A Dam Conundrum: The Role of Impoundments in Stream Flow Alteration

Connor O. Brogan

Thesis submitted to the faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Biological Systems Engineering

Durelle T. Scott, Chair
Robert W. Burgholzer
Julie E. Shortridge

August 2nd, 2018
Blacksburg, VA

Keywords: Impoundment, flow alteration, drought, flood, ponds, reservoirs, hydraulic modeling, artificial waterbodies, water resource management,

A Dam Conundrum: The Role of Impoundments in Stream Flow Alteration

Connor O. Brogan

ABSTRACT

Over the past century, the world's rivers have become increasingly impounded to combat water scarcity and fossil-fuel reliance. Large dams have faded from popularity due to their adverse environmental effects, but small ponds and reservoirs continue to be constructed at high rates. Due to limited data regarding their size and flow, it has been difficult to assess how these smaller impoundments impact rivers. This study combined rainfall runoff data from the Chesapeake Bay Model with the unique routing framework of VA Hydro to create a simplistic hydrologic model capable of analyzing impoundment-induced flow alteration. Using standard design techniques and satellite imagery, a methodology was developed to build realistic stage-storage-discharge relationships for small and large impoundments. Eleven impoundments of the Difficult Run watershed were modeled within VA Hydro to assess their cumulative impact on downstream flow. Multiple models were created with different active impoundments and run for the full model period, 1984 – 2005. Flow alteration increased significantly with additional impoundments. Peak flows were attenuated as water was stored behind outlets, but median flows were increased as this water was slowly released. Average storm duration increased due to extended rising and falling limbs caused by impoundment outlets. Headwater channels increasingly ran dry, decreasing extreme low flows due to impoundment evaporation. Large reservoirs had a greater impact on median flows, but smaller ponds dominated low flow alteration. These results suggest that traditional hydrologic assumptions and metrics may be incapable of analyzing a changing flow regime without explicitly considering small and large impoundments upstream.

A Dam Conundrum: The Role of Impoundments in Stream Flow Alteration

Connor O. Brogan

GENERAL AUDIENCE ABSTRACT

At first look, dams are an excellent solution to water scarcity and energy independence. They trap clean water and direct it through turbines. Unfortunately, their installation and operation creates many negative environmental impacts by fundamentally altering downstream channels, leading to a loss of fish vitality and river function. Large dam construction has decreased in the US because of these effects, but small dams continue to be built at high rates due to growing agricultural and stormwater demands. Their impact on rivers is less understood due to limited data availability regarding their size and function. This experiment used standard design techniques and widely available satellite data to create a representative model for dams of all size. Multiple tests were run, progressively increasing the number of dams within a watershed and analyzing their impact on downstream flow. With increased impoundment, high floods decreased in magnitude. However, more-typical medium flows increased. River flow became more static, with less extreme floods and more medium flows. The modeled dams greatly decreased drought flows as trapped water evaporated and decreased outflow. This impact was particularly noticeable in ponds that drained only a small area as they took longer to refill after drying. Larger dams more greatly impacted medium flows. These results contribute significantly to water availability prediction by more realistically representing dam processes. Although more work is needed to refine the impoundment modeling strategy, this study has effectively demonstrated that small and large dams affect flow in different manners and need to be accounted for accordingly.

Acknowledgements

A number of people helped me get to this point in my brief career as a graduate student. Of course, I'd like to start off by thanking **Dr. Durelle Scott** for always encouraging me to look at all of my options. Way back in my sophomore year, you showed me all of the awesome things hydrologists could do. I've greatly appreciated the enthusiasm you bring to the lab group even as model debugging goes several weeks longer than it is meant to. Thank you for always having time to help me sort through the seemingly illogical flaws in my models!

Since I'm starting off back in sophomore year, I'd like to next thank **Robert Burgholzer** for being one of the best go-to modelers our department has produced. Whether it was a late night or the middle of a Saturday, you were always around to provide a quick answer to my long-winded questions. I've depended on your modeling/R shortcuts for the last few years and would not have been able to accomplish this project on time without them! **Joseph Kleiner**, same goes to you. It's been great working with you since my early days in HARP as it has always assuring to know "Ask Joey" is probably one of the answers to my R questions.

I owe special thanks to **Dr. Julie Shortridge** for signing onto my committee and allowing me to work with her as a GRA. You've had to read through more than your fair share of my "short" update journals. I envy your ability to keep meetings on-track and appreciate your patience as we slowly unfolded the mystery behind the ECHO-VPDES relationship.

I think I owe both a thanks and an apology to the **HARP** group. **Alex Domiano**, **Alyssa Ford,** and **Elaina Passero**, sorry for always taking up 25% of our hour long meetings with my "5 minute update". Hopefully, they weren't as boring as they seemed. Thanks for always sticking with me and providing polite feedback on my unlabeled and unmarked figures. I appreciated getting the chance to onboard all of you and highly enjoyed watching your projects unfold!

Tyler Keys, thanks for staying with this project until the end. I can imagine that your last semester was more than a little stressful, so thanks for always replying to my emails and keeping up-to-date with all the model changes. It was great having somebody else to work through all of the many bugs we ran into. Also, thanks for actually being organized enough to visit Difficult Run. Since I'm now venturing further into Team Scotty, I owe thanks to **Madeline Ryan** and **Mohammad Yazdi** for helping me out throughout the past two years, both in classes and in lab meetings. I've appreciated all the feedback you've given during my project updates and had fun working through the stat and R problems that came up in classes!

A very sincere thanks to **Suri Solis** for listening to my countless rants and babbles about ponds, dams, models, school, and everything between. I wouldn't have been able to get through this project without someone there to hear my stream of consciousness as I programed my scripts!

My family deserves a lot of credit for this project as well. They've supported me through this whole process with constant free thoughts, feedback, and food. Thanks to **Quinn Brogan** for encouraging me to give graduate school a try despite your own misgivings, and special thanks to **Brendan Brogan** for the constant distractions (although fewer hangovers may have helped).

I wouldn't be much of a Captain if I didn't at least owe some thanks to the Hurling Club. The **Blacksburg Scourge** has been a source of pride for me since we started the club. I'm glad you guys gave me a shot at captain, even if I still haven't technically scored a point.

Finally, thank you to all of my friends and roommates. **Caleb Gerry Goertel, Peter "The Pirate" Price, Joshua "No Warm-Up" Rosenthal, Daniel "Manvoice" Ruwe,** and **Joseph "The V is for Victory" Sarver,** thank you for all the sarcastic encouragement that has gotten me through graduate school. I've relied on you guys for academic help, general advice, and, of course, entertainment throughout my collegiate career. Finally, shout out to the **Thursday Lunch Club**.

Table of Contents

List of Table**s**

List of Figure**s**

1 Introduction

Since the early days of Western Colonization, humans have been expanding in both number and space. In just 500 years, the global population underwent more than a 10-fold growth that significantly augmented urban area around the planet (Liu et al., 2014a). In fact, the twentieth century marked the first period in human history where a doubling of the population occurred within a single lifespan (Cohen, 2003). Consequences of this expansion have affected many fields, straining agricultural, industrial, and residential resources. At the root of these issues lay a growing need for freshwater. Over the next 50 years, rising manufacturing and electrical demand is projected to increase world water usage by 55% (OECD, 2012). Unfortunately, water supply and management have become complex issues. Land use changes, water quality, and space limitations present new challenges every day and place much of the population at risk of losing water security (Brinkman et al., 1985; Vörösmarty et al., 2010).

A popular 20th century solution to rising energy, agriculture, and water demands was to dam rivers (Vörösmarty et al., 1997). Dams physically impound water behind large earthen, concrete, or steel structures built directly in the stream channel. Water resource managers control their volume and outflow, shaping impoundments to the available space and present demand (Mays, 2011). Dams serve a variety of purposes, but often store water for irrigation, slow water for hydroelectric operations, and provide opportunities for aquatic recreation (ACE, 2016). Indeed, dams have become a worldwide phenomenon (Döll et al., 2009; Sahagian, 2000; Yang and Lu, 2014). Global storage in dams has increased by nearly 700% over the past 50 years and hundreds of new projects are planned in some of the world's largest rivers (Vörösmarty et al., 1997; Winemiller et al., 2017). Many countries have turned to dams as a potential means of creating sources of freshwater and establishing energy independence (Timpe et al., 2013).

Despite their water supply benefits, large dams have been linked to a number of environmental issues. In fact, the impact of dams and their corresponding impoundments is well-documented (Poff et al., 1997; Poff and Hart, 2002; Williams and Wolman, 1984; Vörösmarty et al., 1997; Vörösmarty et al., 2010). Depending on their management (frequency dredged, water release strategies, etc.), dams may transform aquatic nutrient processing downstream by limiting chemical quantities leaving the impoundment and trapping sediment (Poff et al., 1997; Vörösmarty et al., 1997). In addition, they release low temperature, high-energy water that drives geomorphologic shifts in channel pattern and geometry downstream through intense scouring and erosion (Williams and Wolman, 1984). Multiple studies have further related dams to ecologic damage and decreased biodiversity (Poff et al., 1997; Poff and Hart, 2002; Vörösmarty et al., 2010). By controlling the amount of water discharged downstream, dams effectively curtail the natural flow regime. Impoundments inherently stabilize the typical stream hydrograph, raising low-flows only to attenuate peak floods. Manual controlled outlets (those independent of the water level within the impoundment) may fundamentally change the timing, duration, and frequency of downstream flows if water is discharged on a set schedule (Poff et al., 1997). Native fish and riparian vegetation rely on natural flow patterns for breeding and habitat, depending on flood frequency, magnitude, timing, duration, and rate-of-change to keep them competitive with more generalist species. Since impoundments alter each component of this flow regime, dams may profoundly affect ecosystem biodiversity and vitality (Poff et al., 1997; Poff and Hart, 2002; Vörösmarty et al., 2010).

1.2 Pond Proliferation

1.2.1 Small Ponds

Despite its unsustainable environmental impacts, impoundment creation is not unique to developing nations who are reliant on hydropower energy. In fact, over 90,000 regulated dams ranging from 2-235,500 acre-feet in storage currently exist in the United States (with many more unregulated dams) (ACE, 2016). Over the past 60 years, the construction rate of large dams has fallen significantly as a result of extensive research into downstream impacts (Ayalew et al., 2017). However, the overall impoundment ratio in the United States has remained unchanged due to the proliferation of small dams in the stream network (Downing et al., 2006). Smaller impoundments became popular in the mid-1900s when the US government subsidized pond construction to promote the agriculture and livestock industries (Renwick et al., 2006). This sparked a period of rapid impoundment within the US, where large and small dams were installed throughout the nation's rural river networks (Fairchild et al., 2012). Small pond density within Texas, for example, increased by nearly 350% between 1937 and 2012 (Berg et al., 2016). Overtime, the construction rate of large dams fell with rising environmental awareness, but small dams continued to be built at a rapid pace (Downing et al., 2006; Smith et al., 2002). Since the 1970s, the majority of new impoundments have been constructed in urban areas, reflecting the need for stormwater management and water supply (Renwick et al., 2006; Fairchild et al., 2012). Rates of impoundment vary throughout the country, but tend to be highest in the Midwest and East Coast, due to rising populations and agricultural demand (Berg et al., 2016; Downing et al., 2006; Mogollón et al., 2016).

Despite fluctuations in construction rate, impoundment within the United States has consistently been dominated by smaller structures (Fairchild et al., 2012). Initial investigations into early 21st century national land cover and aerial photography databases revealed 2.6 million waterbodies above 0.25 ac in surface area, but nearly 9 million above 0.006 ac (Smith et al., 2002). Smaller waterbodies are typically found in areas of high limnetic densities (number of impoundments per unit area) and are by far the most numerically dominant (Chumchal et al., 2016). In fact, it has been estimated that as much as 170 million acres of global water is impounded (16% of global surface water) in ponds less than 2.5 ac in area (Downing, 2010).

