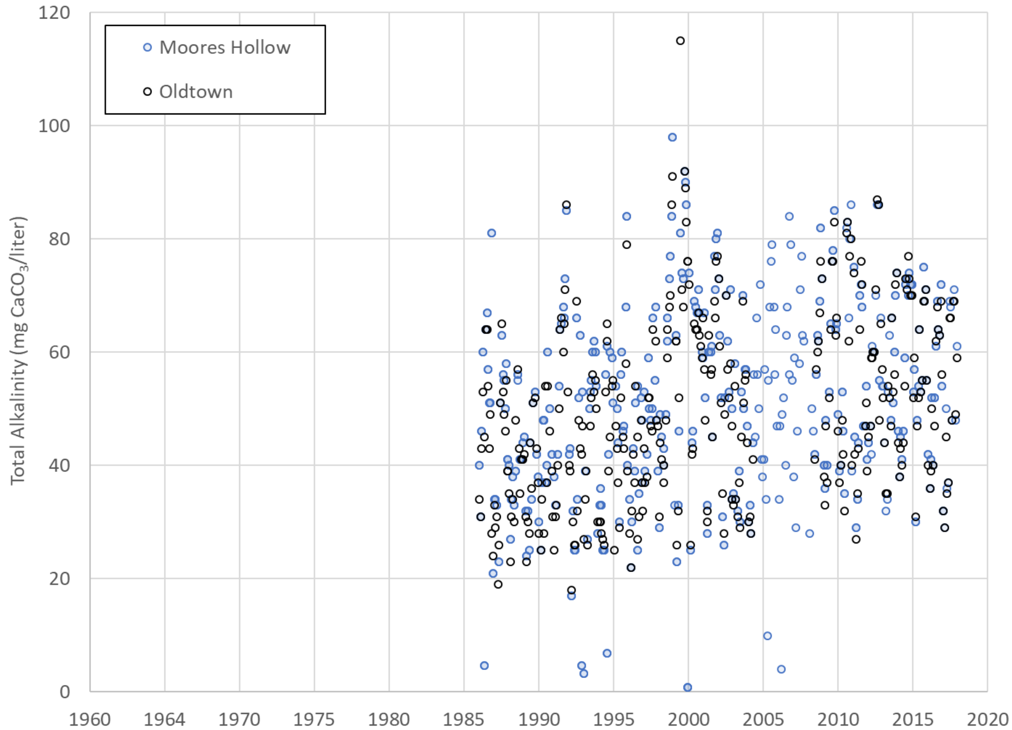


Figure 40. Time series of total alkalinity at Moores Hollow Rd and Oldtown on NBPR mainstem

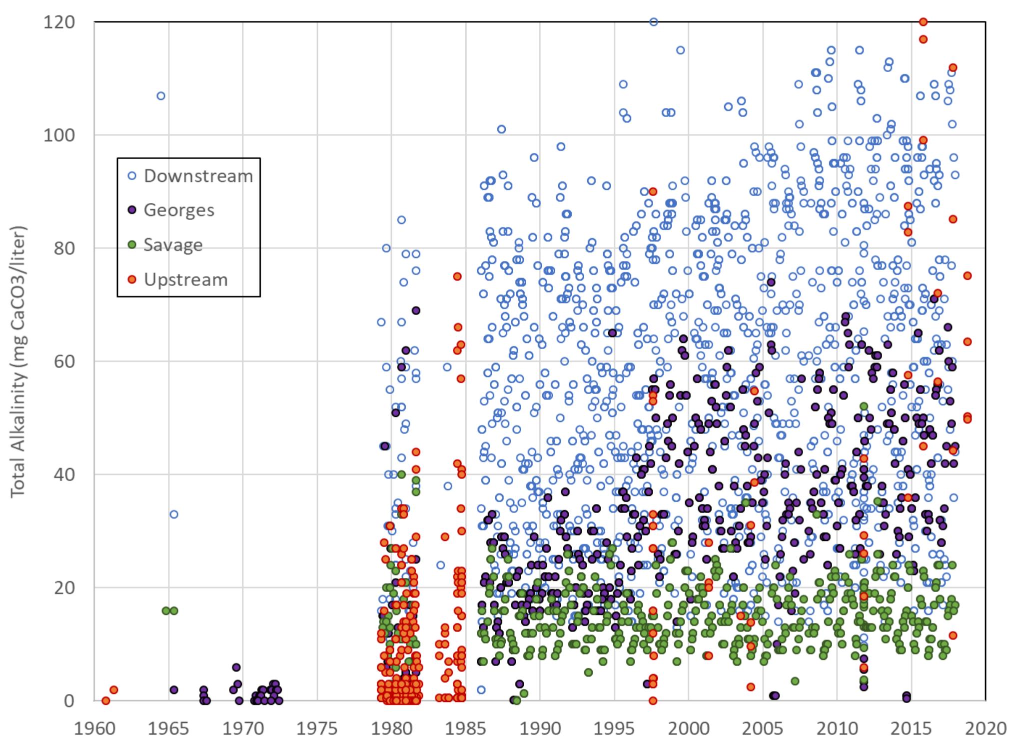


Figure 41. Time series of total alkalinity in NBPR's Downstream, Georges, Savage, and Upstream subwatersheds

3.3.9 Other Parameters

Data for nitrogen, phosphorus, metals, hardness, and other water quality parameters are available, but analysis of these data was outside the scope of this study. Maryland's 1-P designated use has criteria for these parameters and meeting Maryland's 1-P criteria in the NBPR mainstem is a stated goal in the JRL Water Control Plan (e.g., USACE 1997b 7-08 d (3)). An analysis of the influence of JRL operations on these parameters in the lower NBPR mainstem is warranted. Nutrients concentrations and trends in the NBPR watershed should also be considered now in light of the Chesapeake Bay nutrient and sediment Total Maximum Daily Load (TMDL) plans.

3.4 River and Stream Sediments

3.4.1 River Mainstem

During late summer months, the NBPR mainstem can experience conditions where water levels are low, flows are slow, and air temperature is high. Discharged organic solids that settle on the NBPR riverbed are believed capable of smothering fish eggs and lowering bottom DO to levels that harm macroinvertebrate communities. To prevent sedimentation and DO "dead zones" from occurring in the mainstem, USACE schedules two AVF releases a year in summer. The targeted duration, frequency, and intensity of AVFs are thought to remove accumulated organic solids.

The effectiveness of AVFs in flushing settled organic solids downstream has been anecdotally confirmed by operators of JRL and SRR. However, we are not aware of actual measurements that characterize physical habitat along the length of the NBPR mainstem below JRL. There is no information that establishes a relationship between AVFs, sediment transport, and bottom conditions. During the 2000 – 2017 period, dissolved oxygen measurements in the water column of the NBPR mainstem indicate there was no problem maintaining Maryland and West Virginia water quality standards (Figure 34). This result suggests but doesn't confirm the river bottom has adequate DO.

Closure of the Verso paper mill at Luke in June 2019 should significantly reduce industrial loads of organic solids to the NBPR mainstem. This assumes the plant is not reopened as another paper mill applying the same chemical processes to produce paper. Over time, the section of the NBPR mainstem most likely to be impacted by settled organic solids should recover as the solids decompose or storms flush them downstream.

3.4.2 Streams

Erosional processes move sediments into NBPR streams where they are transported downstream to the mainstem and eventually to the Potomac estuary. Habitat scores reflecting instream erosion potential and sediment content have been recorded in the NBPR watershed by stream monitoring programs since 1993. Most monitoring sites were selected randomly. Maryland and West Virginia scores were obtained from the Chesapeake Basin-wide Index of Biotic Integrity (Chessie BIBI) database compiled from multiple federal, state, county and citizen monitoring datasets (ICPRB 2017). Habitat scores are reported on the 0 – 20 scale as defined by Barbour et al. (1999): 16 – 20 is optimal; 11 – 15 is suboptimal but still acceptable; 6 – 10 is marginal; and 0 – 5 is poor. (Note: The individual monitoring programs have tweaked their definitions of some habitat parameters over the years, but we assumed the score values were still comparable.) We examined five sediment-related habitat metrics that are commonly collected. Bank stability measures the amount of actual or potential stream bank erosion (n = 285). Channel alteration indicates the degree of large-scale human-related changes in the stream channel shape (n = 254). Embeddedness is the relative extent to which gravel, cobble, boulders, and snags are covered or sunken into silt, sand or mud on the stream bottom (n = 322). The riparian vegetation score indicates the amount of vegetation in the near-stream portion of the riparian zone that helps minimize bank erosion (n = 291). Epifaunal substrate is the relative quantity and variety of natural structures (e.g., cobble, large rocks, fallen trees, logs and branches, undercut banks) that are available as refugia, feeding, or spawning and nursery sites (n = 285). Ninety-two percent of sites had scores for three or more of these five metrics.

While each subwatershed experienced a wide range of scores, the means of the individual sediment-related metrics in each subwatershed were either suboptimal or optimal with the exception of a marginal riparian vegetation score in Patterson (Table 13). Most subwatersheds have a substantially higher percentages of optimal scores compared to poor scores. Savage River subwatershed has the highest overall mean score and the large percentages of optimal scores for bank stability, embeddedness, riparian vegetation score, and epifaunal substrate. It has no scores classifying as poor. The New and Upstream streams have slightly lower overall mean scores, followed by the Downstream and Patterson streams. Georges subwatershed had too few sites to calculate meaningful statistics. The high scores for embeddedness and epifaunal substrate in the Savage, Upstream, and New subwatersheds suggest sediment loads from these subwatersheds are lower than those from the Patterson and Downstream subwatersheds. Some results for Georges Creek are surprisingly high considering its water quality conditions. This may be due to the low sample numbers for that subwatershed, but it suggests the watershed's streams warrant more sampling.

For Maryland and West Virginia's portions of the NBPR watershed, the average score is 15.5 for bank stability and 15.2 for channel alteration – or approaching optimal. The average score is 14.2 for epifaunal substrate, 13.4 for embeddedness, and 13.3 for riparian vegetation score – or solidly suboptimal. These results should be considered encouraging as they indicate a significant amount of recovery from 20th century sedimentation due to logging, strip mining practices, and AMD. The somewhat lower scores for epifaunal substrate and embeddedness demonstrate that some streams still contain legacy sediments or experience high rates of erosion. The average of these two metrics scored as optimal at only 27% of sites, which suggests sedimentation is an issue at some level in roughly three-quarters of NBPR streams. The lower riparian vegetation scores, especially in Patterson, New and Downstream, suggest a greater loss of riparian protections for streams in these subwatersheds.

Table 13. Sediment-related habitat metric scores in the North Branch Potomac River subwatersheds.
See text for descriptions of habitat metrics and Figure 5 for map of subwatersheds. % sub+marg, percent of suboptimal and marginal scores. The overall mean is calculated from the means of all available sediment-related habitat scores at individual sites. *Too few data to calculate meaningful percentages.