When examining small and large impoundments and their associated dams, it is useful to define a more concrete set of terminology than is present in the literature (Smith et al., 2002). Table 1 describes the defining characteristics of the terms used in this paper. Essentially, the classification of dams (and their impoundments) into "large" (reservoirs) or "small" (ponds) varies, but the Army Corps of Engineers suggests a working rule: small dams are those that are either below 25 feet in height and store less than 15 ac-ft or below 6 ft in height and store less than 25 ac-ft. All others are considered large (2016).

<u>1.2.2 The Problem with Ponds</u>

Ponds are the most numerically dominant type of impoundment, both across the world and within the United States (Döll et al., 2000; Downing et al., 2006). They are popular in rural and urban areas, serving as means of stormwater retention, livestock watering, irrigation, sediment control, etc. (Ayalew et al., 2017; Fairchild et al., 2012; Renwick et al., 2005). In fact, it is estimated that over 20 percent of United States land area lies upstream of at least one pond (Renwick et al., 2005). Despite their prevalence in the flow network, however, these smaller structures have received significantly less attention than their reservoir counterparts (Downing et al., 2010; Poff and Hart, 2002; Sahagian, 2000). Studies are restricted both by the limited available information on ponds and the fact that smaller waterbodies are often underrepresented in impoundment datasets due to differences in regulation and photographic resolution (Smith et al., 2002). In Virginia, for instance, construction permits and impoundment safety regulations only apply to reservoirs; ponds are unregulated and may be built at whim. Although the Army Corps of Engineers requires reservoir managers to submit information about impoundment geometry and storage, no such effort is made for ponds (ACE, 2016). An additional challenge is that there is little formal documentation or quantification on pond longevity. These structures are often poorly maintained and fill rapidly with sediment (Berg et al., 2016). Although construction rates tend to surpass disappearance rate, pond density and counts fluctuate greatly with time (Downing et al., 2010; Fairchild et al., 2012; Smith et al., 2002).

The limited availability of small pond data has led to wide-scale assumptions that they either negligibly effect stream characteristics or that their impact is overshadowed by larger structures (Ayalew et al., 2017; Berg et al., 2016; Downing, 2010). However, preliminary research on small impoundments (both ponds and small reservoirs) shows that ponds may both individually and cumulatively play a large role in determining downstream water quality/quantity. For instance, when estimating the number of waterbodies across the United States, researchers found that small waterbodies trapped 300 tons/km^2 of sediment per year, representing nearly half of all sediment held in impoundments (Smith et al., 2002). They found that sediment accretion rates were high in smaller impoundments, creating shallow ponds that experience more evaporation and temperature change than their larger counterparts. Ponds may cumulatively impact downstream sediment deposition by as much as 50%, greatly slowing downstream aggradation rates (Berg et al., 2016). Recent estimates at a global carbon budget show that small ponds contribute disproportionately to carbon dioxide and methane emissions as well. Accounting for only 9% of the freshwater surface area on Earth, small ponds contribute up to 15% of global CO_2 and 40% of CH_4. The ponds interact more regularly with their shoreline due to small surface areas and volume. This leads to larger sediment processing rates that bolster carbon consumption, increasing CO_2 and CH_4 production. However, unlike reservoirs, ponds are so shallow that methane generated in the bed rises rapidly to the surface with little water column oxidation into carbon dioxide. Combined with their large carbon metabolism, ponds dominate the global methane budget by generating high volumes of the gas and releasing it without significant attenuation (Holgerson et al., 2016). The high rates of infilling further suggest that ponds bury a significant amount of carbon each year. In fact, some studies have inferred from the active carbon processing and accretion rates that ponds annually sequester as much as carbon as the world’s ocean (Downing, 2010).

Small impoundments are hotspots for biogeochemical processing, providing higher temperatures, dissolved oxygen concentrations, and sediment interaction than larger reservoirs (Downing, 2010). The impacts of ponds on water quality can readily be traced to their hydrological effects. For instance, several studies suggest that even these ponds can increase water retention time within a reach (Downing, 2010; Smith et al., 2002). The increased residence time allows for nutrient processing and settling, contributing to the sediment deposition and carbon metabolism mentioned earlier. By increasing the travel time in a reach, ponds also alter peak and low flows, resulting in attenuated floods and increased drought flows (Liu et al., 2014b). In general, small reservoirs and ponds stabilize river flow regimes by complementing decreased peak flows with significantly increased medium sized floods (Ayalew et al., 2017). Ponds may also affect annual flows when water use is high and farm impoundments run dry. A study conducted in Botswana found that dry farm ponds and small reservoirs lowered downstream flow by as much as 10% while filling (Meigh, 1995). Additionally, impoundments (an assortment of ponds and reservoirs) used in place of irrigation diversions in California impaired state mean annual flows by as much as 25% when allowed to empty and fill (Deitch et al., 2013).

1.2.3 Impounding the World's Most Biodiverse Rivers: A Case Study

A flurry of planned hydroelectric dams in the world's three most biodiverse rivers–the Mekong, Congo, and Amazon–has prompted closer examination of how a network of ponds and reservoirs may cumulatively impact hydrology (Winemiller et al., 2017). One research group paired a rainfall-runoff model with a 2D hydraulic model of the Mekong basin to investigate how 50 planned and constructed dams would affect an important downstream reservoir, the Tonle Sap. They found medium sized floods were reduced in magnitude, but fed increased low flows. In general, this resulted in more stationary lake levels, decreasing seasonal inundation and the rate of water level rise and fall. They projected these changes will result in major ecological disruptions due to the dependence of native species on natural flow conditions (Arias et al., 2014). Although this study involved both large and small impoundments, it is clear that hydrologic models must capture the cumulative effect of dams to examine adequately the flow regime. In this particular study, impoundment played a large role in determining flood magnitude, timing, and duration (Arias et al., 2014)

A similar study was conducted in the Amazon, where researchers Timpe et al. (2013) observed 33 streams before and after dam construction. The magnitude of floods and low flows altered only slightly after closure (the beginning of dam operation). The rate-of-change of river flow and overall flood frequency, however, changed dramatically. Peak flows became less frequent as the river hydrograph stabilized. The authors linked these changes to longer storm durations, as impoundments artificially extended rising and falling limbs of storms downstream. This was particularly the case downstream of smaller dams, which experienced the greatest overall alteration. The researchers further found that multiple dams on a reach compounded the change to the natural flow regime, with more altered flow on more heavily impounded reaches. Ultimately, the dams are cumulatively expected to diminish floodplain connectivity and aquatic diversity by eliminating extreme flows and creating a more stable environment for generalist species (Timpe et al., 2013).

These studies of large river basins demonstrate the importance of understanding how ponds and reservoirs affect water quality/quantity and why it is necessary to view their impact from a cumulative perspective (Winemiller et al., 2017). Studying impoundments in isolation can limit observations of larger scale processes. Timpe et al. (2013), for instance, found increasingly altered river rise and fall rates when moving downstream within a network of impoundments. Many studies agree that flow alteration from impoundment is dependent on a number of factors including drainage area, depth, and storage (Downing, 2010; Deitch et al., 2013; Timpe et al., 2013). To quantify basin-wide affects, it is necessary to observe how a network of impoundments including both ponds and reservoirs affects river flow, rather than trying to extrapolate from just a few individual case studies (Winemiller et al., 2017). This is particularly true for smaller impoundments and ponds, which are often overshadowed in studies examining the cumulative impact of large dams (see Timpe et al., 2013).

1.3 Understanding Impoundment Characteristics

1.3.1 Design Perspective

Although it is clear that impoundments differentially alter the flow regime, it remains a difficult task to capture these effects in a comprehensive hydraulic model. Indeed, the aforementioned studies all relied on depth-discharge relationships (Arias et al., 2014; Liu et al., 2014b) or bathymetrical surveys (Meigh, 1995) specific to the study region. Unfortunately, such rating curves and geometric information are not widely available in the United States. The Army Corps of Engineers collects basic information on reservoir storage, but contains no data describing unregulated ponds (ACE, 2016). In addition, the Corps' data collection system, the National Inventory of Dams (NID), contains inaccurate storage, depth, and geometry that affects up to two thirds of their reported reservoirs (Poff and Hart, 2002).

Without adequate information regarding impoundment characteristics, it is necessary to estimate the two most important components of artificial waterbody design: the storage (determining how much water may be retained within the impoundment) and the outlet (setting the rate at which water is discharged from the impoundment) (Ayalew et al., 2017; Meigh, 1995). Unfortunately, this data is not often present in public databases. As mentioned earlier, the NID collects information pertaining to the volume of reservoirs, but lacks any information regarding ponds (ACE, 2016). To further complicate matters, impoundment characteristics vary spatially across a watershed. Waterbody designated use, available space, management, and upkeep differentially drive impoundment design geometry and outlet (Mays, 2011). For instance, a hydroelectric dam built under a design impoundment depth can vary in surface area and volume based on the bathymetry of the bed or the amount of purchased land around the dam. The impoundment behind a hydroelectric dam would be deeper than a similar recreational pond/reservoir due to the required head for power generation (Mays, 2011).

With site-dependent constraints and criteria, it is difficult to estimate impoundment characteristics from simple regressions or mathematical formulations. However, the United States Department of Agriculture (USDA), National Resource Conservation Service (NRCS), and the Virginia Commonwealth government maintain several useful guidelines and regulations intended to inform impoundment design. From these standards, it is possible to better grasp how impoundments vary across a landscape. For instance, the USDA published impoundment design guidelines in 1982 to aid farmers and urban planners in designing small ponds. For ponds excavated and dug out around a stream channel, they recommend building a rectangular basin for ease of construction. These should be graded to the surrounding landscape using a side slope of 1:1 or flatter (USDA, 1982). The USDA emphasizes that depth is the most important variable in impoundment design, and that all ponds should be built to a minimum depth of 5 – 14 ft depending on physiographic province, geology, and soil (generally around 6-7 ft in Virginia) (USDA, 1982). No maximum depth for impoundment was listed, but it is generally noted that ponds require two feet of freeboard near the top of their outlet or embankment that should only be filled by water during extreme floods (NRCS 378, 2011). Excavated pond geometry is likely to follow these guidelines and create rather static relationships between pond volume and overall surface area; however, embankment impoundments (those created by simply damming a channel and allow water to flood the surrounding land) may vary more complexly (USDA, 1982). It is difficult to determine whether a pond is excavated or embanked without detailed bathymetry data, but the USDA guidelines offer preliminary insight into how impoundment design varies in a watershed.

While geometry guidelines are vague and often dependent on site conditions, outlet size is heavily regulated. To prevent flooding, dam bursts, and excessive storm surges, state regulators passed Virginia state code 4VAC50-20-50 explicitly subjecting impoundments to outlet sizing restrictions. All reservoirs must pass either the probable maximum flood or the 100-year storm event, depending on dam hazard class (likelihood of loss of life or property because of dam failure). Small ponds are generally considered low hazard due to their low volume and shallow depths, meaning most ponds would only need to pass the 100-year storm (Code 4VAC50-20-40).