Subwatershed	Statistic	Bank Stability	Channel Alteration	Embedded-ness	Riparian Vegetation Score	Epifaunal Substrate	Overall Mean
Downstream	maximum	20	20	20	20	19	
	minimum	2	5	1	0	3	
	% optimal	43.5%	20.9%	13.1%	56.9%	25.9%	
	% sub+marg	54.3%	72.1%	83.6%	20.7%	70.7%	
	% poor	2.2%	7.0%	3.3%	22.4%	3.4%	
	mean	15.4	13.5	13.3	13.7	12.3	13.6
	count	46	43	61	58	58	
Georges	maximum	20	20	20	20	18	
	minimum	15	10	2	4	3	
	% optimal	*	*	*	*	*	
	% sub+marg	*	*	*	*	*	
	% poor	*	*	*	*	*	
	mean	19.0	14.7	12.2	18.0	11.9	14.8
	count	10	10	13	13	13	
New	maximum	20	20	20	20	20	
	minimum	7	3	1	2	4	
	% optimal	52.8%	55.2%	35.9%	37.1%	46.9%	
	% sub+marg	47.2%	41.4%	59.0%	37.2%	50.0%	
	% poor	0.0%	3.4%	5.1%	25.7%	3.1%	
	mean	15.6	15.8	13.7	11.9	14.8	14.3
	count	36	29	39	35	32	
Patterson	maximum	19	20	19	19	18	
	minimum	4	7	3	2	4	
	% optimal	41.1%	55.4%	8.4%	13.9%	25.7%	
	% sub+marg	56.8%	44.6%	90.5%	67.1%	71.6%	
	% poor	2.1%	0.0%	1.1%	19.0%	2.7%	
	mean	14.5	15.4	12.5	9.6	13.1	13.0
	count	95	74	95	79	74	
Savage	maximum	20	20	19.5	20	20	
	minimum	9	10	10	7	8	
	% optimal	60.0%	28.0%	73.5%	96.7%	79.4%	
	% sub+marg	40.0%	72.0%	26.5%	3.3%	20.6%	
	% poor	0.0%	0.0%	0.0%	0.0%	0.0%	
	mean	16.8	14.3	16.4	19.4	16.9	17.0
	count	25	25	34	30	34	
Upstream	maximum	20	20	19	20	19	
	minimum	2	5	4	0	6	
	% optimal	58.9%	56.2%	33.8%	51.4%	61.0%	
	% sub+marg	38.4%	42.4%	62.3%	40.0%	39.0%	
	% poor	2.7%	1.4%	3.9%	8.6%	0.0%	
	mean	15.7	15.9	13.1	14.3	15.3	14.8
	count	73	73	77	70	77	

4 Discussion

Analyses of USGS streamflow gage measurements in the NBPR watershed confirm the substantial effects of JRL operations on mainstem flows below JRL. The effects are strongly evident at the Barnum and Luke stream gages. During high flow events, the dam reduces and delays the rise of water level in the mainstem downstream of the dam and substantially reduces peak levels. During low flow periods, releases from the dam increase the baseflow and annual minimum levels downstream. The evidence of flow regulation weakens with distance downstream as watershed size increases and tributary flows enter the mainstem.

Flooding along the 100-mile NBPR mainstem is difficult to control due to the river valley's steep sides and narrow floodplains. During the 2004 – 2018 water years (10/1/2003 – 9/30/2018), coordinated JRL and SRR dam operations successfully prevented water levels from exceeding the NWS flood stage of 10.5 ft at the Luke gage located on the NBPR mainstem about 8 miles below JRL. Figure 2 shows JRL operations reduce annual 1-day and 3-day maximum flow rates below JRL and this may equate to fewer instances of the mainstem flooding along most of the lower mainstem. Towns downstream of the lake, however, were not necessarily protected. Flood stage at the Georges Creek gage in the town of Westernport, MD (8 ft) was exceeded on eleven dates. Georges Creek flows through Westernport before entering the NBPR about 10 miles below JRL. Similarly, news reports document flooding in Keyser, WV and much of that flooding is attributed to New Creek. New Creek passes through Keyser before entering the NBPR 15 miles below JRL. Wills Creek, which passes through downtown Cumberland, MD before joining the NBPR, is estimated to have exceeded flood stage (10 ft) on 15 dates in water years 2004 - 2018. JRL and SRR operations can prevent flooding in the 8 mile river reach from JRL to Luke and we suspect they significantly alleviate flooding on NBPR-facing riverbanks near McCoole, MD and Keyser, WV. However, the influence of JRL and SRR flood mitigation efforts is lost by the time the river reaches the gage near Cumberland, located in the NBPR mainstem approximately 41 miles downstream of JRL. Flood stage at this gage (17 ft) was exceeded an estimated seven times in water years 2004 – 2018.

Augmenting, or increasing, flows with the JRL's selective withdrawal system is intended to improve four features of the water quality in the lower NBPR mainstem when natural flows are low: pH, temperature, pollutant concentrations, and settled organic solids (USACE 1997b, 7-08). A relatively large volume of JRL's conservation pool (55.44%) is allocated for improving downstream water quality. The long, deep JRL reservoir is also intended to serve as a sink for precipitates of AMD contaminants and heavy metals. The current Master Manual for Reservoir Regulation says JRL operators are supposed to "use as much of the available water quality storage as needed every year to produce the greatest possible improvement in water quality, both in-lake and downstream" (USACE 1997b 7-08). Except for two days in November 2010, coordinated JRL and SRR dam operations successfully maintain flows at Luke that were greater than the prescribed 120 cfs minimum. The following discussion evaluates the role of JRL's low-flow augmentation strategies in raising pH, cooling summer water temperatures, diluting pollutants, and flushing organic solids.

4.1 pH

pH values have increased significantly throughout the NBPR watershed since the mid-20th century. pH values in the Upstream subwatershed still do not meet the Maryland and West Virginia criteria of 6.5 all the time, but the overall trend is upward. The Savage, Georges, Downstream, New and Patterson subwatersheds have all maintained pH values between 6.5 and 8.5 since 1995 except in a few locations. In the NBPR mainstem before it enters JRL at Kitzmiller and for its entire length below JRL, pH values have stayed between 6.5 and 8.5 with very few exceptions since 1995.

JRL operations played little if any role in the NBPR watershed's pH improvements. Some of the improvement can be attributed to reductions in acid deposition (acid rain), a result of the Clean Air Act of 1970 and subsequent regulation. The upward pH trends apparent in the Savage, Patterson, and New subwatersheds, exclusive of their known hotspots, are examples of areas that probably benefited from reductions in acid precipitation. pH improvements elsewhere in the watershed are due in part to lime dosers installed in acid-impacted streams, other acid mine drainage remediation efforts, and enactment of the federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Hansen et al. 2010). The higher pH levels in recovered waters tend to encourage precipitation of toxic metal pollutants such as copper, zinc, cadmium, iron, and aluminum out of the water column, further improving aquatic habitat conditions. There are still acid-impacted mining sites, both abandoned and active, in the watershed but pH trends should continue to improve and stabilize if Maryland and West Virginia enforce mining and acid rain regulations and support acid mine drainage remediation.

Section 7-08 d 3 (a) in Appendix A of the Master Manual for Reservoir Regulation (USACE 1997b) lists four operational approaches for JRL to control downstream pH: 1) store low pH waters entering JRL as long as possible and release them when high flows and higher pH are occurring downstream; 2) if the lake is chemically stratified, release a blended outflow from different lake depths using the dam's the selective withdrawal system; 3) increase outflow rates when acid slugs develop in the downstream reach of NBPR; and 4) regulate JRL in conjunction with SRR to achieve water quality standards and flow targets at Luke. These operational guidelines should be reevaluated. Contrary to scenarios expressed as recently as 2019 (e.g., JG&A 2019), JRL flow regulation does not eliminate extreme variations in pH and acidity. pH at Kitzmiller above JRL and at Barnum/Bloomington below JRL have closely tracked each other since at least 1986 and their regression approximates the 1:1 line. The analysis indicates JRL and its operations do not increase pH as water travels through and out the lake. Lake operations in fact appear to slightly reduce pH from a median of 7.6 above JRL at Kitzmiller to a median of 7.4 below JRL at Barnum/Bloomington during the 2000 – 2017 period. The lake is not capable of buffering against low pH and the purported need to use JRL to improve downstream pH is weak at best.

4.2 Temperature

JRL's natural thermal stratification has allowed dam operators to modify downstream temperatures using the dam's selective withdrawal system to release blended outflows from different JRL depths. Dam operations have been highly successful in meeting Maryland's trout stocking guidelines of 4 – 20 ^{o}C in the NBPR mainstem immediately downstream of JRL. The result after about the mid-1990s has been cooler waters in summer and warmer waters in winter. Diminishing traces of the cold water releases in summer are seen as far downstream as Keyser/McCoole and sometimes beyond. The drop of as much as 5^{o}C during summer and the higher temperatures in winter has increased the proportion of time the river mainstem meets optimal temperatures for trout. The effect is augmented by Savage River releases which typically meet the guidelines throughout summer. The likely outcome of the cooler summer and warmer winter temperatures is longer periods of active feeding and growth in the fish in a larger reach of the NBPR mainstem, which ultimately encourages and supports survival and reproduction.

Elsewhere in the NBPR watershed summer temperatures meet the Maryland trout stocking guidelines to varying degrees. Routine monitoring data show that, since 1996, the recommended 4 – 20 ^{o}C range was attained between 79% and 100% of the time in four of five NBPR subwatersheds in April, May, June, September, and October (there is insufficient data for the New, the sixth subwatershed). The exception was Patterson. In the Upstream, Savage, Georges, and Downstream subwatersheds, summer attainment rates were lowest in July or August but still met the guidelines more than half the time. Results of the high frequency temperature readings from nine loggers deployed in 2013 and 2014 support these findings. The logger data show the NBPR mainstem above JRL at Kitzmiller met the 4 – 20 ^{o}C guideline infrequently in June, July, and August (< 15%) whereas 1st, 2nd and even 3rd order streams across the NBPR watershed met them more often (41.9% - 100%). The frequent occurrence of temperatures meeting trout stocking guidelines in the subwatersheds indicates NBPR tributaries, and especially Savage River, offer summer-time temperature refugia for trout and other cold-water taxa. In the smaller tributaries, contributions of groundwater to surface flow would be proportionally larger and would have a cooling effect on stream temperatures in summer and a warming effect in winter. The amount of forest cover also appears to influence summer temperature attainment rates.

We hypothesize that some of the success in native and stocked trout species in the NBPR watershed can be attributed to better thermal connectivity in summer. During summer, cold-water fish are normally forced by warmer mainstem temperatures to retreat upstream to temperature refugia in small tributaries where their ability to move and avoid other stressors is limited. With the JRL cold-water releases, the NBPR mainstem and tributary habitats are well connected with respect to temperature. Fish no longer have to retreat upstream and gain the freedom to migrate if and when water quality or other factors become stressful.

4.3 Pollutants

Recent pollutant levels in the NBPR watershed and its mainstem are discussed in this report section. Figure 42 is a schematic of the major sampling locations along the NBPR mainstem. Only those locations in the river mainstem or near the confluences of the five larger tributaries are shown. Median values of the available data collected since 2000 are indicated for pH, SpCond, TDS, turbidity, TSS, and alkalinity.

4.3.1 Conductivity and Total Dissolved Solids

SpCond and TDS are conservative measures of water quality because they tend to persist in the environment and are not easily changed physically or chemically. SpCond measures the ability of water to conduct electricity and is a rapid and consistent way of quantifying water's ionic content. As shown in Figure 29, SpCond aligns closely with TDS which are salts, metals, and other compounds that disassociate in water into ions, or atoms and molecules with an electric charge. High levels of both SpCond and TDS indicate pollution and because of their conservative nature, both parameters offer a useful way to trace pollution to its sources. SpCond does not indicate which elements and compounds constitute the TDS, and composition varies depending on the sources of dissolved solids. USEPA, Maryland, and West Virginia consider SpCond values exceeding 500 µS/cm and TDS concentrations exceeding 500 mg/liter as stressful to aquatic life. Freshwater fish, macroinvertebrates, and other taxa are physiologically adapted to low ionic concentrations and typically do not have osmoregulation mechanisms that can deal with high ionic concentrations. Excess SpCond and TDS also cause taste and odor problems in drinking water.

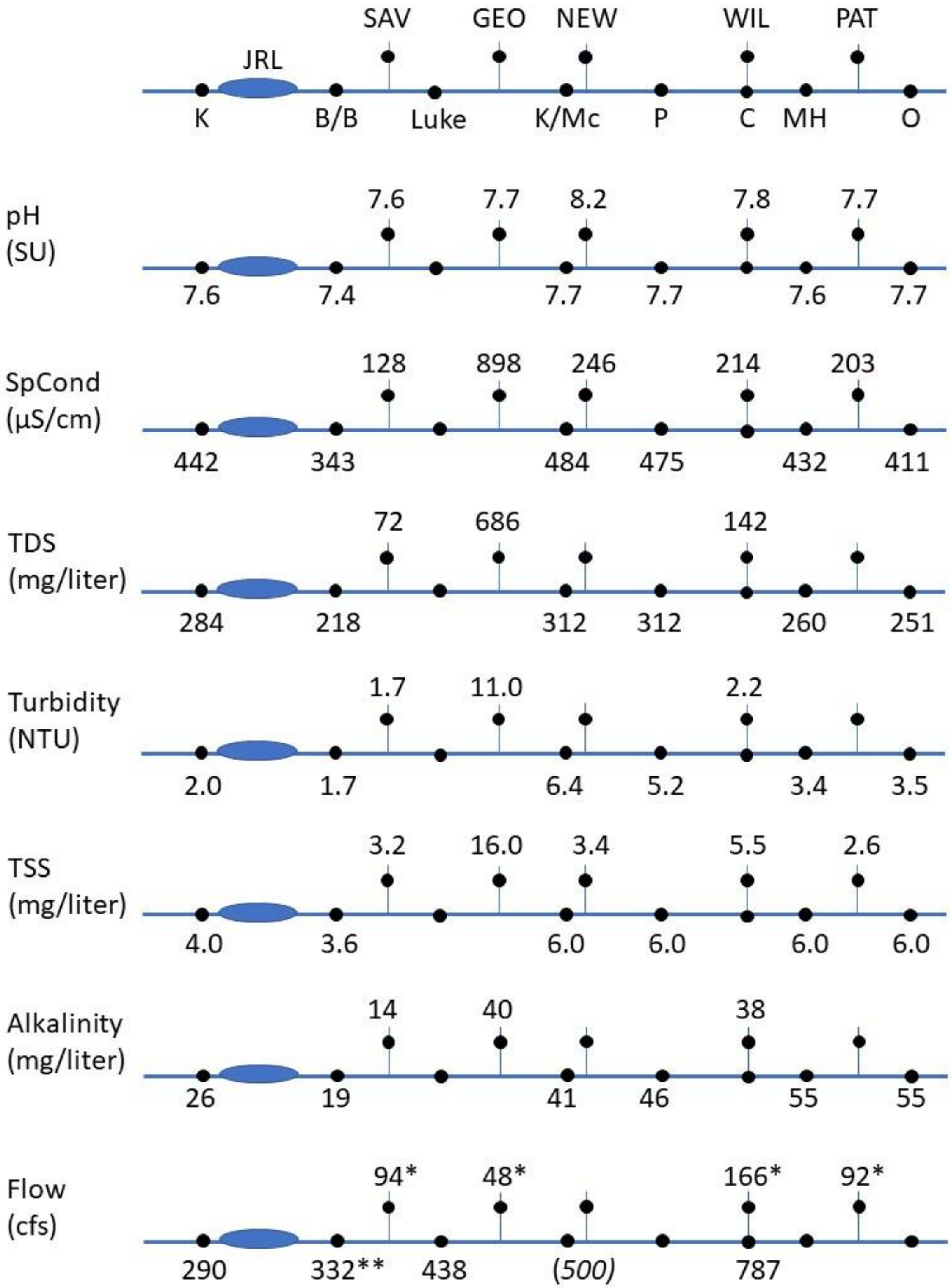


Figure 42. Schematic of North Branch Potomac River and major tributaries (distances not to scale) showing median values for all available 2000 – 2017 data

*Mainstem: K, Kitzmiller; P, Pinto; C, Cumberland; MH, Moores Hollow Rd; O, Oldtown. Tributaries data are only for long-term site located closest to mouth: SAV, Savage River; GEO, Georges Creek; NEW, New Creek; WIL, Wills Creek; PAT, Patterson Creek. *, adjusted to reflect flow at tributary mouth; **, adjusted to reflect flow at Bloomington. The 500 cfs at Keyser/McCoole is median of daily sums of Luke and Georges Creek flows.*

SpCond and TDS concentrations are high and increasing over time in parts of the NBPR mainstem and many of the watershed's streams. SpCond is exceeding levels that can be considered background in the post-acid rain era as well as the 500 µS/cm stress threshold for aquatic life. Background levels are caused by normal weathering of rock and soil, and anthropogenic disturbances increase SpCond and TDS above these background levels. SpCond in two subwatersheds indicate the NBPR watershed's background levels should average about 200 µS/cm and not exceed 500 µS/cm. SpCond in the Savage subwatershed, excluding the Aaron Run and Mud Lick hotspots, averaged 111.3 µS/cm (SD = 34.1, n = 861) from 1967 to present. This subwatershed is currently 85% forested and 9% agricultural, with 0.16 % impervious cover (NLCD 2006). Over the same 50 year period, SpCond in the somewhat more populated Patterson Creek averaged 233.9 µS/cm (SD = 95.9, n = 1,112). Patterson is about 76% forested and 18% agricultural, with 0.46% impervious cover. SpCond concentrations in these two watersheds are relatively stable and have not changed much since the 1960s. TDS was not measured as frequently as SpCond in the NBPR watershed but based on Figure 29 we can estimate background TDS concentrations should average about 100 mg/liter and not exceed 350 mg/liter.

The upward trends in several subwatersheds since the 1980s should be considered an emerging threat to aquatic life as values start to exceed 500 µS/cm. Mining as a source of high SpCond and TDS is implicated in several places in the NBPR watershed. An additional source of TDS and high SpCond is likely the lime dosers used to treat AMD at abandoned mines because they release very large quantities of calcium carbonate ($CaCO_3$). Aaron Run in the Savage and an unnamed tributary to New Creek each flow near one or more active and/or discontinued surface mining operations. Each has SpCond above 500 µS/cm and TDS concentrations are correspondingly high in the Savage. In the Upstream subwatershed, SpCond above 500 µS/cm is found in Abrams Creek, Laurel Run, Stony Run and Sand Run, all of which have active or discontinued mining operations in their catchments. In the heavily mined Georges Creek subwatershed, SpCond has exceeded 500 µS/cm in 92% of samples collected near its mouth at Westernport since 2000.

The river mainstem between Bloomington and Keyser/McCoole is another hotspot for TDS and SpCond. Water from Georges Creek is one source of the dissolved solids to this river reach. However, flow from Georges Creek contributes only about a tenth of total flow in the mainstem and does not contain enough SpCond and TDS to raise mainstem concentrations to the levels seen at Keyser/McCoole. The cluster of townships along this reach of the mainstem collectively have a small population, but are home to coal transfer stations, logging industry, the Verso paper mill, and Westernport WWTP. Discharges from the towns themselves, and particularly from the Westernport WWTP, are apparently the larger sources of SpCond and TDS. This reach of the NBPR mainstem is strongly influenced by JRL and SRR releases during low flow periods, and diluting pollutants in this reach was one of the original authorized purposes of JRL. Pollutant concentrations discharged to this reach are changing due to the recent closure of the Verso paper mill. If the plant remains closed, JRL's role in diluting pollution here will be worth reassessing.

Mainstem concentrations of SpCond and TDS decrease gradually beyond Keyser/McCoole, and do not increase as they pass Cumberland, MD located more than 40 miles downstream of JRL and SRR. Cumberland is a relatively large metropolitan area of over 103,000 residents (2010 census) with a recent history of industrial and manufacturing plant closures and changing demographics. Wills Creek enters the NBPR at Cumberland and Patterson Creek enters a few miles below Cumberland. Collectively, these two tributaries increase NBPR mainstem flows by roughly 40%. SpCond and TDS concentrations in both tributaries are presently lower than in the mainstem (Figure 42). Wills and Patterson creeks appear to be more important than JRL and SRR releases as a means of diluting dissolved solid concentrations at this point in the river mainstem.

Pair-wise comparisons of SpCond and TDS concentrations above and below JRL suggest the lake may be to some extent a sink for dissolved solids. Values entering the lake at Kitzmiller are typically higher than those measured downstream at Barnum/Bloomington. This has been the case since the 1960s, under varying ranges of lake acidity. Median concentrations of SpCond and TDS below the lake at Barnum/Bloomington are 343 µS/cm and 218 mg/liter, respectively, and overlap background ranges for the NBPR watershed (above).

4.3.2 Alkalinity

Alkalinity measures the disassociated anions of salts that give water its ability to buffer, or neutralize, acid (H+) inputs. In most instance, carbonate (CO_3^{2-}) and bicarbonate (HCO_3^{1-}) are the dominant anions of alkalinity. Although technically a constituent of SpCond and TDS, alkalinity is generally not considered a pollutant. It is dynamically linked to many other water quality parameters, and a waterbody's health is often dependent on its alkalinity levels. For example, first order streams with low alkalinity do not have sufficient mineral content to buffer them from rapid changes in pH which can harm biological populations. High levels of acid (low pH) can be generated by acid deposition ("acid rain") or the decomposition of mine waste during and after mining. The resulting nitric acid, sulfuric acid, and H+ ions severely deplete surface waters of their alkalinity. Alkalinity is now increasing in much of the eastern United States with the decline in acid deposition (e.g. Kaushal et al. 2013).

Median alkalinity concentrations were 26 mg $CaCO_3$/liter at Kitzmiller above JRL and 19 mg $CaCO_3$/liter below JRL at Bloomington. This 27% drop as water passes through JRL indicates precipitates of carbonate and the other bases are being trapped to some extent by the lake. Entrapment of dissolved and particulate solids is a normal function of lakes, and the drop in JRL alkalinity parallels a 23% drop in TDS and a 22% drop in SpCond. In the case of JRL, waters coming into the lake do not have much buffering capacity and passage through JRL is further reducing this capacity. While JRL is reducing overall levels of specific conductivity and TDS to below-harmful levels, it is also reducing the alkalinity that can buffer in-lake and downstream waters against pH swings.

Historically, streams in the NBPR watershed with pH less than 6 were frequently associated with alkalinity levels below detection limits. Alkalinity is clearly trending upward in the watershed and paralleling improving (increasing) trends in pH. After 2000, median alkalinity concentrations in the NBPR mainstem below Bloomington were well above 20 mg $CaCO_3$/liter considered to be the minimum level needed to maintain stable pH levels and protect aquatic life. The Georges, New, Downstream, and Patterson subwatersheds now have fairly high median concentrations. Median concentrations are still relatively low in the Upstream and Savage subwatersheds. These areas appear to still be recovering from earlier acidification despite having relatively good pH levels.

4.3.3 Turbidity and Total Suspended Solids

JRL appears to have less of an entrapment effect on suspended particles than it does on dissolved solids. Pair-wise comparisons of concentrations upstream of JRL at Kitzmiller and downstream at Bloomington show turbidity readings drop 15% and TSS concentrations drop 10%. (Turbidity and TSS are not tightly correlated because turbidity indicates the amount of all particles in the water whereas TSS measures only those larger than 1-2 microns.) When suspended particles settle, they cover or embed gravel and cobble bottoms that are important to many kinds of aquatic life. Lake currents and high flow events in streams and rivers periodically resuspend the particles and move them downstream, eventually flushing them out of the watershed. Analysis of five sediment-related stream habitat metrics suggested that while some streambeds in the NBPR watershed classify as optimal, a substantial number may still be receiving above-background loads of sediment.