It should be noted that these requirements apply to the combined discharge leaving the impoundment (NRCS 378, 2011). As shown in Figure 1, impoundments typically have two spillways used to pass water from the waterbody to a receiving channel: the principal and the auxiliary spillway. Principal spillways are optional under USDA guidelines, but control normal pool elevation (long-term average water level) when implemented by releasing typical, daily flows. These structures are designed to release the 1- to 10-year storm flow and may take a variety of forms (USDA, 1982). Often constructed as orifices, many principle spillways carry water through the dam or embankment. Other common structures include those in the impoundment itself, including hooded drop inlets, morning glories, and simple weirs. The specific type of outlet used in a given impoundment may depend on aesthetic appeal, site criteria, and cost as many of the designs are interchangeable. Outlet discharge, on the other hand, is more constrained. All structures are sized as a function of design storm flow and available hydraulic head above the spillway (Mays, 2011). In other words, outlets are sized to pass the 1- to 10-year storm without violating the freeboard allotted to the dam based on its geometry (USDA, 1982).

The auxiliary spillway carries the remainder of the flow. Also known as the emergency spillway, these outlet structures often take the form of large weirs or diversion channels and are placed about 1-2 ft above the crest of the principal spillway (NRCS 378, 2011). If a principal spillway is present, the auxiliary spillway is designed to only be active during extreme flows, with dimensions sized to pass anywhere from the 25- to 100-year floods (USDA, 1982; NRCS 378, 2011). Some small ponds exclusively have auxiliary spillways, in which case the structure acts to pass both typical and extreme flows. It is often required that the auxiliary spillway pass the design flows listed under Virginia state regulations even if the principal spillway is blocked or otherwise dysfunctional (USDA, 1982).

In general, outlets are sized by selecting design storms under state regulations, examining draft impoundment bathymetry to determine available hydraulic head, and then back-calculating outlet dimensions from hydraulics equations (DEQ, 1999; VDOT, 2011). Design storm hydrographs are routed through the basin to ensure storms pass without violating freeboard requirements. Structures are otherwise incrementally increased in size until storms are passed successfully (USDA, 1982). Design flows are commonly calculated using the rationale formula, the soil conservation service approach, or some other function of land use and/or drainage area (DEQ, 1999; USDA, 1982; VDOT, 2011). Available stormwater and impoundment guidelines do not recommend any one method, but instead insist that the best available information be used to select flows. Storm routing is emphasized as an effective means of confirming outlet dimension calculations (DEQ, 1999; VDOT, 2011).

1.3.2 Large Data Perspective

National, state, and local guidelines and regulations show general patterns in impoundment design. Impoundments are recommended to be evenly shaped, but may follow the pattern of the land. They have outlet structures sized strictly to design storms based on maximum head and impoundment drainage area (NRCS 378, 2011; USDA, 1982). Although geometry is still largely determined by available land and intended use, many researchers have begun piecing together regulations with field data to establish general impoundment relationships. For instance, several studies have demonstrated strong power relationships between waterbody surface area and storage (Downing, 2006; Yang and Lu, 2014). These set relationships support the general guideline that impoundments are built with some common geometry. Surface area would otherwise scale unevenly with volume and create poor fits. Some researchers have noted the large differences in perimeter to surface area ratios between excavated (more static) and embanked (more dynamic) impoundments and attempted to estimate volume through an average distance-to-shoreline calculation. It was assumed that embanked ponds would have lower values due to their branching geometries. However, these relationships failed to improve volume estimates compared to the standard procedure of assuming a geometry and back calculating volume from surface area (Hollister and Milstead, 2010). A similar study on natural lakes found a strong relationship between surface area and surrounding relief with volume (Heathcote et al., 2015). These results further suggest that even embanked impoundments that tend to have less even bathymetry still maintain generally predictable volumes.

Although trends in impoundment geometry have been increasingly studied over the past decade, hydraulic modelers have yet to find a scaling methodology to estimate outlet structure size or behavior. A lot of studies require extensive surveys or pre-existing rating curves in order to model outflow from ponds (Arias et al., 2014; Ayalew et al., 2017; Liu et al., 2014b; Meigh, 1995). When this data is unavailable, some studies have instead selected to model impoundments as either full or empty. In these cases, impoundments are initiated completely empty and slowly fill over the model period. Once full, they release all incoming water as outflow. They otherwise do not discharge water (Deitch et al., 2013). Other modelers have selected to aggregate impoundments, summing waterbody volume or surface area across a given river length. These studies examine stream gauge data over long reaches before and after dams are constructed to determine how impoundment has cumulatively affected flow (Batalla et al., 2004; Timpe et al., 2017).

Despite the limited hydraulics in many of these models, current studies clearly suggest a relationship between impoundment and flow alteration. In general, a higher number of impoundments within a network produces more alteration. In fact, many authors have normalized results using some form of the "impoundment ratio". This metric typically expresses aggregate impoundment storage over reach mean annual flow (Batalla et al., 2004). In doing so, the impoundment ratio measures the degree to which a given channel has been modified by ponds and reservoirs (Yang and Lu, 2014). One study examining recent dam construction in Spain found a strong correlation between the impoundment ratio of a river and changes in flood magnitude after dam closure (Batalla et al., 2004). It is in general assumed that the larger this ratio, the greater the impact of impoundment on the flow regime (Yang and Lu, 2014). If future models are to estimate outlet structures more specifically, it should be expected that reservoirs in headwater regions will have a more pronounced effect on the flow regime than downstream ponds (small volume and higher mean annual flow, resulting in a small impoundment ratio).

1.4 Impoundment Model Framework

1.4.1 Goals and Objectives

There is a present need to develop a modeling framework capable of analyzing impoundment from a network level perspective (Winemiller et al., 2017). Preliminary studies reveal that ponds and reservoirs may have substantial impacts on watershed hydrology and water quality (Downing et al., 2010; Yang and Lu, 2014). An optimal model would examine pond/reservoir hydraulics at fine spatial and temporal resolutions, capturing all alterations to the river flow regime. The lack of information available on impoundment construction and geometry indicates that such a model will require broad inference regarding pond/reservoir design (Hollister and Milsead, 2010). The model should be instructed by available guidelines and regulations to ensure accurate illustrations of impoundment characteristics. Bathymetry may be further refined through guiding relationships, like the power correlations described in Yang and Lu (2014) and Downing et al. (2006). With high spatial and temporal resolutions, outlet structures may be designed through industrial approaches: selecting design storms, back calculating required dimensions, and routing storms to ensure proper function (DEQ, 1999; USDA, 1982; VDOT, 2011).

It is the goal of this project to create such a framework. Using widely available data and standard design approaches, impoundment geometry and outlet behavior may be estimated such that their impact on flow alteration can be studied in a rainfall-runoff model. Rainfall-runoff methodologies prevail in hydrologic research to such an extent that many calibrated models are available to serve as a basis for more advanced calculations. Indeed, several different models already exist that generate accurate runoff and flow data for use in impoundment design and analysis. In fact, the Virginia Department of Environmental Quality (DEQ) created an in-house framework–termed VA Hydro–that serves as an excellent means for examining impoundment-induced flow alteration.

By examining small impoundment in the context of a hydrologic model, this project intends to investigate how low flows are affected by impoundments. Since impoundments are built within the river channel and increase retention time, it is likely they attenuate peak flows and store water. But, their effects of critical ecologic flows and water availability during droughts is less clear. Further, by analyzing how ponds and reservoirs differentially impact river flow, this project will determine whether hydrologic questions need to be examined in the context of upstream impoundment. The impoundment framework will explore how ponds and reservoirs both individually and cumulatively effect flow during droughts, baseflow, and peak flows. So, the three guiding questions of this project are:

1. Can small impoundents be modeled with limited field data?
2. How do small impoundments impact peaks flows?

3. Is the flow regime (flow magnitude, frequency, rate-of-change, timing, and duration) a function of upstream cumulative impoundment?

1.4.2 VA Hydro

VA Hydro is a comprehensive, modular flow model that combines several empirical and deterministic approaches to examining watershed flow, as illustrated in the conceptual diagram in Figure 2. Runoff is generated from the calibrated Chesapeake Bay Model. An extensive water quality model funded by the Environmental Protection Agency, the Chesapeake Bay Model is a Hydrologic Simulation Program Fortran (HSPF) model developed to examine pollutant flow into the Chesapeake Bay from 1984 - 2005. It models water, nutrient, and sediment generation and transport using a variety of empirical and deterministic equations throughout the 64,000 square mile watershed that spans six states on the United States East Coast (USEPA, 2010). The model operates on fundamental hydrologic response units termed land-river segments that are derived in a two-step process. First, the Chesapeake Bay watershed was split along county lines to form land segments. These serve as the basic unit for water quality simulation, representing contaminant sources, sinks, and processes across the landscape. Large rivers (those with mean annual flow greater than 100 cfs) were then divided into roughly 1000 river-segments. Estimated hourly rainfall/evapotranspiration and long-term average land use are evaluated to generate infiltration, runoff, groundwater flow, interflow, and storage at each reach using an hourly timestep over the model period (1984-2005). These processes were calibrated against 272 daily flow gauges run by the United States Geologic Survey (USGS) at river segments outlets. River segments were intersected with land segments to form the base response unit, land-river segments. These fundamental model units are thus capable of expressing model water quality and quantity, with the pollutants and runoff generated in land segments flowing into river segments for routing (USEPA, 2010).

VA Hydro uses the calibrated Chesapeake Bay model for its hourly output of rainfall, evaporation, and runoff. It estimates runoff per unit area by calculating combined hourly outputs of interflow, surface quickflow, and baseflow at each land-river segment and dividing by the basin area. In doing so, it normalizes output runoff from the Chesapeake Bay model and converts it into a form capable of working with downsized catchments. VA Hydro is based on a catchment-scale water mass balance. The conceptual image in Figure 2 demonstrates how small catchments are operated and linked in larger VA Hydro watershed models. In essence, a watershed is broken into reaches at each large river conjunction, impoundment, or any user-selected attribute. Each catchment receives area-scaled runoff from the nearest Chesapeake Bay river segment. This water is routed through artificial channels with lengths defined in the revised USGS National Hydrography Dataset (NHDPlus) using the Muskingum procedure (Chow, 1959; Grill, 1978; USEPA, 2012). Channel geometry (width, depth, cross-sectional area) and roughness are estimated using USGS regional curves based on the catchment physiographic province and drainage area (Lotspeich, 2009). At the most downstream point of each catchment, water is optionally routed through a user defined impoundment. The user specifies stage-storage-discharge relationships, with water routing through the pond or reservoir using the Modified Puls method (Mays, 2011). Chesapeake Bay model precipitation and evaporation are referenced within this calculation to ensure climatic conditions over the waterbody are adequately accounted for. Users may further specify point source discharges or withdrawals within the area. Water released from the bottom of the reach (or from the optional impoundment) is fed to the next most-upstream basin. A VA Hydro watershed may be compared to USGS gauge data by examining output flow at the most-downstream segment containing the gauge. The model may be calibrated by adjusting the parameters of the Chesapeake Bay HSPF simulation, changing channel lengths, or modifying the impoundment dimensions.

VA Hydro serves as a useful framework for investigating the impact of impoundment on flow alteration. By drawing in pre-calibrated runoff and climate variables, VA Hydro modelers ignore the initial steps of formatting land use, calibrating hydrology variables, and validating runoff data. Instead, they may instantly begin shaping their watershed using scaled-Chesapeake Bay flow data. The toggle switch for impoundments at the bottom of each catchment facilitates flow alteration analysis, enabling routing with and without impoundments. Furthermore, the object oriented programming of VA Hydro makes it easy to model complex networks of channels and impoundments by simply creating more upstream or downstream catchments and modifying drainage areas, channel lengths, and impoundment stage-storage-discharge relationships. Various impoundment and outlet configurations may be tested within a single VA Hydro model to determine how estimated relationships differentially alter flow. Finally, since the Chesapeake Bay model offers 20 years of data, long-term testing may be conducted to determine how impoundments not only affect daily and annual flow, but also flood/drought frequency.