Sources of suspended particles in the NBPR watershed are industrial discharges and disturbed landscapes, including mining, agriculture, development, and ‘legacy sediments’ from historical logging and strip mining. Major hotspots for turbidity and TSS are Georges subwatershed and the entire NBPR mainstem below Bloomington. In recent years, turbidity levels in the mainstem jump 276% and TSS concentrations 67% as the river flowed 7.5 miles past Bloomington, Luke, Westernport, and Piedmont to Keyser/McCoole (Figure 42). High turbidity and TSS levels from the Georges Creek subwatershed enter this mainstem section at Westernport MD and contribute to the increase; however, Georges Creek cannot account for all of the increase seen in the mainstem. The largest source of turbidity appears to be the Westernport WWTP which processes industrial wastewater from the Verso paper mill in Luke and municipal sewage from neighboring towns. Unregulated discharges and runoff from other facilities along this reach’s riverbank may be additional sources of suspended sediments.

Individual streams in the Upstream, Downstream, Patterson, New, and Savage subwatersheds also have instances of high turbidity and TSS, some of which appear linked to active mining. Streams with high concentrations include Wills Creek, Braddock Run, Jennings Run, Sand Spring Run, and Winebrenner Run. Flows in these affected streams are small compared to the NBPR mainstem flow volume and thus have relatively little impact on mainstem concentrations.

Maryland and West Virginia do not have numeric water quality criteria for TSS although they recognize sediment bearing waters should not cause violations of state standards in receiving waters. As mentioned above, Maryland water quality standards require that “turbidity may not exceed levels detrimental to aquatic life” and “turbidity in the surface water resulting from any discharge may not exceed 150 units [NTU] at any time or 50 units [NTU] as a monthly average” (COMAR §26.08.02). West Virginia standards for turbidity state:

> “No point or non-point source to West Virginia's waters shall contribute a net load of suspended matter such that the turbidity exceeds 10 NTU's over background turbidity when the background is 50 NTU or less, or have more than a 10% increase in turbidity (plus 10 NTU minimum) when the background turbidity is more than 50 NTUs. This limitation shall apply to all earth disturbance activities and shall be determined by measuring stream quality directly above and below the area where drainage from such activity enters the affected stream. Any earth disturbing activity continuously or intermittently carried on by the same or associated persons on the same stream or tributary segment shall be allowed a single net loading increase”
>
> and
>
> exemptions “…shall not apply to trout waters” (WV §47CSR2).

Literature suggests levels greater than about 25 NTU will begin to harm aquatic life (e.g., Alabaster and Lloyd 1982). Using turbidity as a surrogate measure of suspended sediment, however, can be problematic because correlations between the two are not necessarily identical (Henley et al. 2010). This is because the relationship is affected by a watershed’s individual soil and geologic conditions and sediment grain sizes.

Since the largest inputs of suspended particulates to the mainstem occur between Bloomington and Keyser/McCoole, low-flow augmentation with the comparatively clearer waters from JRL and Savage should dilute their concentrations in this reach. The importance of this role for JRL is likely to change with the recent closure of the paper mill at Luke and the continued remediation of AMD in Georges Creek.

4.4 Organic Solids and Dissolved Oxygen

The Westernport WWTP which processes municipal and industrial (paper mill) waste has a Maryland discharge permit with effluent limits for biological oxygen demand (BOD), turbidity, DO, total nitrogen (TN), total phosphorus (TP), fecal coliform, and *E. coli*. Effluent meeting these limitations are assumed to be discharging organic solids that will not harm downstream designated uses. Organic solids settling on a river bottom are known to smothered fish eggs and harm macroinvertebrate communities because they consume large amounts of oxygen as they decompose.

DO concentrations in the water column above the riverbed presently meet Maryland and West Virginia DO criteria the entire length of the NBPR mainstem, indicating organic loads to the river are not high enough to depress water column DO. AVFs from JRL during the summer low-flow period are intended to flush sediments downstream, however there are no empirical data documenting their effectiveness. There is also no data documenting DO levels in the sediments and whether they are low enough to harm aquatic life. The need for AVFs from JRL should be investigated more closely as their purported importance in flushing sediments could be lessened with the paper mill closure. Furthermore, high flows that are comparable to the 850 – 1000 cfs AVFs are recorded at the Barnum gage below JRL about 30.9 times in a given year and these high flows presumably also flush accumulated organic solids below Luke. Most high flows appear to be related to heavy rain events and JRL releases that are made to avoid rapidly rising or high water levels in the lake.

Spills of untreated sewage are one notable source of organic pollution to the lower NBPR mainstem in the vicinity of Cumberland, MD. For example, during the particularly rainy period of June 2018 to May 2019, 64 of 72 spills reported in the NBPR watershed were from pump stations, wastewater treatment plants, and combined sewer overflows in the Wills Creek subwatershed which empties into NBPR at Cumberland (PotomacSpills listserv). The spills totaled over 83 million gallons. JRL is too far upstream to have a dilution effect on these spills.

5 Conclusions

The landscape of the North Branch Potomac River is changing. Historical problems caused by erosion, acid rain deposition, and unregulated mining practices are resolving naturally or being remediated. Industries and municipalities continue to discharge pollutants; however, demographics in the four counties bordering NBPR are changing and a major industry, the Verso paper mill at Luke, MD, recently closed. Streams and rivers reflect this changing landscape to a large extent. pH levels in most of the watershed had climbed to desirable levels by the 1990s, a result of aggressive AMD remediation efforts and regulatory enforcement. Concentrations of alkalinity, the bases that give water its capacity to neutralize acids, are rising in areas previously impacted by AMD. Streams in undisturbed catchments with reestablished forests now often meet the summer temperature needs of cool- and cold-water taxa. On the other hand, sedimentation (embeddedness, epifaunal substrate) is still an issue in roughly three-quarters of streams. Concentrations of particulates in the water (TSS, turbidity) spike as the NBPR mainstem passes Georges Creek and the various industries and riverbank communities near Luke, MD. Trends in dissolved solids concentrations (SpCond, TDS) are mixed, with low, relatively stable concentrations throughout most of the Savage, New, and Patterson subwatersheds but higher concentrations and increasing trends in the mainstem and Upstream, Georges, and Downstream subwatersheds. The increasing SpCond and TDS trends, and particularly the higher concentrations near active and remediated mines, are an emerging threat to aquatic life.

Flood prevention in the NBPR is the first and foremost authorized purpose of JRL. Coordinated JRL and SRR operations successfully prevent the river mainstem from exceeding flood stage at Luke, MD, 7.5 miles downstream of JRL. They do not prevent flooding 15 miles below JRL in the mainstem at Cumberland, MD and cannot prevent flooding in the watershed's tributaries. Tributaries entering below Luke that bisect communities on the mainstem have overflowed their banks multiple times since JRL was built, e.g., Georges Creek which enters NBPR at Westernport, MD, New Creek at Keyser, WV and Wills Creek at Cumberland, MD. JRL and SRR flood control operations actively lower water levels in the mainstem as it receives tributary flood waters, so they are alleviating flooding in the communities below Luke. Flood control operations are still essential to the welfare of communities on the mainstem's riverbank.

Another authorized purpose of JRL is the dilution and removal of pollutants in discharges and runoff entering the mainstem downstream of the lake. The objective is to achieve Maryland water quality standards in the region of Luke, MD and improve downstream aquatic habitats. Low flow augmentation has not prevented SpCond, TDS, turbidity, and TSS from regularly exceeding protective water quality thresholds or criteria in the vicinity of Luke, MD. Pollutants discharged to the NBPR mainstem or entering from Georges Creek are still a significant problem in this mainstem reach. Evidence that artificially varied flows (AVFs) remove settled organic solids in the mainstem is anecdotal at best because quantitative river bottom data are not collected. Organic solids may not be a problem because DO concentrations in the water column of the mainstem consistently meet standards, suggesting "dead zones" created by decomposing solids do not occur. Streams in the watershed still contain legacy sediments and sites with active erosion. These tributary sediments will eventually move into the mainstem, but their impacts on aquatic habitats there are not known. JRL operations currently have little if any influence on downstream pH, absent a tributary AMD "blowout."

Releases of blended outflows from different JRL depths using the dam's selective withdrawal system have been very successful in cooling downstream waters and improving fish habitat. Maryland's trout stocking guidelines (4 – 20 °C) are now achieved during the summer for approximately 15 miles below JRL to Keyser/McCoole and sometimes beyond. As a result, cool and cold water refugia in NBPR tributaries are more connected during the summer. This thermal connectivity is presumed to benefit both stocked and naturally reproducing trout populations because it allows for migration if and when water quality or other factors become stressful and promotes population resiliency.

The lake environment of JRL removes both particulate and dissolved solids from river water. Comparisons of river water entering and leaving the lake show that about 15% of the water's turbidity and 10% of its TSS settle out in the lake. Similarly, about 22% – 23% of the water's dissolved solids (SpCond, TDS) are removed. While the removal of suspended particles and dissolved solids is generally beneficial to the river downstream, the lake is also removing alkalinity—a component of TDS—by about 27%. NBPR waters therefore have *less* ability to buffer against pH swings and slightly *lower* pH levels when they exit the lake. Despite this loss of alkalinity through natural processes in the lake, watershed sources are increasing alkalinity concentrations and buffering capacity in much of the lower mainstem. Normal daily and interannual swings in pH are within ranges protective of aquatic life.

USACE should reassess JRL operations outlined in the 1997 Water Control Plan that were intended to improve downstream water quality and habitat. Some lake operations are no longer effective approaches or do not have a useful purpose due to improvements (pH, alkalinity) or degradation (SpCond, TDS) occurring in the watershed and outside of JRL's direct influence. With closure of the Verso paper mill at Luke, the need for JRL operations to dilute discharged pollutants may also be losing importance. JRL operations that keep downstream temperatures cool in summer could become economically and ecologically more important as aquatic life continues to recover. Given current conditions in the North Branch Potomac River watershed and USACE's ongoing development of flow and temperature models for the river, a reassessment of JRL's water quality storage allocation (55.44% of the usable conservation pool), use of AVFs, and the 120 cfs minimum flow-by requirement at Luke is also warranted in our opinion.

6 References

Alabaster, J. S., and R. Lloyd. 1982. Water quality criteria for freshwater fish, 2nd edition. Butterworths, London.

Barbour, M. T., J. Gerritsen, B. D. Snyder, and J. B. Stribling. 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish. Second Edition. EPA 841-B-99-002 U. S. Environmental Protection Agency, Office of Water, Washington D.C. http://www.epa.gov/OWOW/monitoring/techmon.html.

Chadwick, J. G. and S. D. McCormick. 2017. Upper thermal limits of growth in brook trout and their relationship to stress physiology. Journal of Experimental Biology 220: 3976-3987. doi:10.1242/jeb.161224.

Henley, W. F., M. A. Patterson, R. J. Neves, and A. Dennis Lemly. 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Reviews in Fisheries Science 8(2):125-139. https://doi.org/10.1080/10641260091129198.

Hansen, E., A. Collins, S. Zegre, and A. Hereford. 2010. The benefits of acid mine drainage remediation on the North Branch Potomac River. Report prepared by Downstream Strategies, Morgantown, WV. Available online at www.downstreamstrategies.com.

Hill, J., M. Dail, C. Sparks, and E. Jones. 2017. Stressor Analysis in Virginia: Data Collection and Stressor Thresholds. Virginia Department of Environmental Quality (VADEQ). VDEQ Technical Bulletin WQA/2017-001.

John Gallup & Associates LLC (JG&A). 2019. Jennings Randolph Lake Master Plan, Garrett County, MD and Mineral County, WV. Report prepared for U. S. Army Corps of Engineers, Baltimore District.

Kaushal, S. S., G. E. Likens, R. M. Utz, M. L. Pace, M. Grese, and M. Yepsen. 2013. Increased river alkalization in the eastern U.S. Environ. Sci. Technol. 47(18):10302-10311.

Maryland Department of the Environment (MDE). 2009. Maryland Biological Stressor Identification Process. Available online at: https://mde.maryland.gov/programs/Water/TMDL/Documents/BSID_Reports/BSID_Methodology_Final_2009.pdf

Maryland Department of the Environment (MDE). 2017. Maryland's Final 2016 Integrated Report of Surface Water Quality. Environmental Assessment and Standards Program (EASP). Available online at: https://mde.maryland.gov/programs/Water/TMDL/Integrated303dReports/Pages/2016IR.aspx

Smith, Z., C. Buchanan, and A. Nagel. 2017. Refinement of the Basin-Wide Index of Biotic Integrity for Non-Tidal Streams and Wadeable Rivers in the Chesapeake Bay Watershed. Interstate Commission on the Potomac River Basin. Report 17-2. Available at www.potomacriver.org.

Selckmann, G. M., and C. Buchanan. In prep. Review of Habitat and Biological Conditions of the North Branch Potomac River with Consideration of the Influence of Jennings Randolph Lake Dam Operations. ICPRB Report.

United States Army Corps of Engineers (USACE). 1997a. *Jennings Randolph Lake 1997 Master Plan Update and Integrated Programmatic Environmental Impact Statement*. U.S. Army Corps of Engineers – Baltimore District, October.

United States Army Corps of Engineers (USACE). 1997b. *Master Manual for Reservoir Regulation, North Branch Potomac River Basin, Appendix - A, Jennings Randolph Lake, West Virginia and Maryland*. U.S. Army Corps of Engineers – Baltimore District, July.

United States Environmental Protection Agency (USEPA). 1993. Method 180.1. Determination of turbidity by nephelometry. Environmental Monitoring Systems Laboratory, Office of Research and Development. Cincinnati, OH. https://www.nemi.gov/methods/method_summary/5217/.

United States Environmental Protection Agency (USEPA). 1997. EPA's Volunteer Stream Monitoring - A Methods Manual. EPA 841-B-97-003. Available online at: https://www.epa.gov/sites/production/files/2015-06/documents/stream.pdf.

United States Environmental Protection Agency (USEPA). 2011. A field-based aquatic life benchmark for conductivity in Central Appalachian streams. Office of Research and Development. EPA/600/R-10/023F. Available at http://cfpub.epa.gov/ncea/cfm/ recordisplay.cfm?deid=233809.

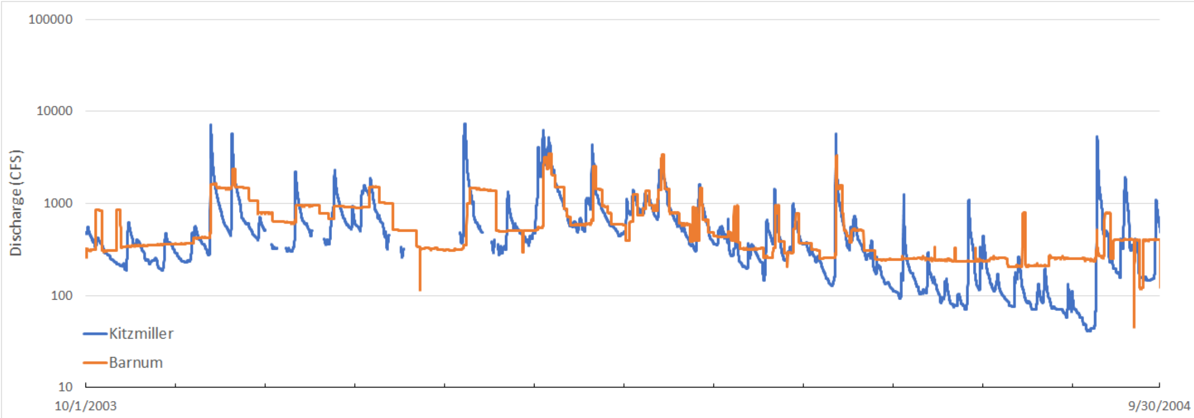
West Virginia Department of Environmental Protection (WVDEP). 2016. 2016 West Virginia Integrated Water Quality Monitoring and Assessment Report. Division of Water and Waste Management. Available online at: https://dep.wv.gov/WWE/watershed/IR/Documents/IR_2016_Documents/USEPA_Approved_IR_303d_Complete%20Document.pdf

West Virginia Department of Environmental Protection (WVDEP). 2018. Chapter 2. Instructions for assessing the stream site (including setting up the site, site documentation, and guidelines for completing the stream assessment forms). Watershed Assessment Branch, Field Standard Operating Procedures for 2018.

Wetzel, R. G. 2001. Limnology: Lake and River Ecosystems, 3rd edition. Academic Press.

Appendix A: Sub-daily flow measurements at Kitzmiller and Barnum for water years 2004 - 2018

Water Year 2004



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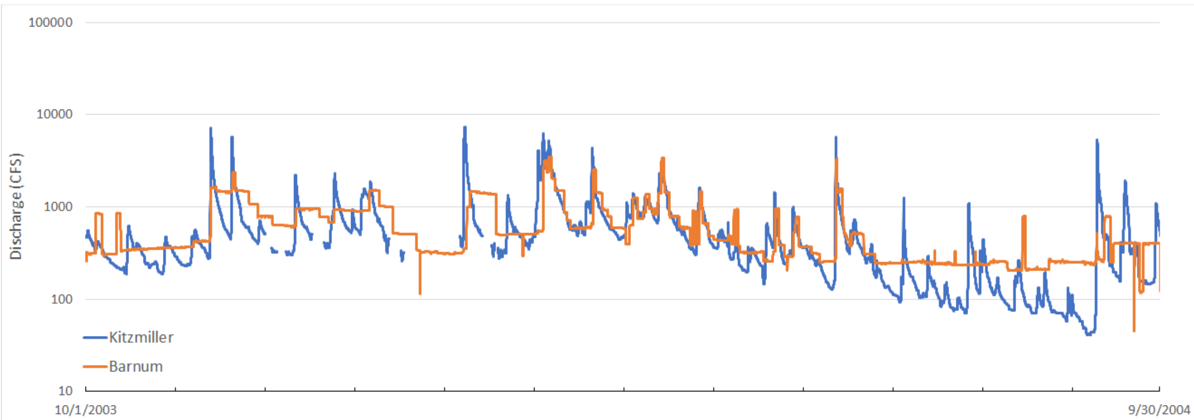

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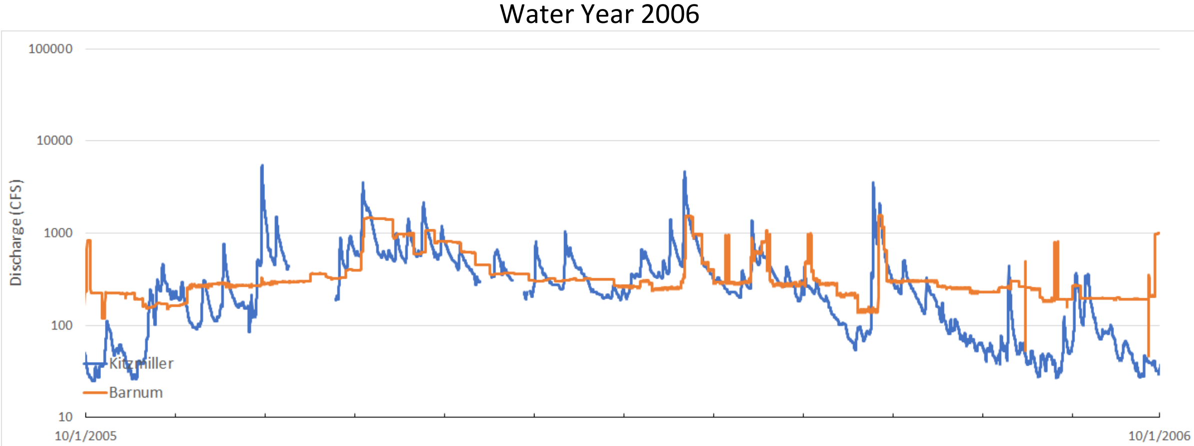

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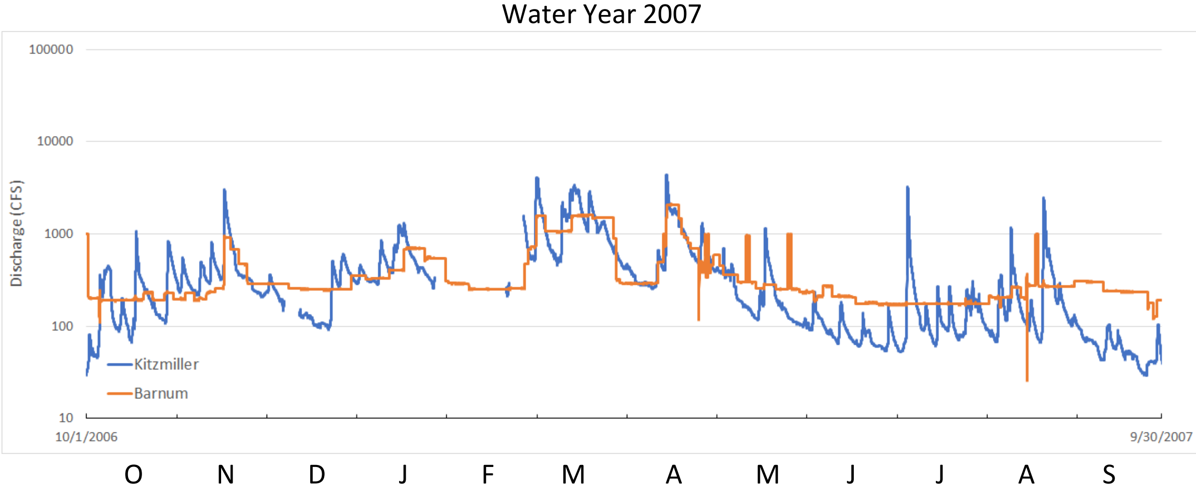

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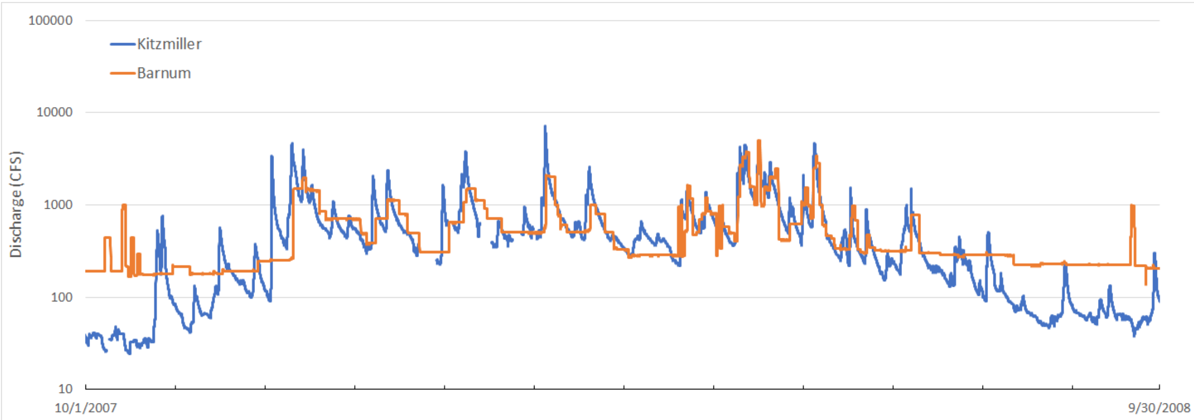