1.5 Low Flow Analyses

This study focused on a small watershed to hone impoundment relationships and test outlet/geometry configurations. Each impoundment within the study site was converted into a VA Hydro catchment and assembled into a basin-wide model. Power regressions were established to relate limited reservoir storage information to surface area available from satellite imagery (Downing, 2006; Yang and Lu, 2014). Impoundment geometry was interpolated from this relationship and available guidelines, assumed as some function of set side-slope and surrounding topography (DEQ, 1999; Heathcote et al., 2015; USDA, 1982; VDOT, 2011). Long-term flow from a USGS gauge at the outlet of the watershed was examined to derive design flows. These flows were scaled by catchment area and used to size impoundment outlet structures. An iterative calibration procedure was employed to increment structures that failed to pass design storms upon routing. With the VA Hydro model assembled, several simulations were conducted. First, the model was run to determine baseline flow over the 21-year period. Impoundments were toggled off and flow was compared to gauge data to ensure proper model fit. After switching impoundments on, a second run was conducted to analyze the impact of impoundment on flow alteration. In particular, this study was interested in the possible correlation between impoundment and drought water availability. By examining the change in the river low flow regime, the results of this study may be used in evaluating how critical drought habitat changes with impoundment, assessing water availability models for the area, and improving future point source discharge permitting (which relies heavily on low flow limits) (Saunders III et al., 2004).

Low flow analyses quantify changes in the magnitude, frequency, timing, rate-of-change and duration of drought flows. One common metric used in regulatory planning is the 7Q10: the lowest expected weekly average flow likely to occur within a ten-year period (Saunders III et al., 2004). By aggregating data to a weekly average, the 7Q10 metric examines how alteration to low flows influences both magnitude and duration of flows. Longer droughts would be reflected in lower 7Q10s, whereas higher magnitude low flows would increase weekly average flow and thus the 7Q10 statistic. In addition, by evaluating data over a decadal timespans, 7Q10 is capable of capturing changes in low flow frequency, with more frequent droughts reflected by a lower 7Q10. Other metrics of the same form (30Q2, 7Q2, etc.) are capable of analyzing more specifically how droughts are affected over different return periods or durations.

Unfortunately, 7Q10 depends on extensive low flow records. Accurate analyses involving metrics of this kind require 50-60 years of daily flow data (Sharma et al., 2015). In addition, 7Q10 fails to assess low flow timing, instead analyzing their duration, frequency, and magnitude. So, this study supplemented the traditional 7Q10 analysis with additional low flow metrics including August low flow (ALF) and September 10% flow that respond within the 21-year study period (Arias et al., 2014). These metrics compute the median minimum August flow and the 10% quantile September flow, respectively. In doing so, they analyze how low flow timing may change by demonstrating alteration in monthly flows. August and September are hot, dry months on the US East Coast and typically produce the lowest flows in an annual hydrograph. So, these statistics are useful to capture how impoundment may delay flood or drought pulses. If impoundments slow droughts, ALF may increase, but September 10% decrease. In addition, earlier low flows may respond in an opposite manner, with lower ALF but increased September 10%. The drought of record (the minimum 90 day average flow) was further used in this analysis. It measures duration, frequency, and magnitude of low flows like 7Q10, but requires as little as 20 years of data to analyze (Arias et al., 2014).

1.6 Assumptions and Limitations

With an adequately calibrated VA Hydro model, this study examined the impact of impoundment on low flow alteration. A useful methodology was established and tested to model both ponds and reservoirs with readily available information and standard design practices. The results of the VA Hydro model simulation may improve water availability models during periods of droughts, scaling estimates off of cumulative impoundment. However, this study is limited by the baseline assumptions of the VA Hydro framework, the downscaling of Chesapeake Bay model outputs, and the accuracy of available information. Despite the high rate of infilling associated with small impoundments, it was not practical to create a sediment transport model within VA Hydro (Berg et al., 2017). Thus, it was assumed all ponds and reservoirs had constant stage-storage-discharge relationships. This assumptions contrasts the highly dynamic relationship found in modern impoundment networks, but is balanced by the fact that only present day dams were considered in the analysis. No information was available regarding pond and reservoir construction date during the 1984-2005 study period, so all impoundments currently in the study area were assumed to have been built in this timeframe. The number of impoundments was kept static, despite the high growth rate associated with ponds (Ayalew et al., 2017; Downing, 2010).

Furthermore, to model pond and reservoir geometry, it was necessary to create power relationships between surface area and storage. The only widely available estimates of storage are those offered in the NID for reservoirs. Despite issues commonly associated with these values, this study assumed the NID was sufficiently accurate to model impoundments within the study area (Poff and Hart, 2002).

The Chesapeake Bay model contains useful outputs that drive VA Hydro runoff and channel flow calculations. However, this modeled flow is derived from a large HSPF model that spans several states and considers only a few reservoirs in its flow routing (less than 50 for the entire 64,000 square mile watershed). All other impoundments were assumed to have a negligible impact on flow. Thus, all flow alteration caused by these ponds and reservoirs was calibrated for in-mass by other hydrologic parameters. In essence, the effect of impoundment is already present within the Chesapeake Bay model data (USEPA, 2010). By downscaling this data and introducing it to the impoundment network of a VA Hydro model, it is likely that overall model fit to outlet gauge data will worsen. In this sense, it is impossible to use observed data to calibrate impoundment-modeling methodologies. However, VA Hydro allows for easy manipulation of stage-storage-discharge relationships, enabling extensive sensitivity and uncertainty analysis that may inform all model results. In addition, gauge data may still be used to verify model structure and ensure model performance (although the extensive calibration and validation of the Chesapeake Bay HSPF model ensures output flow is at least somewhat similar to gauge flow) (USEPA, 2010). This analysis is primarily interested in demonstrating the potential impact of impoundment on flow alteration using generalized hydraulic relationships. With sufficient uncertainty and sensitivity analyses, VA Hydro serves as a useful framework to test impoundment relationships, construct networks of ponds and reservoirs, and ultimately examine how such structures impact low flow alteration.

2 Methods

2.1 Study Area

Although impoundments are found throughout the East Coast (Berg et al., 2016; Mogollón et al., 2016), Virginia represents a unique opportunity for case study. The Commonwealth contains only two natural lakes, but tens of thousands of artificial impoundments. These impoundments vary in size, ranging from less than 0.25 acres in surface area to over 50,000 acres (NID, 2016).

Unfortunately, the 70,000 impoundments within the Commonwealth are simply too numerous to model efficiently. A single channel network containing multiple ponds and reservoirs, however, is sufficient to analyze the impact of impoundment on drought flows. For this reason, modeling efforts were focused on a single watershed. An ideal study area would be located within a headwater region, as they contain the highest density of small impoundments and require no upstream calibration (Smith et al., 2002). The outlet of the watershed should further contain a USGS gauge with a flow record covering the entire study period, from January 1st, 1984 to December 31st, 2005. Difficult Run fit these criteria.

Difficult Run is a nearly 375,000 ac (151 km^2) headwater watershed located in Northern Virginia. It is the fifth order stream depicted in Figure 3 that feeds directly into the Potomac and discharges a mean annual flow of 62.3 cfs. Recent reports have shown that peak flows over the last 20 years are generally in the range 998 – 1200 cfs (Hupp et al., 2012). The highest point in the watershed is reported as 516 ft above sea level and the lowest as 68 ft per the national elevation dataset (USGSa, 2017). Urban surfaces and forests dominate land use within the watershed as illustrated in Figure 4, with 77% of the land area covered by development and impervious surfaces, 17% by forest, and the remaining 6% by pastures and water. Although there are no precipitation gauges within the watershed itself, Dulles Airport (located about 10 miles from the center of Difficult Run) has an active weather station that reports an average annual rainfall of 42 inches and a mean 22 inches of snowfall (NCEI, 2016). In addition, the watershed's channels contain three USGS gauges, including one at the outlet. Only the outlet gauge, however, recorded flows during the study period.

As shown in Figure 3, the watershed contains a number of impoundments. According to the NID, there are 20 regulated, reservoirs within the area (2016). The NID contains useful information about these permitted reservoirs to guide the model calibration process. There are an additional 170 small impoundments within the area not present in the NID. Collectively, waterbodies in Difficult Run cover only about 1% (171 ac) of the watershed. Impoundments within the watershed vary by shape, size, and position in the river network serving as an inclusive dataset for investigating the role of ponds and reservoirs in altering flow. The gauge at the outlet of the watershed recorded flows throughout the study period and serves as a potential means of calibration and validation. In this manner, Difficult Run serves as an informative case study in understanding the impact of impoundment on Virginia streamflow.

2.2 Impoundment Dataset

Before assembling a VA Hydro model of the Difficult Run watershed, it was necessary to first develop a comprehensive dataset of impoundments within the area. NHDPlus flowlines serve as the base channel network within the VA Hydro framework due to their high resolution and basic information on flow and geometry. However, the NHDPlus waterbody dataset is limited and biased towards larger structures. On the other hand, its predecessor, the NHD, is significantly more detailed. Containing over 70,000 waterbodies for the Commonwealth, the NHD quite literally fills the gaps in the NHDPlus dataset (USGS, 2018). An initial waterbody dataset was created for the study area by combining NHD and NHDPlus waterbodies within Difficult Run. Repeat waterbodies were identified as intersecting features and resolved by removing NHD features in favor of those in NHDPlus. The resulting dataset may be seen in Figure 3 and contains 170 waterbodies within the study area.

The combined NHD and NHDPlus dataset gave reliable information on waterbody location and surface area. However, the databases contained no other relevant information. The Army Corps of Engineers are responsible for dam maintenance and inspection across the country and thus record basic information about waterbody size, storage, and use in their NID database. Although this dataset is not nearly as extensive as those of the NHD and NHDPlus, the NID contains information on a variety of reservoirs (both large and small) and may be queried to develop predictive relationships about impoundment attributes.

In this instance, all NID dams across Fairfax County were used to drive geometry power regressions. Larger queries could have been used to create more detailed relationships, but Fairfax County maintains several impoundment guidelines that could confound the regressions (Fairfax County, 2018). There are 101 total NID reservoirs within the county. Based on the relationships established in Downing et al. (2006) and Yang and Lu (2014), it was believed the attributes within the NID could be used to develop simple empirical relationships between surface area and volume. A strong correlation between these attributes could be extended to provide a means of estimating pond storage from NHD and NHDPlus surface area. The NID contained several potentially useful variables for analysis including drainage area, maximum discharge, storage, and height. However, only normal surface area, normal storage, and maximum storage were populated with sufficient data to form meaningful relationships (those with coefficients of determinations of 0.5 or higher)

(Moriasi et al., 2007). Normal and maximum area/storage are illustrated in Figure 1 and represent waterbody characteristics at the outlet structure (normal) and when full (maximum).

As the power regression required data to be transformed into log space, dams with zero value attributes (such as dry detention impoundments) were eliminated from analysis. Overall, 73 dams had non-zero surface area and maximum storage, and 58 had non-zero surface area and normal storage. The surface area attribute within the NID was assumed to represent the area of the impoundment water surface at normal pool elevation (see Figure 1). Although not every NID reservoir had an NHD waterbody, the majority of impoundments had similar reported surface areas in both datasets. It was then assumed that the NHD surface areas were also representative of the normal pool. With similar reported surface areas, the relationships gleaned from the NID are likely similar to those that would be observed in NHD ponds had sufficient data existed (Yang and Lu, 2014).