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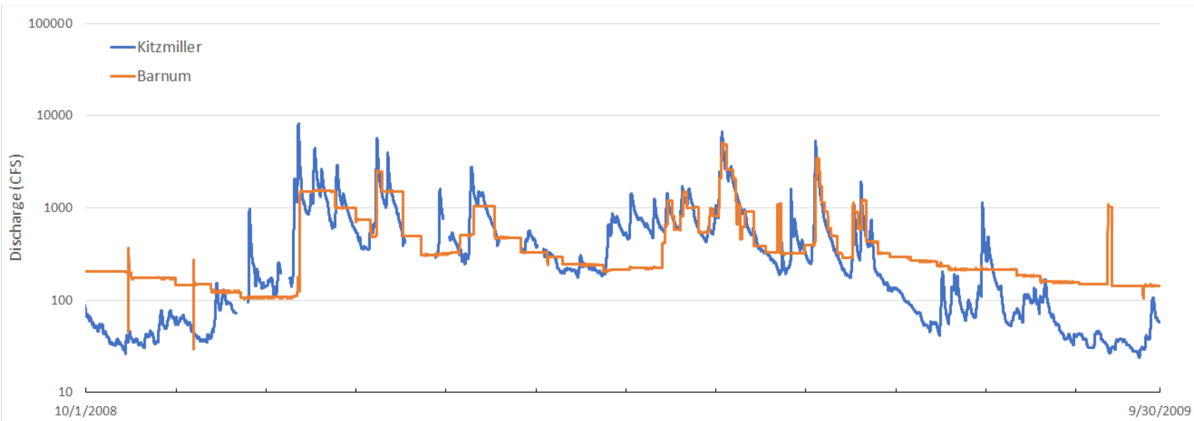

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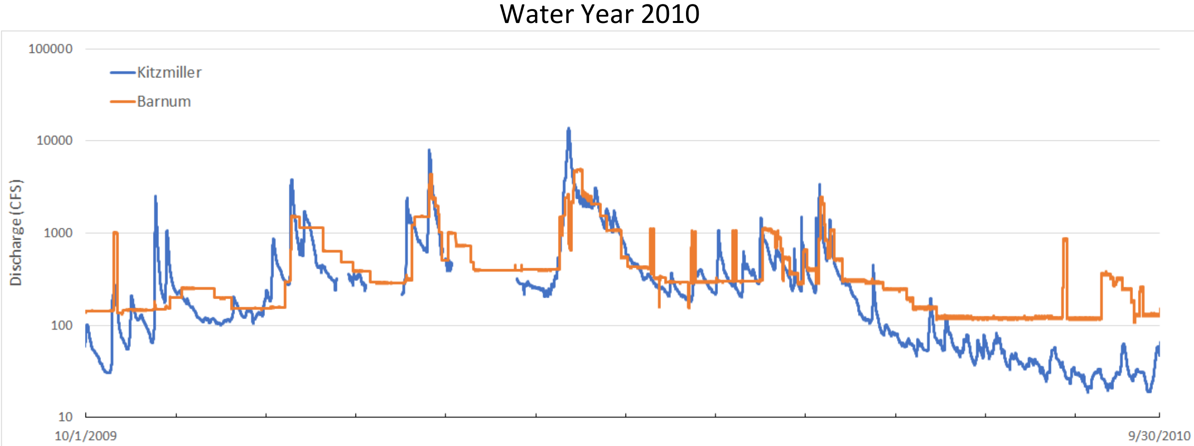

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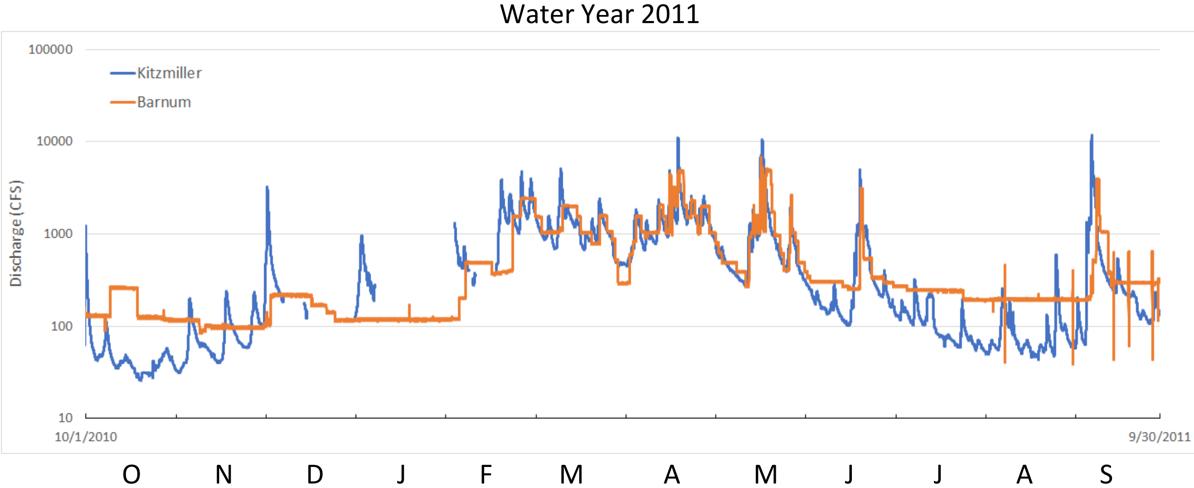
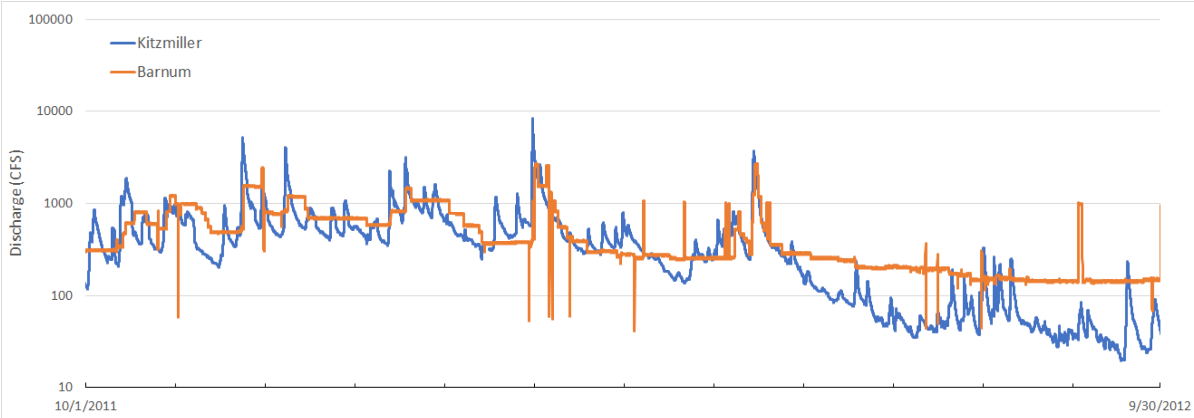


Water Year 2012



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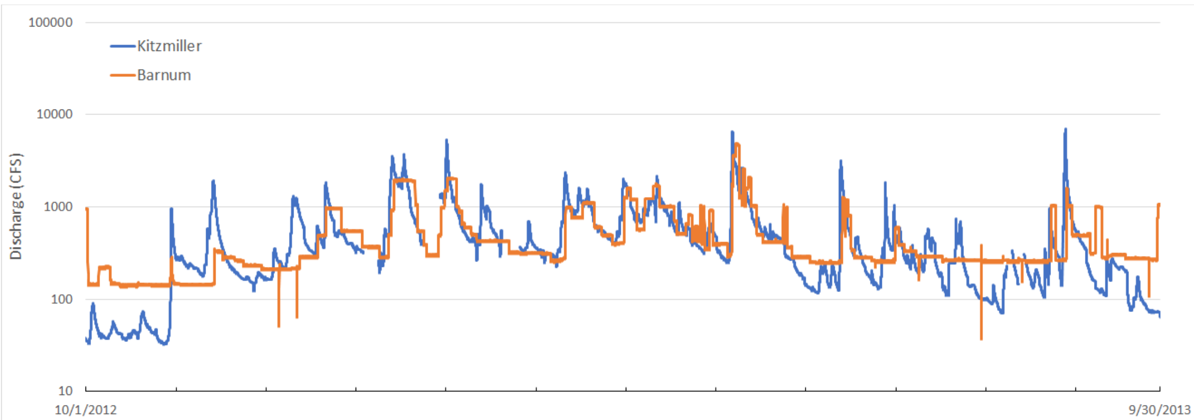

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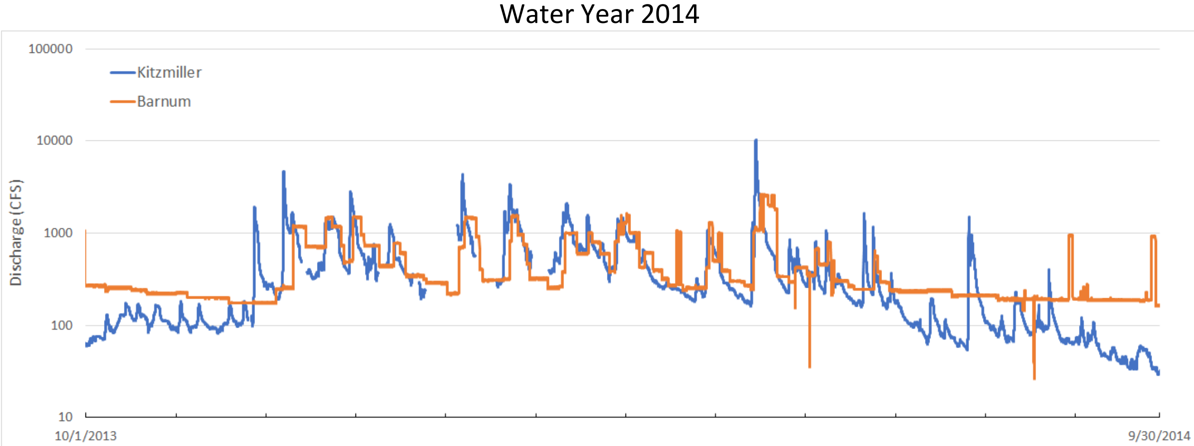

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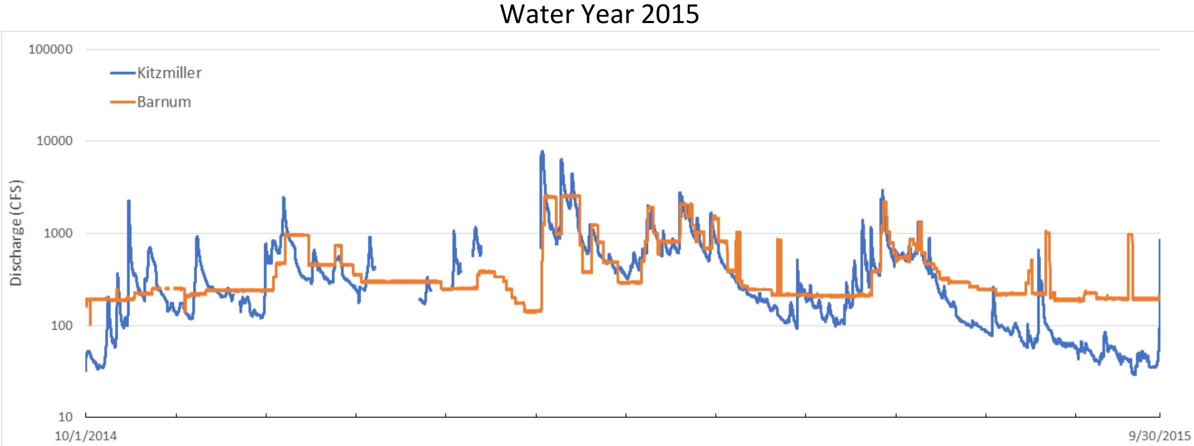
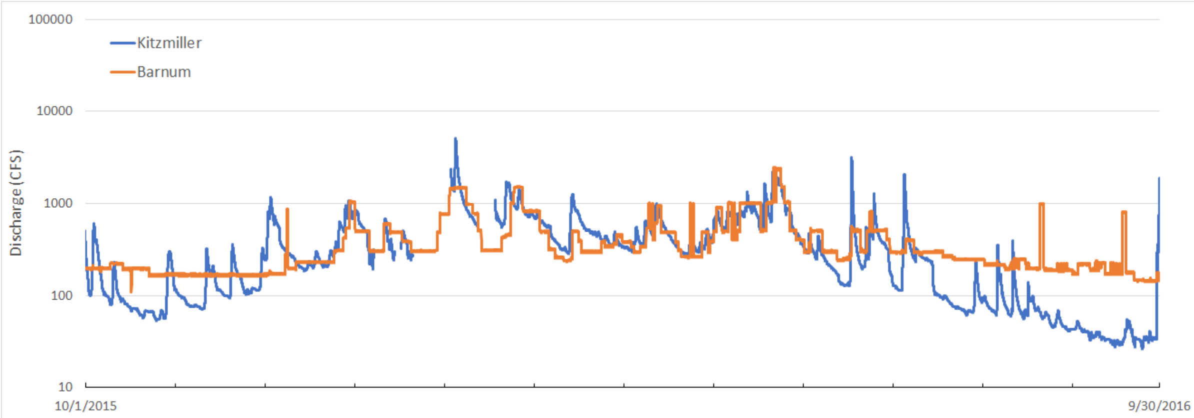


O N D J F M A M J J A S

Water Year 2016



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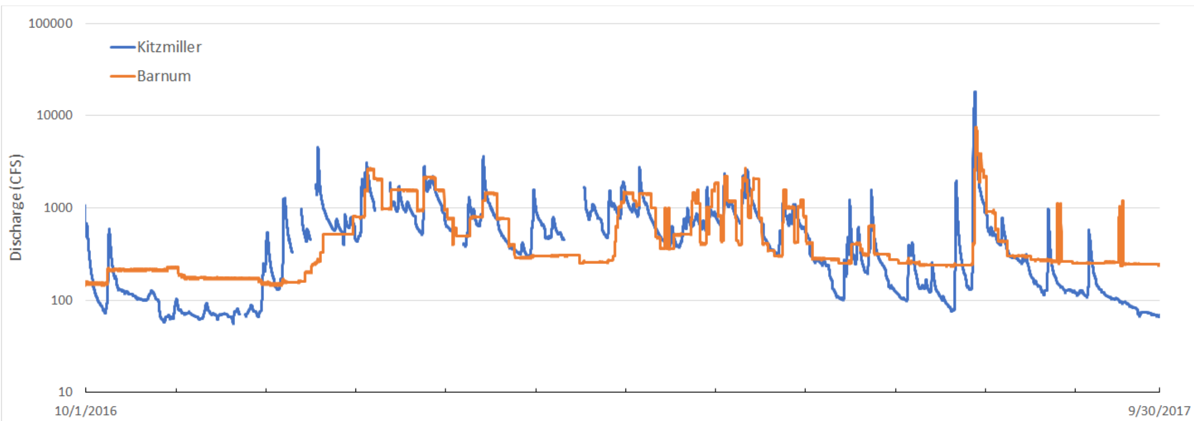
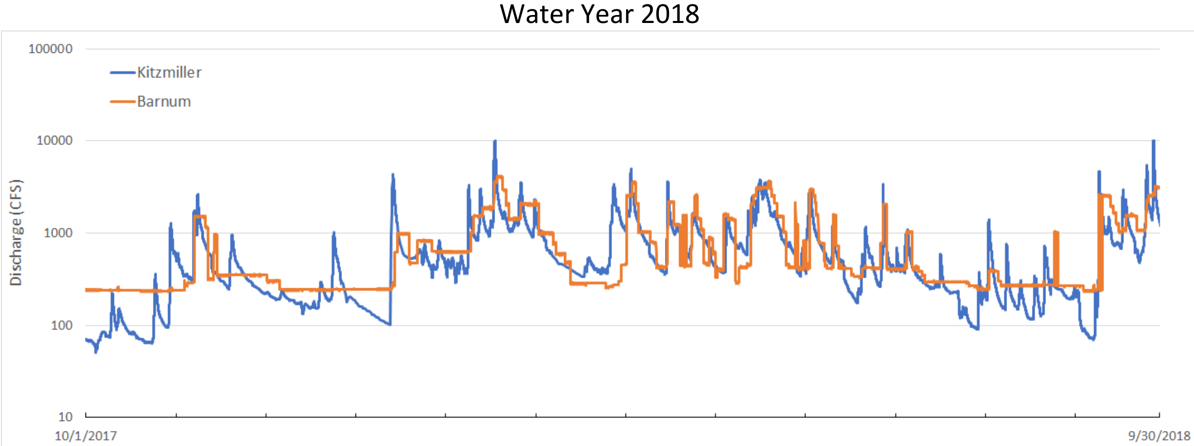


Water Year 2018



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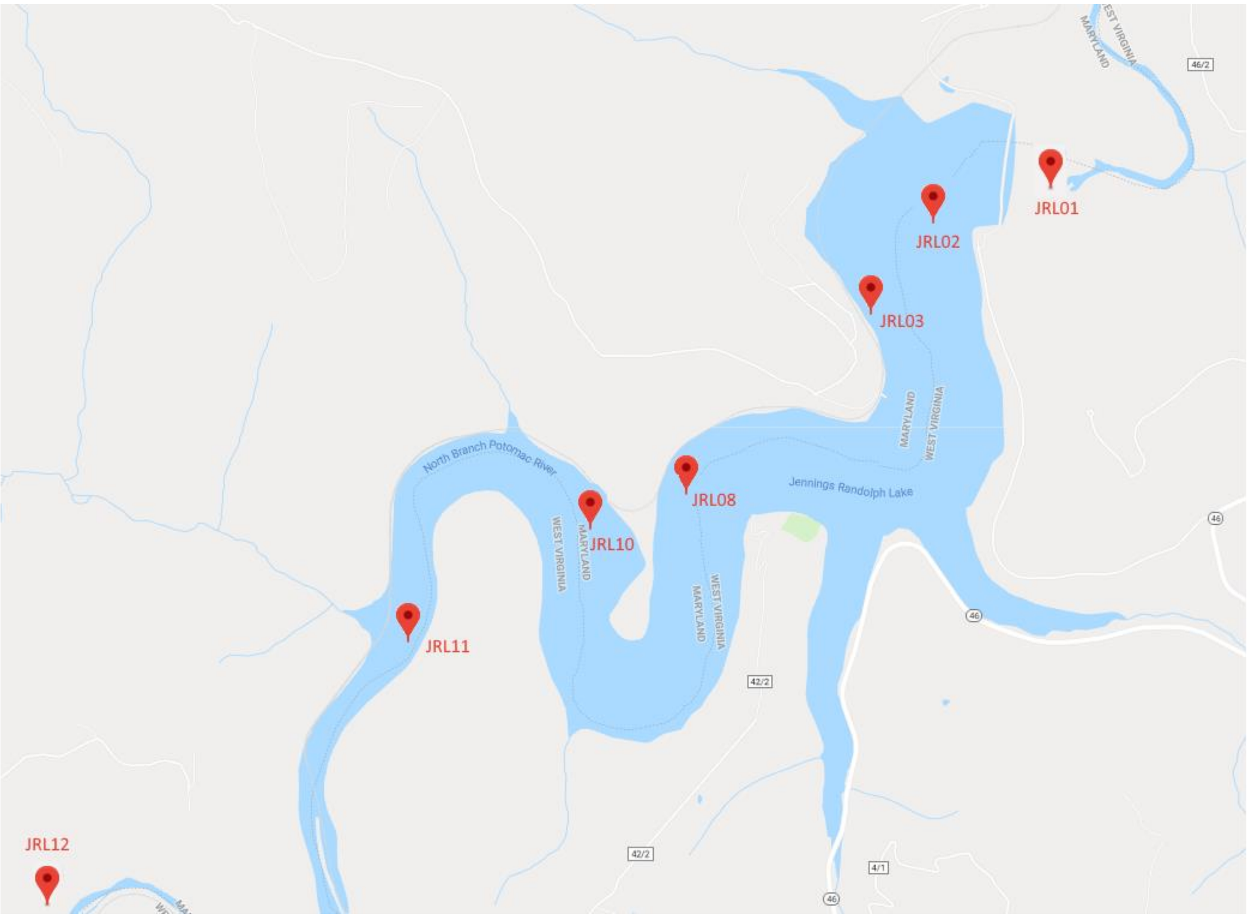
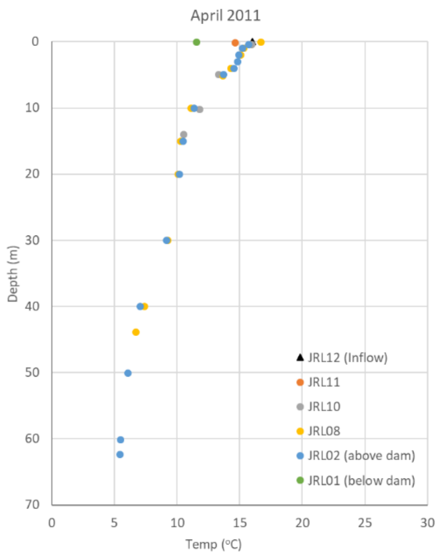
Appendix B: Jennings Randolph Lake water quality depth profiles

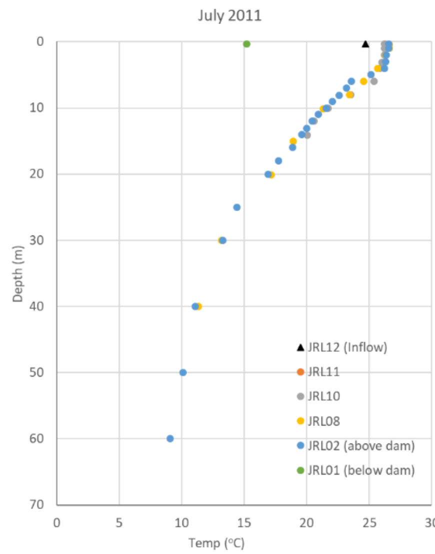
Data from USACE

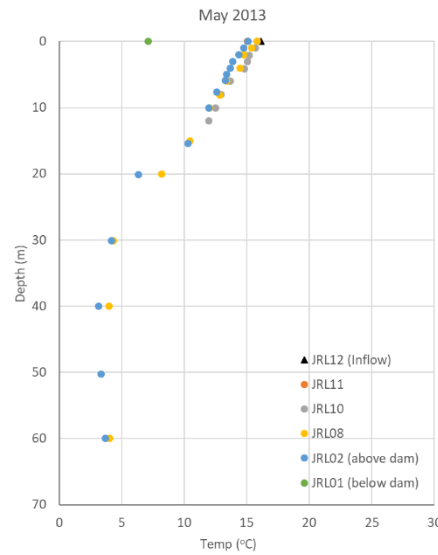


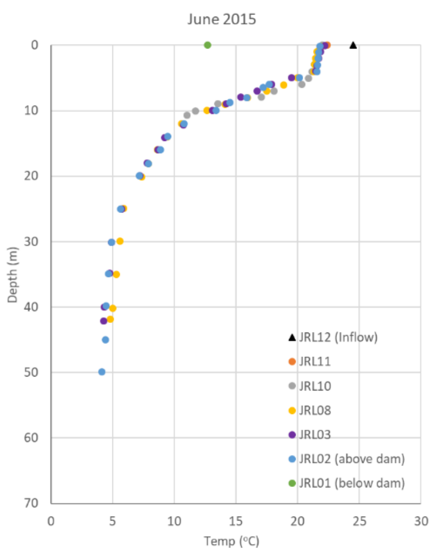
Station locations in Jennings Randolph Lake