Multiple relationships were tested to find the strongest correlation between NID normal surface area and normal/maximum storage. First, surface area was tested against normal and maximum storage individually to develop simple power correlations. A breakpoint analysis was then conducted, introducing a single break in the relationship to develop a comprehensive understanding of surface area and volume variation. The breakpoint essentially developed two power relationships for both normal and maximum storage, with separate lines on either side of the break. Multiple breaks were tested, but they ultimately failed to dramatically improve model fit and were discarded due to their added complexity.

The individual power regressions between NID surface area, normal storage, and maximum storage yielded acceptable fits and served as a basis for pond bathymetry estimation. Lower limits for the regression were set by the smallest NID reservoir, 0.82 acres in surface area. As illustrated in the histogram in Figure 5, these relationships are applicable to many of the ponds in Difficult Run. VA Hydro assumes that impoundments are located on the NHDPlus flow network at the most downstream location within the catchment. For this reason, the waterbody dataset was filtered to include only those intersecting NHDPlus flowlines. These 37 impoundments were further processed to remove ponds with surface areas below the regression limits. There were thus 26 impoundments considered for analysis: 7 reservoirs and 19 ponds. A visual review of aerial photography revealed a number of the ponds were separated by only small bridges or overlying structures. For this reason, only a random sample of four ponds were included the model, along with all seven reservoirs. The final impoundment dataset is described in Table 2 and visualized in Figure 5.

2.3 VA Hydro Model Development

With the impoundment dataset finalized, a VA Hydro model was constructed for Difficult Run. Each individual impoundment was converted into a VA Hydro catchment with an empty impoundment at the outlet and a single upstream channel. Catchment characteristics are listed in Table 3. Chesapeake Bay Model data was fed into the catchment based on the location of the impoundment outlet. Latitude and longitude of the outlet were manually derived through a geographic information system (GIS) analysis by locating the most downstream waterbody vertex intersecting the NHDPlus flowlines for each impoundment. VA Hydro used these coordinates to identify the Chesapeake Bay Model river segment that contained the waterbody. Hourly values of area-normalized runoff, precipitation, and evapotranspiration were taken from this river segment and lumped to form net runoff.

Since the VA Hydro framework requires impoundments to be located at the outlet of a catchment, the coordinates further served as a useful means of generating catchment area. An R script was written to query the REST services of the USGS StreamStat program to generate drainage area from location (USGSb, 2017). In this manner, catchment delineation was simultaneously derived with river segment identification. The StreamStat drainage areas were input to VA Hydro as appear in Table 3. These values served as the basis for VA Hydro flow generation, weighting the normalized runoff drawn from the Chesapeake Bay Model to serve as incoming flow to the catchment channel shown in Figure 2.

The last component of the VA Hydro catchments was characterizing the upstream channels. This channel represents the stream path between the impoundment and either the outlet of the next most upstream impoundment or the headwaters, displayed roughly in Figure 2. USGS regional curves provide empirical estimates of channel roughness, slope, and geometry based on drainage area and physiographic province (Lotspeich, 2009). By identifying the province of each impoundment outlet through GIS operations, VA Hydro calculated almost all of the required information to route water via the Muskingum algorithm. However, it was expected the user supply channel lengths.

By assuming each impoundment is on the NHDPlus network, VA Hydro requires an upstream channel with travel times greater than the hour timestep used in the simulation. A sensitivity analysis was conducted on multiple catchment configurations to determine minimum necessary channel lengths. In essence, the upstream channel was gradually elongated under multiple 15-day flow simulations to examine changes in downstream flow. Alteration increased with channel length until about 1000 feet in length, at which point alteration became relatively stable. Additional details on the sensitivity analysis are discussed in the Sensitivity and Uncertainty portion of the methods. For now, it is important to note that all upstream channels had to be at least 1000 feet long to ensure proper function of routing algorithms.

NHDPlus flowlines were split along the 11 impoundments selected for study. Upstream flow lengths were measured for each impoundment and recorded in Table 3. Some impoundments were located in the headwaters of the NHDPlus network, such that no upstream channel existed. In other cases, upstream channel between consecutive impoundments were relatively short and fell below the 1000 foot limit derived in the sensitivity analysis. In either scenario, VA Hydro utilized internal GIS operations to plot impoundment outlet coordinates along with NHDPlus catchments. Since each NHDPlus catchment has a corresponding flowline, the model located the nearest flowline and assumed its channel length was representative of upstream flow paths. In reality, many of these channels were artificial flow paths that lay within the impoundments themselves. However, without a higher resolution network with which to identify upstream channel paths, these flowlines served as a useful default length.

VA Hydro catchments were connected as demonstrated in Figure 6. Impoundments that lay successively on the same channel path–e.g. Lake Fairfax and Lake Anne–were linked together such that outflow from the upstream impoundment fed into the channel of the downstream catchment. Due to the limitations of the VA Hydro framework and the hour timestep imposed by the Chesapeake Bay Model, only one channel was modeled in each catchment. Branching channels were ignored as branches were assumed to have travel times well below one hour. Only the primary river lengths in each catchment were input to the model. A catchment was created at the outlet of the watershed based on the USGS gauge coordinates and StreamStat delineation. No impoundment was set at the outlet, but a single channel was created. Channel length was set to the longest distance of the Difficult Run main stem until impounded waters entered the river. In other words, the distance from the gauge to the most downstream impoundment was used to drive the Muskingum routing at the outlet.

With only one channel in each catchment, all upstream catchments were fed directly into the outlet channel (see Figure 6). In fact, all of the catchments listed in Table 2 and shown in Figure 6 entered the outlet catchment channel at the same most upstream point. Although this does a poor job of representing the true form of Difficult Run (Figure 5), it better reflects model assumptions than a branching network would. The Chesapeake Bay Model limits VA Hydro to an hourly timestep. In doing so, it coarsens the input channel network by eliminating streams with travel times less than one hour. The 1000-foot channel limit is only applicable to upstream channels, which are required by VA Hydro routing algorithms. VA Hydro is forced to assume runoff generated in a catchment takes one hour to reach the impoundment to accommodate sheet, shallow concentrated, and open channel flow upstream of the waterbody. However, no such processes occur as water leaves the impoundment downstream, so the 1000-foot limit was not applicable. Water velocity varied within downstream channels, making it further difficult to predict minimum flow lengths. Difficult Run was thus modeled with the simplified network imposed by a one-channel-per-catchment rule.

Once the VA Hydro model was constructed for the base channel network (with all impoundments turned off such that flow is instantly routed through to the outlet), outlet flow was validated against the USGS gauge at the outlet of the watershed, seen in Figure 5. The model was run for the full 21 year period from January 1st, 1984 to December 31st, 2005. Observed flow data at the gauge was only available at a daily timestep so model hourly data was aggregated to mean daily flow. Model performance was evaluated against observed data using a Nash-Sutcliffe efficiency (NSE), as suggested by the American Society of Agricultural and Biological Engineers (ASABE):

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}\right)^2}$$

Where: Y = Mean daily discharge (cfs)

n = Number of days in record (constant between data sets)

The VA Hydro model was considered successfully validated if an NSE of 0.5 or higher was achieved (Moriasi et al., 2007). If the model failed validation, HSPF parameters could be adjusted within the Chesapeake Bay Model or additional catchments could be added within VA Hydro.

2.4 Impoundment Creation

Upon validation of the VA Hydro catchment and channel network, a methodology to model the impoundments themselves was developed. Due to limited information about waterbodies within the area, it was necessary to infer impoundment characteristics from present guidelines and regulations. Impoundment design was focused on two main attributes: geometry and outlet structure. The following sections describe each in detail, relating how extensive literature and regulation reviews were combined to create a physical impoundment model for hydraulic analyses.

2.4.1 Geometry

The geometry of an impoundment refers to the structure of the waterbody bed and banks behind the impounding structure. Sometimes termed bathymetry, this defining characteristic determines the relationship between water elevation (stage) and water volume (storage) as the impoundment fills overtime. In doing so, it plays an essential part in guiding impoundment design. A waterbody built too shallow for a dam of set height may end up flooding more area than is owned. The bank side slopes can be built steeper to narrow the waterbody, but too steep risks collapse and erosion (USDA, 1982).

Impoundment geometry is often decided by its construction process. Embanked dams simply flood the surrounding landscape, leading to relatively complex bed and bank slopes. Excavated dams, on the other hand, are dug out in a set geometry. Excavations are expensive and are recommended only for smaller ponds (USDA, 1982). However, despite the more complex bathymetries associated with embankment, multiple studies have shown that artificial waterbodies tend to have a strong power relationship between surface area and storage. This implies that storage generally increases steadily with surface area despite complex bed patterns. Thus, impoundment bathymetry can be represented through a single unifying geometric approach. Indeed, Hollister and Milstead (2010) found that complex relationships between impoundment depth and surface area performed no better than a simple conical interpolation. Other research on natural lakes found strong correlations between surface area, storage, and surrounding landscape slope (Heathcote et al., 2015). Impoundment guidelines often suggest a set side slope, but it is likely that larger reservoirs just fill to the surrounding slope due to excavation costs and maintain a similar relationship to surrounding slope as natural lakes (USDA, 1982).

Ponds and reservoirs were modeled slightly differently based on available data, but each used the same geometric interpolations. Under the assumption that a simple geometric shape could be used to represent the waterbodies, all impoundments were designed similarly to the rectangular excavations described in USDA guidelines (USDA, 1982). As demonstrated in the side profile in Figure 7, all impoundments were designed with a flat bed of some unknown surface area. This bed was graded to normal pool elevation (stage) using a set side-slope of 4:1 as suggested by farm pond design guidelines. It is possible that impoundments in Difficult Run have a steeper side-slope due to their more urban nature, but it likely varies between 1:1 and 5:1 (USDA, 1982). Water is released through outlet structures beginning at normal stage, implying water is largely controlled to this level. From normal to maximum stage, it was assumed the impoundments flooded into the surrounding landscape. The variable buffer introduced by Heathcote et al. (2015) was used to calculate an average landscape slope from national elevation dataset models (USGSa, 2017):

$$B = 2\sqrt{\frac{A}{\pi}}$$

Where: B = Buffer diameter (ft)

A = Impoundment surface area (ft^2)

In this manner, the impoundment geometry model shown in Figure 7 reflects the principle of Downing (2010), Heathcote et al. (2015), the USDA and NRCS guidelines (1982; 2011), and Hollister and Milstead (2010). Impoundments are modeled through a simple geometry to hold the relationship between surface area and storage. In addition, impoundment volume is assumed a function of both surrounding landscape slope and a simple geometry.

By modeling all impoundments as inverted trapezoidal prisms, it was possible to create stage-storage tables for each waterbody in the dataset by interpolating from maximum and normal pool. For the seven reservoirs within the waterbody dataset, normal and maximum storage were derived from the NID database. Normal surface area was calculated from NHD/NHDPlus waterbodies under an appropriate Universal Transverse Mercator reference system. With normal volume and surface area known, a system of equations was constructed based on the assumed geometry to calculate normal stage. The geometric shape imposed on the impoundments caused surface area and storage to vary nonlinearly with stage. As shown in Figure 7, the normal pool elevation is a function of normal storage, bed surface area, normal pool surface area, and assumed side slope. The storage, normal surface area, and side slope were known, so it was possible to solve for bed surface area and normal stage. Maximum stage was solved in a similar process. The side slope was assumed to be equal to that of the surrounding landscape and maximum storage was derived from the NID. In this case, maximum surface area and maximum stage were unknown. With no constraints available for either of these parameters, stage was iterated until the known maximum storage was achieved. Reservoir bathymetries are described in Table 2.

The four ponds in the waterbody dataset were modeled similarly, but with fewer known attributes. Normal and maximum storage were not directly available through the NID. Instead, each of these had to be interpolated from the power relationships established between normal surface area and normal/maximum storage. Using the surface area of the ponds calculated from the NHD/NHDPlus, it was possible to estimate both normal and maximum storage. As depicted in Figure 7, pond bathymetry was then generated in the same manner as with the reservoirs. Normal stage and bed surface area were estimated from the imposed inverted trapezoidal prism geometry, normal surface area, normal storage, and the assumed 4:1 side slope. Maximum stage was iterated until the regressed estimation of maximum storage was achieved under the average surrounding landscape slope. Final pond geometries are also listed in Table 2.

2.4.2 Outlet Structures

Although impoundment geometry had to be inferred from available guidelines and empirical relationships, the second component of impoundment modeling (outlet structure) is more heavily regulated. Virginia state regulations require all impoundments with maximum storages above 25 ac-ft (including all 11 studied impoundments) pass the 100-year storm (4VAC50-20-40). More specific regulations exist for stormwater and other best management practices that require peak flows to be attenuated to some specific degree (DEQ, 1999; VDOT, 2016). However, without detailed knowledge of the intended use of each impoundment within the database, it was assumed that all studied waterbodies were built to follow the broader impoundment guidelines.

Per USDA guidelines, many impoundments control the design 100-year storm by splitting flows between a principal and an emergency spillway. As shown in Figure 1, the principle spillway is typically constructed at normal stage to control water level. It is designed to release the 10- to 25- year storm without violating the 2-ft freeboard suggested for all impoundments (NRCS, 2011). Principal spillways may take a variety of forms, from labyrinth weirs to morning glories. Based on site inspection of several impoundments in Difficult Run, it was found that the most common structures were grated horizontal orifices in large riser structures. This study is primarily interested in investigating the impact of impoundment on flow alteration rather than creating a highly accurate hydraulic model of Difficult Run. For this reason, it was assumed that the outlets for all impoundments in the dataset could be modeled using horizontal rectangular orifices sized to the 10-year storm as shown in Figure 1. On the other hand, the emergency spillway is typically set right below freeboard and is designed to release all other water that may enter an impoundment during a large storm. These typically take the form of large weirs or diversion channels (USDA, 1982). All impoundments were assumed to have weirs capable of passing all flow not captured by the principle spillway.

With the specific form of an outlet selected, the structures were drafted by back-calculating dimensions from design flows and impoundment geometry. Structures were tested by routing an appropriately sized storm through the impoundment to ensure freeboard was not violated. The design flow may be calculated through various methods including the rationale equation, the Soil Conservation Service approach, and inferences made from gauged data (DEQ, 1999; VDOT, 2016). Although the Chesapeake Bay Model provided some form of land cover data that could guide flow approximation, it was ultimately decided that design flows would be selected by simply downscaling from observed data at the outlet gauge. Annual peak flows were downloaded from the outlet USGS gauge for the study period from 1984 to 2005. A simple peak flow frequency analysis was conducted by finding the 90^{th} percentile annual maximum flow, roughly 4819 cfs. This flow served as the 10-year design storm and was normalized by area to determine flow at each VA Hydro catchment. Thus, the design flows listed in Table 2 were calculated using:

$$Q_{catchment} = Q_{outlet} * \frac{DA_{catchment}}{DA_{outlet}}$$

Where Q = 10-year design flow (cfs)

DA = Drainage area (mi^2)

It should be noted that no 100-year design flow was selected. Emergency spillways within VA Hydro were modeled as oversized weirs such that water was passed instantaneously through the weir. These structures were set at freeboard as shown in Figure 1. This design prevented freeboard violations by instantly discharging all remaining flow from large storms.

The principle spillway, on the other hand, were designed to the 10-year flows listed in Table 2. Essentially, each structure was modeled as a rectangular orifice using the following hydraulics equation:

$$X_{area} = \frac{Q_{catchment}}{C\sqrt{2gH}}$$

Where X_{area} = Orifice cross sectional area (width multiplied by height, $X_{area} = wh$)

Q = 10-year design flow (cfs)

C = Orifice constant, here assumed 0.6

g = Gravitational constant (32.2 ft/sec^2)

H = Available hydraulic head (ft)

Orifices were assumed to follow the standard orifice equation with a constant of 0.6 (VDOT, 2016). The hydraulic head was taken to be the difference between the start of freeboard (two feet below maximum stage) and normal stage. Orifice cross-sectional area could then be calculated from catchment design flow. All structures were assumed two feet tall, allowing for the calculation of orifice width as shown in Table 2.

VA Hydro routing passed water through impoundments using a bisection approximation of the Modified Puls method. In essence, this water balance approach simultaneously solved for storage and discharge using outlet rating curves and impoundment stage-storage relationships. As impoundments filled, outlet structures became active after water elevation surpassed normal stage. However, the outlet hydraulics only behave as orifices after complete submersion. Before that, all orifices function as weirs (VDOT, 2016):

$$Q_o = C_w w H^{1.5}$$

Where Q_o = Weir outflow (cfs)

C_w = Weir constant, typically 3.2

w = Orifice/weir width (ft)

H = Hydraulic head (ft)

At the instantaneous moment of submersion, standard weir and orifice equations are discontinuous. The bisection approximation of the Modified Puls method required a continuous function such that a simultaneous solution of discharge and storage was solved iteratively through a narrowing solution space. Thus, a slight adjustment was made to the weir coefficient to force equation continuity (USEPA, 2017):

$$C_w = 0.6\sqrt{g}$$

2.5 Initialization, Calibration, and Simulation

All impoundments were created at the bottom of their corresponding VA Hydro catchment following the methodology outlined above. This completed the VA Hydro model of Difficult Run. At this point, the model was validated against gauge data. Once again, model discharge at the model watershed outlet was compared to mean daily flow from the USGS using NSE. The model was considered successfully validated if an NSE of 0.5 or higher was achieved (Moriasi et al., 2007). It was expected that the inclusion of impoundments would produce a lower NSE since the Chesapeake Bay Model already lumped their impacts into its calibration. However, it remained important to ensure model data was at least similar to outflow at the gauge to ensure realism. Significant differences between model and observed data may indicate poor impoundment initialization or disconnected catchments (Meigh, 1995; Deitch et al., 2013).

Several scenarios were tested and analyzed to determine the cumulative impact of impoundments on streamflow alteration. The overall experimental diagram may be seen in Table 3. First, to provide a state of reference, all impoundments were toggled off such that inflow was instantly passed as outflow at the outlet of each catchment. This served as a null dataset such that natural streamflow could be evaluated for tested metrics (i.e. a dataset with no impoundment-induced flow alteration). The opposite extreme was tested as well. All 11 impoundments were toggled on to analyze maximum possible alteration. Each of these simulations were conducted for the full 21-year study period, January 1st, 1984 to December 31st, 2005. Then, impoundments were individually switched off to illustrate the cumulative nature of alteration analysis. In separate simulations, the relative effects of reservoirs and ponds were analyzed by switching off one class of impoundments or the other. In this manner, the alteration caused by ponds versus that induced reservoirs was quantified directly. Two more simulations were conducted leaving only a random subset of 5 or 8 impoundments on. In this manner, the cumulative impact of impoundment was demonstrated by illustrating the increase in alteration metrics with additional dams in the network. A last run was tested with just Lake Audubon left on due to its large size and small outlet. These models were run only for a five-year span, from January 1st, 1984 to December 31st, 1989.

For each model simulation, all impoundments were initialized at normal stage. This assumed that the model period began under average weather conditions such that water levels were at the orifice openings. Water thus immediately began flowing, ensuring channels were filled quickly within the simulation. Impoundment outlets were calibrated using two design storms: May 15th – May 30th and July 1st – July 15th, 2005. Within the null run (no impoundments), these storms produced peak discharges at the outlet of 4859 and 4772 cfs, near the 4819 cfs 10-year design storm. Since the rectangular orifices used in each impoundment were designed to handle the 10-year storm, these storms were routed through the network. If an impoundment's emergency spillway became active, the orifice width was incrementally increased. The 10-year storm should entirely be passed through the orifice without engaging the emergency spillway. When calibrating impoundments downstream of another dam, the upstream impoundments were switched off.

2.6 Analysis

An array of metrics were used to evaluate flow alteration at the watershed outlet. Values were compared to the null scenario to illustrate how ponds and reservoirs differentially affected downstream river flow. Effort was made to capture changes in all parts of the flow regime including magnitude, frequency, timing, duration, and rate-of-change. To better understand the need for high spatial and temporal resolution in understanding impoundment-induced alteration, all analyses were conducted from both an hourly and a mean-aggregated daily flow perspective. In this manner, the results of this experiment tested the performance of traditional regulation metrics like daily peak flow and 7Q10. If these analyses proved inadequate in assessing alteration, the hourly metrics would demonstrate the alteration missed by standard flow evaluation.

Low flows were the particular focus of this project and were evaluated through an analysis of August Low Flows (ALF), September 10% flows, Drought of Record (DoR), 7Q10, and 30Q2. The ALF metric is a two-step calculation that first determines the lowest flow occurring in August at each year on record. It then computes the median of these low flows to give an indication of both low flow magnitude and timing. Higher flows are reflected in higher ALFs. If droughts occur earlier or later in the year, ALF may increase or decrease accordingly. However, to capture a timing change, it is necessary to evaluate flow at other months as well. For this reason, the September 10% metric analyzes the 10 percentile flow in all September months on record. September 10% measures magnitude, frequency, and timing and may be used in conjunction with ALF to detect shifts in drought timing. Delayed, more frequent droughts will raise ALF but lower September 10%.

DoR, 7Q10, and 30Q2 do not capture changes in flow timing, but can be used to demonstrate alteration in the magnitude, frequency, and duration of flows. The drought of record is the minimum 90-day flow on record. Longer, more intense, or more frequent droughts can result in lower DoR metrics. By examining data over an extended period, changes in DoR illustrate long-term drought alteration. The 7Q10 and 30Q2 are slightly more complex metrics. In essence, these metrics are calculated in a manner to show the lowest 7- or 30-day average flow likely to occur over a two or ten year period. Extreme low flows are reflected in the 7Q10 due to its lower frequency of occurrence and duration, whereas more frequent, monthly lows are calculated in the 30Q2. These metrics are computed by taking the rolling 7- or 30-day flow average for each year on record. The annual minimums of these averages are fit to a log-Pearson III distribution (here conducted using the PearsonDS package in R; see Becker and Klößner, 2017). The distribution is then analyzed for an adjusted probability to find the flow representative of a 0.1 or 0.5 probability despite missing or censored data (Austin et al., 2011a).

By analyzing ALF, September 10%, DoR, 7Q10, and 30Q2, this experiment captured changes in low flow magnitude, timing, duration, or frequency. However, rate-of-change was not adequately reflected in this suite of metrics. This component of the flow regime was instead analyzed by separating model output into a series of storms. A script was written in R to take in model flow data and analyze it for local minimums and maximums to isolate storm events based loosely on the procedure described in Shuster et al. (2008). Baseflow was separated from model outflow and a series of horizontal line regressions was conducted on the resulting quick flow data to find the relative baseline. Local minimum and maximum were then located throughout the study period. A storm event was classified as any period between two local minimums that occur at or below the horizontal baseline regression. Storms were filtered for those with local maximums above an arbitrary 10% buffer of the horizontal baseline. To assess the relative rate-of-change, exponential regressions were fit to the rising and falling limbs of each storm event taking the form of:

$$Q = Be^{kt}$$

Where Q = Flow (cfs)

B = Regression constant

k = Rate of rise or fall (d^{-1} or hr^{-1} depending on timestep of analysis)

As in Shuster et al. (2008), higher k values indicate faster rise rates. Falling regressions always produce a negative k such that more negative k values result from quicker recessional curves. Data was filtered to include only storms that produced rising and falling regressions with coefficients of determination of 0.7 or higher. In this manner, the average storm rise and fall rate was calculated to show alteration in yet another component of the flow regime. Average storm duration, too, was calculated by simply calculating the average number of hours (or days, depending on the temporal resolution) elapsed in each storm.