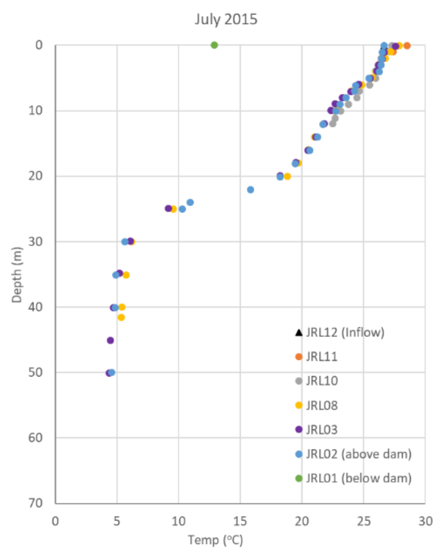
Depth Profiles of Temperature

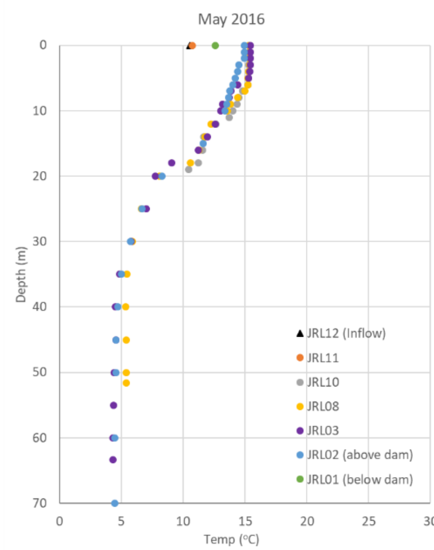


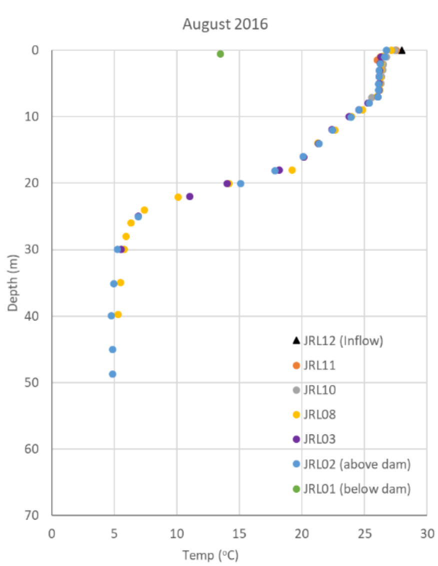


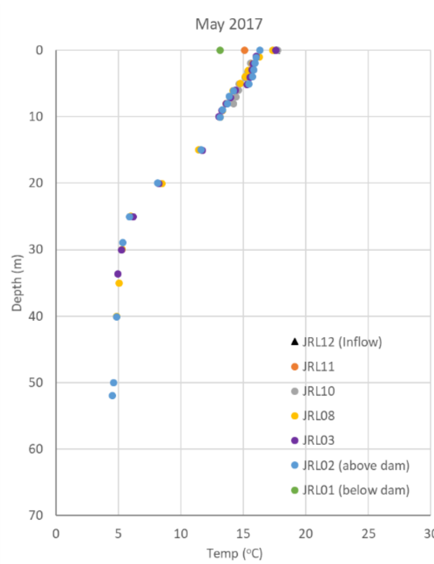


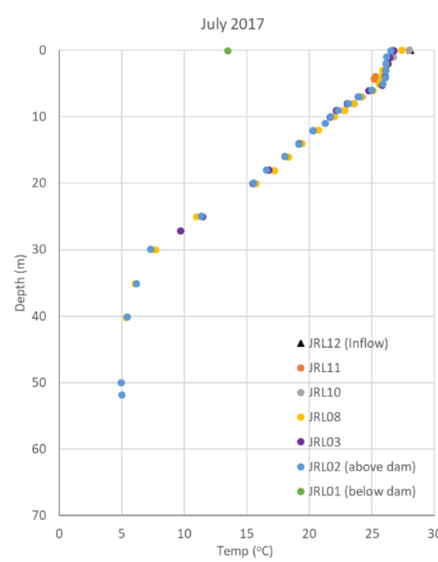




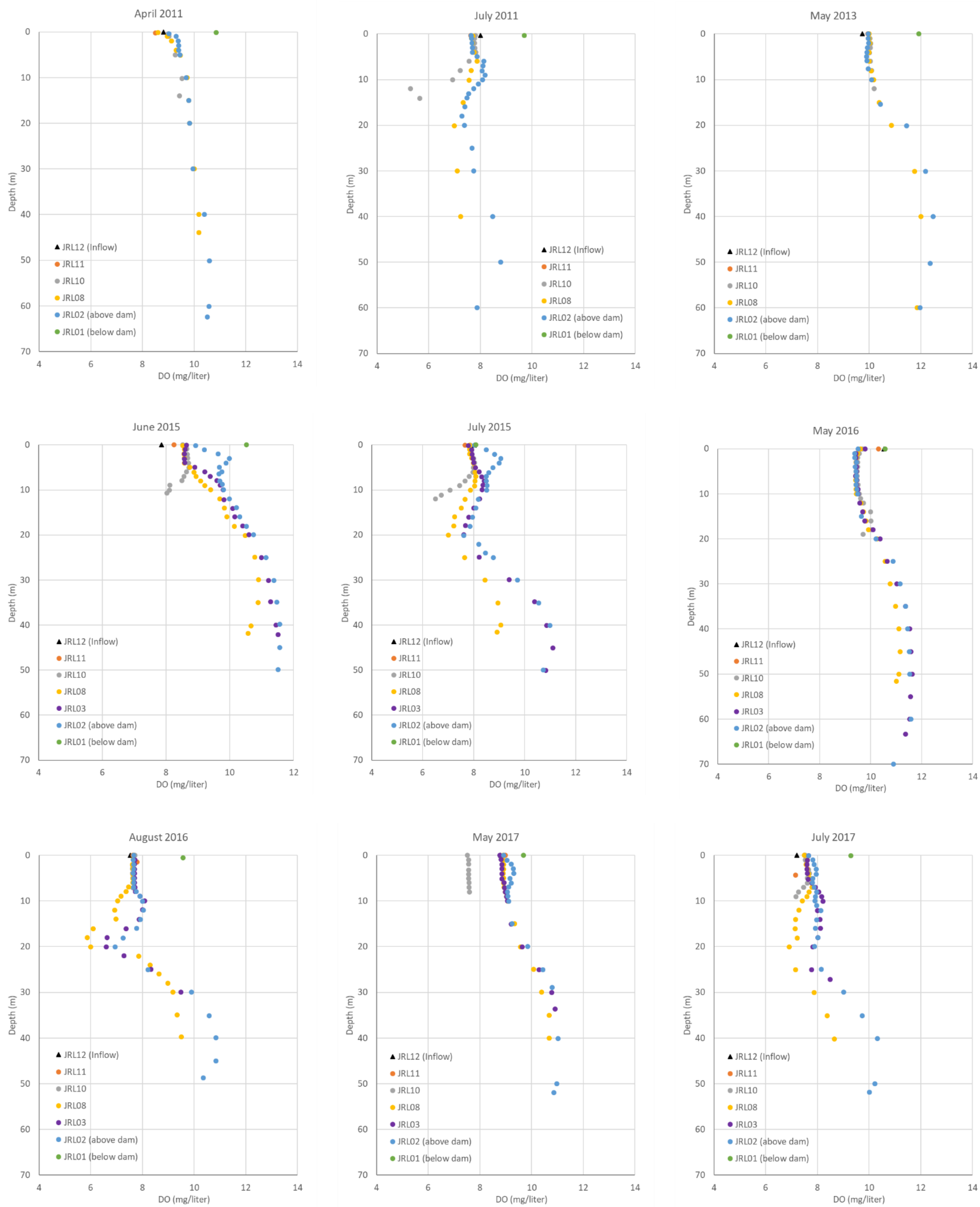




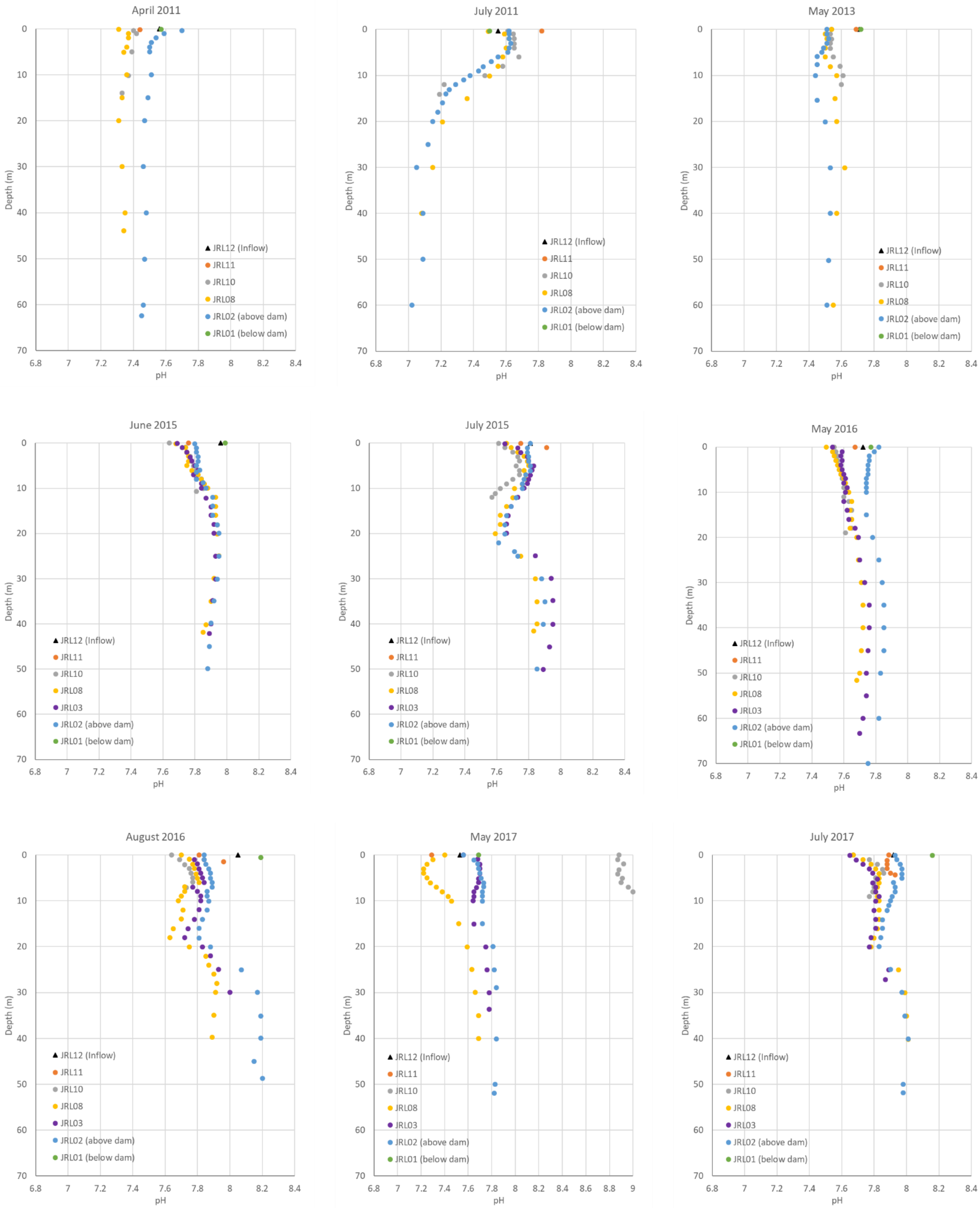




Depth Profiles of Dissolved Oxygen



Depth Profiles of pH



Depth Profiles of Specific Conductivity