Model flow was further analyzed for more common frequency and magnitude metrics. The 10, 25, 50, 75, 90, and 99% flows were found under each model scenario to reflect changes in different parts of the annual hydrograph. Extended low flows could decrease 10% flow, but attenuated peaks would likely be made up in higher 90% flows. Mean flow was also evaluated as well as the number of timesteps of zero flow. This metric provides a useful look at how many timesteps the outlet channel runs dry. If impoundments worsen extreme droughts, the number of hours/days of zero flow is likely to increase. Mean baseflow was also evaluated by passing data through the separation algorithm used in the R EcoHydRology package (Fuka et al., 2015).

Flow duration curves were created from outlet flow under each modeled scenario. These distributions showed the likelihood of a particular flow being exceeded at any given time and were used to compare magnitude and frequency across the entire study period and between scenarios. Flow duration curves visualized changes in the hydrograph by showing how low flows, baseflow, and peak flows were differentially altered. They were used to identify flows that became more common as well as those that have been significantly reduced in magnitude. Ultimately, they showed the overall distribution of flow. Differences in flow duration curves was statistically quantified through the Kolmogorov-Smirnov (KS) test. This statistical procedure analyzes two data sets and determines whether the distributions themselves are significantly different, based on the shape and size of each distribution.

Additional statistical analyses were considered but ultimately not used. Since outflow is available immediately downstream of each impoundment, non-parametric Wilcoxon tests could be used to demonstrate flow metrics that vary significantly after impoundment. Data would be paired by VA Hydro catchment to control for inflow and climate conditions. A power analysis was conducted to determine the minimum number of samples needed to test for differences in flow. Assuming the difference in normalized flow metrics would ultimately be a non-normal distribution (7Q10 of major river basins across the state normalized by drainage area is non-normal), a simple bootstrap was used to calculate power from a one sample Wilcoxon test (Austin et al., 2011b). It was estimated that the presence of impoundments would decrease flow metrics by about 25% (Liu et al., 2014). At an alpha of 0.05 and power of 0.8 on a paired test with an assumed difference of 25%, the power analysis resulted in a necessary sample size of about 78 waterbodies (shown in Figure 8). However, only 11 impoundments were used in experimentation. A simple bootstrap power test shows then that the expected power for this analysis is less than 0.3, which indicated statistical testing would be highly prone to producing false negatives (thereby incorrectly demonstrating no difference between null and impounded scenarios) (EPA, 2015). Thus, no statistical tests other than the KS test were considered in examining flow alteration.

2.7 Sensitivity and Uncertainty

Before any model scenarios were conducted, a brief sensitivity analysis was performed to better understand VA Hydro inputs. Each variable was incrementally decreased/increased as others were held constant to understand how model output changed under different scenarios. First, an artificial, isolated catchment was created within VA Hydro. An impoundment was placed at the most downstream location of this catchment. The catchment was assigned inputs based on the average characteristics of all waterbodies within the dataset. In this sense, it was given the average drainage area of about 0.9 square mile, maximum storage of 90 acre feet, and a corresponding outlet width of five feet. Using a fifteen-day period in May 1989 (the second largest storm on record), multiple configurations of the impoundment and corresponding catchment were tested to understand impact on outlet flow. Drainage area, upstream channel length, normal storage, maximum storage, impoundment side slope, and outlet width were all changed individually over the range of values present in the impoundment dataset as the other components were held constant. Then, multiple parameters were changed while keeping others static. For instance, several models were created that only changed impoundment outlet width. Then, outlet width was altered along with impoundment geometry. Under each scenario, the average rate of fall was assessed, as well as quantile flow and 1-day maximums. These statistics were useful in assessing how each VA Hydro input ultimately affected downstream flow.

By isolating sensitive variables and assessing how they change with outlet flow alteration, this analysis gave a brief glimpse at overall model uncertainty. Unfortunately, due to the fact the Chesapeake Bay data was calibrated around impoundments, it was impossible to guide the modeling process with gauge data. However, sensitive parameters can be changed by fixed amounts to estimate the uncertainty bounds of model output data. The two most sensitive parameters (outlet width and storage, see Results) were increased and decreased based on the statistical uncertainty created by the power regression between surface area and storage. A 95% confidence interval for the slope and intercept were used to bound uncertainty and provide minimum and maximum estimates for storage and subsequently outlet width. The outlets of all impoundments were set to the minimum and maximum values in separate five-year model runs.

This allowed for direct assessment of how uncertainty in outlet dimensions may ultimately impact model flow alteration. The stage-storage relationship of Lake Audubon was then altered to examine storage uncertainty. All other impoundments were switched off and the model was run for five years under bathymetries created through the upper and lower bounds of the power regression. The resulting data was compared against a five-year model run with the base stage-storage table for Lake Audubon. All uncertainty model scenarios were analyzed with a subset of the flow metrics used in the larger impoundment analysis due to the shorter model time period: ALF, DoR, September 10%, 30Q2, rate of rise/fall, storm duration, mean baseflow, and 10/50/90/99% flow. Without a more sophisticated approach to estimating error bounds on output flow alteration, however, it is important to note that results of this experiment should be viewed as a first order estimate of impoundment network hydrology.

3 Results

3.1 Power Regression

Multiple regressions were conducted in an attempt to develop relationships between surface area and storage through the 101 NID reservoirs around Fairfax County. Following the work of Downing et al. (2006) and Yang and Lu (2014), all relationships were created in log-log space via power regression such that reservoirs with no or zero reported surface area or storage were eliminated from calculations. Due to limited information regarding pond geometry, the regressions of particular interest were those capable of estimating storage from surface area. Power regressions were tested both with and without breaks to find the ideal model.

In total, there were 58 NID reservoirs with non-zero surface area and normal storage. The surface area of each impoundment was tested as a potential breakpoint such that separate regressions were conducted above and below that point. Resulting relationships were analyzed by their ability to predict storage from surface area on both sides of the break, mainly through the model coefficient of determination (R^2). The break with the lowest coefficient of determination occurred at an impoundment with a 2.9 ac surface area. Possibly illustrating a difference in relationship between small and large reservoirs, the overall model produced an R^2 of 0.94. However, further testing revealed the change in neither slope nor intercept at the break was statistically significant. This indicated the relationship between surface area and normal storage can be assumed static across all 58 NID reservoirs. The final power regression may be seen in

Figure 9. This relationship was developed by removing the breakpoint and analyzing all 58 impoundments at once. Both the slope and intercept are significant, with an overall model R^2 of 0.91. Normal storage in acre-feet was thus predicted from normal surface area with the following equation (95% confidence interval for slope and intercept parameters in brackets):

$$\ln(Normal\ Storage) = 1.21[\pm 0.1] * \ln(Surface\ Area) + 1.43[\pm 0.34]$$

Maximum storage was reported at a higher frequency than normal storage within the NID. There were 73 NID reservoirs in Fairfax County with non-zero surface area and maximum storage. The same analyses were conducted on these reservoirs as was used to derive the normal storage/surface area relationship. After using all 73 reservoirs as potential breakpoints, it was found that the ideal breakpoint was still located at 2.9 acres in surface area. In this instance, there was a statistically significant difference in intercept between the two power regressions on either side of the break. Slope changes were once again negligible. The overall model produced a coefficient of determination of 0.89. However, without a significant change in slope, the break point was once again discarded in favor of the more general, single power regression seen in Figure 9. With an R^2 of 0.86, this model explained only slightly less variation than it did with a breakpoint and still maintained a significant slope and intercept. As occurred in Downing et al. (2006) and Yang and Lu (2014), NID reservoirs had strong relationships between surface area and storage. Maximum storage was predicted through the equation shown in Figure 9:

$$\ln(Maximum\ Storage) = 1.23[\pm 0.12] * \ln(Surface\ Area) + 2.36[\pm 0.26]$$

3.2 VA Hydro Sensitivity

Before running any simulations on the full VA Hydro model, a short sensitivity analysis was conducted to determine the extent to which model inputs influenced downstream flow alteration. A single, isolated impoundment was created using averaged characteristics of the other 11 impoundments within the dataset. Inputs were iterated through a range of values representative of the 11 VA Hydro catchments. Variables were changed both individually and in conjunction with one another. Input variables can be grouped by their function within the VA Hydro framework: they describe either the catchment or the impoundment. Catchment variables included drainage area and upstream channel length. On the other hand, impoundment inputs were side-slope, storage, and outlet structure. All tests were conducted over a large, 15-day storm in May, 1989. As variables were changed, the impact on outflow alteration was tracked through the average rate of fall, quantile flow, and 1-day maximum flow. Alteration was tracked at both an hourly and daily resolution but only hourly results are displayed here. Daily results expressed similar patterns as the hourly, but were more muted.

3.2.1 Catchment Variables

The two catchment-scale variables (drainage area and upstream channel length) affected downstream flow in significantly different manners. Drainage area somewhat influenced flow alteration. As a key variable in the VA Hydro framework, flow to a given catchment is determined by area-weighting flow from the Chesapeake Bay model river segment. In this manner, catchments with larger drainage areas always receive more flow than their smaller counterparts. So, an increase in drainage area resulted in more flow through the impoundment. These larger magnitude floods were less impacted by the impoundment, resulting in less alteration. This can be seen in Figure 10, which depicts several hydrographs and resulting changes in flow metrics (compared to inflow). Drainage area was in general a moderately sensitive parameter, with smaller catchments producing more alteration than larger ones.

Channel length was significantly less sensitive than drainage area. As depicted in Figure 11, channel length generally did not produce significant flow alteration. Muskingum routing used in the upstream channels delay and extend peak flows to some degree. However, channels in Difficult Run are in general short enough to prevent significant attenuation. Fall rates decreased with elongating channels as the channels slightly decreased maximum flows and shrank the overalls storm hydrograph. In general, channel lengths below 1000 feet produced different patterns of alteration. From 10 to 1000 feet, alteration significantly increased with length. This pattern is attributed to VA Hydro's routing algorithms, which require travel times to be greater than the hour timestep. For this reason, 1000 feet was used as the minimum upstream channel length to prevent channels from improperly influencing results.

Channel length was also altered simultaneously with drainage area. These results may be seen in Figure 12. With increased drainage area and channel length, alteration generally decreased in a pattern similar to that in Figure 10. Drainage area seemed to be a more sensitive parameter than channel length. However, in smaller catchments, channel length did alter flow. The alteration observed in small catchments is slightly different between Figure 10 and Figure 12. Larger drainage area catchments, regardless of channel size, generally produce less alteration than small catchments. In small catchments, larger channels will diminish impoundment-induced alteration.

3.2.2 Impoundment Variables

The three impoundment-scale variables (side slope, maximum volume, and outlet structure) were in general more sensitive than the catchment-scale inputs. Side slope produced the lowest overall effect on output alteration. Normal and maximum storage were held constant but the side slope between the bed and normal storage was changed. Steeper slopes resulted in deeper impoundments. However, this change in stage barely affected output flow, as seen in Figure 13. The deeper impoundments with steeper side-slopes had more hydraulic head, but the extra foot or two of head was only engaged briefly during peak flow. The stage-storage-discharge relationship in the impoundments largely remained constant, thus inducing little additional alteration with increasing slopes.

Volume was a more sensitive parameter. These test impoundments were developed by changing maximum storage. Surface area was back-calculated with the regression shown in Figure 9 and used to calculate a new normal storage. Side-slopes were kept constant. It is clear from Figure 14 that larger impoundments in general produced more alteration. With more available storage, larger impoundments fill more slowly and release water under lower hydraulic heads. This greatly slows the rate of water discharge from the impoundment and results in significant alteration. Unlike side-slope, even small changes in volume produced substantial alteration downstream, as seen in the steady increase in alteration of quantile flow metrics.

For similar reasons, outlet width, too, was a highly sensitive input with results seen in Figure 15. Alteration exponentially decreased with increasing outlet width. This is a direct result of the hydraulics equation described in the methods section. Smaller outlets released substantially less water under the same hydraulic head as larger structures. In fact, increasing outlet width to infinity should produce a theoretical structure that instantly passes inflow as outflow. Decreasing outlet width compressed the storm hydrographs illustrated in Figure 15. Peak flows were attenuated, but low flows increased due to elongated recessional curves (smaller rates of fall). Outlet width is thus one of the most sensitive parameters within the VA Hydro model.

An additional test was conducted changing both outlet width and impoundment volume to determine how combinations of these sensitive parameters affected output flow. Volume was selected by changing maximum storage and using the regressions to estimate normal storage. Based on available hydraulic head, outlet width was then calculated using the hydraulics equations presented in the methods section. As displayed in Figure 16, hydrographs resemble those in Figure

14 produced just by changing volume. Larger impoundments experienced more alteration than smaller structures. By assigning them smaller outlets, low and peak flow alteration increased. However, the changing orifice widths in smaller impoundments had a large effect on alteration, creating a more exponential curve in Figure 16 than in Figure 14 (where volume was the only variable changed). These smaller impoundments were assigned larger outlet structures than before and passed flow more quickly, resulting in less alteration. The differences between Figure 14 and Figure 16 indicate that both volume and outlet structure were sensitive variables.

3.2.3 Catchment and Impoundment Variables

One final sensitivity test was conducted by altering both drainage area and outlet structure. Increasing drainage areas were assigned increasing outlet widths. All outlets were calibrated using the same May, 1989 storm employed in the sensitivity analysis. Structures were increased in width to prevent emergency spillways from becoming active. Resulting hydrographs and relative alteration can be seen in Figure 17. The impact of outlet structure on downstream flow alteration was more apparent in this scenario. Small drainage areas experienced significantly more alteration in flow statistics than did larger catchments due to their small assigned orifice widths. These catchments may receive less flow than their larger counterparts, but this flow is significantly more altered as the smaller orifices release it slowly over time. Extremely small drainage areas produced different patterns, but this was a direct result of the VA Hydro framework. Runoff is likely generated, impounded, and discharged within an hour's span in these smaller catchments. Since these travel times are significantly less than the hour timestep imposed by the Chesapeake Bay model, this data should be viewed skeptically.

3.2.4 Conclusion

The results of the sensitivity analysis revealed that outlet width, impoundment storage, and catchment drainage area had the most significant impact on flow alteration. Flow was most impacted by increasing impoundment storage, decreasing outlet width, or decreasing drainage area. It should be anticipated that large headwater impoundments (high storage, low drainage area) would impart the most alteration, particularly if assigned small orifice widths. Volume and outlet width were the most sensitive parameters, causing large differences in alteration with even slight increases in value. Flow metrics were affected differentially across the sensitivity analysis, implying the need for a close examination of the flow regime to understand the impact of impoundments.

3.3 Network Validation

Once sensitive variables were established, the VA Hydro model was set up in full with all eleven catchments. Catchments and impoundments were designed following the approach described earlier in the Methods section. To ensure model realism, modeled flow at the outlet catchment was compared to the observed flow record from the outlet USGS gauge seen in Figure 5. Data was mean aggregated to daily flow to match the temporal resolution of the recorded gauge data. Two models simulations were conducted from January 1st, 1984 to December 31st, 2005: the impounded and the null scenarios. Each model run was compared against gauge flow individually.

The null run was set to contain all eleven VA Hydro catchments, but impoundments were turned off at the outlets. Water still flowed through catchment channels, but was allowed to pass unhindered through the outlet (rather than through a waterbody and outlet structure). This base scenario created discharge at the outlet of Difficult Run similar to gauge flow. Figure 18 shows the overall model performance by displaying gauge flow for a given day against modeled flow for the same day. The black one to one line shows data that has been perfectly predicted in the model. The null scenario (shown in red) was clustered about this line, capturing medium and high flows particularly well. The model performed well and produced an NSE value of 0.707, above the 0.5 suggested for most hydraulic models (Moriasi et al., 2007). The null scenario was thus found to predict flow sufficiently when compared to observed gauge data.

The impounded model run performed similarly well. Producing an NSE of 0.708, flow was better predicted by the impounded scenario than the null. As seen in Figure 18, the impounded scenario increased low flows to enhance model prediction during times of drought, perhaps leading to the higher overall NSE. Since the Chesapeake Bay Model was calibrated without impoundments, it was impossible to correlate the increased model performance to the exact methodology used to design the impoundments. Nonetheless, the high NSE value indicated the impounded run produced realistic discharge and did not violate the water budget in some way. Figure 19 illustrates a single year of modeled data, displaying the differences between the null and impounded scenarios. The impoundments clearly altered peak flow, and undoubtedly modified other portions of the storm hydrograph such that low flows were ultimately increased to improve model fit.

3.4 Full Model Simulations

Once model performance was validated successfully against observed gauge data, outlet discharge from the null and impounded scenarios was evaluated to assess changes in the flow regime. Flow duration curves were plotted for each scenario and displayed in Figure 20. Although the two distributions appear similar, there were several distinctions between the null and impounded scenarios. First, impoundments clearly attenuated peak flows. Figure 19 demonstrated that the impounded run produced similar storm hydrographs to the null run, but with lowered peak discharge. This is made more obvious in Figure 21, where the percent difference between the null and impounded flow duration curves is visualized. The decrease in peak flows (99% flow fell from 660 cfs to 630 cfs with the introduction of impoundments) was accompanied by an increase in medium sized floods. The 7 – 93% flows increased in magnitude, producing the inverted parabolic shape shown in Figure 21. Medium size flows around 20 – 40% were particularly impacted, increasing by nearly 10% (e.g. 25% flow increased from 8.8 cfs to 9.6 cfs, a 9% change). Extreme drought flows were altered, with all flows up to the seventh percentile decreasing by as much as 20% (the first quantile–1 % flow–changed by 20%, decreasing from 0.38 cfs to 0.3 cfs). The KS test was employed to check for a statistically significant difference in overall flow distribution after impounded. The results indicated there was less than a 0.001% chance the data points in the impounded run were from the same distribution as those in the null, indicating impoundment significantly impacted the flow regime.

To quantify impact, the suite of flow metrics described in the Methods section was employed to understand changes in the flow resulting from the introduction of impoundments. Statistics at the outlet of Difficult Run are described in Table 4 at both an hourly and daily resolution. These are further illustrated in Figure 22, which displays a select few metrics at the watershed outlet. In general, hourly and daily metrics agreed in how impoundments alter flow and were similar to the disagreement between the flow duration curves. However, there were a few differences worth noting.

At an hourly resolution, low and peak flows were clearly impacted. Figure 21 shows a clear distinction between the two model scenarios, with low and peak flows decreasing because of increased medium floods. Low flow metrics did not quantify a universal decrease. August Low Flow (ALF) increased by nearly 7% when impoundments were introduced to the model (increasing from 2.0 to 2.2 cfs). This was one of the more moderate drought metrics: by quantifying the median of monthly low flows, ALF examined a rather frequent drought. Figure 21 similarly shows that 7 – 10% low flows increased upon the inclusion of impoundments. On the other hand, the 10% September flow decreased by over 10%, falling from 1.0 to 0.9 cfs. This metric analyzed low flows in a period of drought and thus observed smaller flows than the ALF. It was further possible that impoundments caused a shift in flood timing, with drought occurring later in the year due to impoundment. August flows would thus increase and September flows decrease. However, it was more likely that impoundments caused more frequent, small droughts. The 7Q10 flow decreased roughly from 0.20 to 0.15 cfs (a 25% fall) after impoundments were activated. Weekly low flows became more common and produced frequent enough droughts to dramatically lower the 7q10. The 30Q2 also decreased, but only by about 4% (4.8 to 4.5 cfs). Thus, while droughts were extended after impoundment, monthly low flows were hardly impacted. The 90-day Drought of Record (DoR) did not change from 9.8 cfs, suggesting that weekly droughts were the most impacted. The number of hours of zero flow remained constant.

All listed quantile flows within Table 4 increased with the introduction of impoundments except for the peak 99% flow. The 25 percentile flow increased by nearly 10% (8.8 to 9.6 cfs) and median flows by 8% (23.8 to 25.6 cfs). These metrics confirmed the pattern seen in Figure 21, with all floods between 7 and 93% increasing in magnitude. These metrics suggest that medium floods became more frequent after impoundment. Higher flows became rarer as peaks flows were attenuated, leading to additional medium size floods. This was further suggested by the 7% increase in mean baseflow as it rose from 33.4 to 35.6 cfs, which implies that rivers tended to have more water at all times after impoundment. The typical storm hydrograph was compressed, with peak and low flows decreased and medium flows increased. This concept is shown in Figure 23, which shows the storm hydrograph for one of the largest storms on record. As peak flows decreased and medium flows increased, the storm hydrographs were extended. Rising and falling limbs grew longer despite the lower peak flows, as was observed in the decreased rates of rise and fall described in Table 4. The average storm duration grew by nearly 6 hours from 17.4 to 23.0 hours, showing a 32% increase from the null scenario.

In general, flow alteration was dampened when calculated at a daily temporal resolution. Low flow statistics performed rather similarly, with ALF increasing and the rest remaining relatively constant or decreasing. Many of these statistics performed identically at a daily level compared to an hourly level, with 7q10 and 30q decreasing by about 25 and 4%, respectively.

However, the daily hydrographs were too coarse in resolution to capture changes in storm duration. Rise and fall rates still decreased (fall rates, for instance fell from 1.0 day^{-1} to 0.9 day^{-1}), but only by 0 – 7% instead of 10 – 15%. The average storm duration barely changed. It should be noted that average storm duration was roughly 20 hours when calculated at an hourly resolution and nearly 6 days at a daily resolution. The daily hydrographs had significantly longer rising and falling limbs due to the data aggregation process, which often merged multiple small hourly storms into a single daily timestep. When combined, these storms created exaggerated rising and falling limbs, which was read as a longer storm by the calculation process described in the methods.

While low flows remained relatively constant, peaks flows changed heavily when calculated at a daily resolution. Figure 24 shows the difference between the daily null and impounded scenario flow duration curves. Peak flows of up to 90% decreased after impoundment. The same figure for hourly data (Figure 21) shows peaks flows only decreasing after the 93 percentile. This is further reported in Table 4, which highlights that the 90% flow decreased upon impoundment at a daily resolution (149.4 to 149 cfs)), but increased under an hourly resolution (136.3 to 139.5 cfs)). The magnitude of change was smaller than at an hourly resolution as shown in Table 4, but this was anticipated due to the mean aggregation process that naturally reduced hourly peak flows. Baseflow increased by only around 0.6 cfs, largely because medium floods did not become as frequent after impoundment as they had from an hourly resolution. However, the overall pattern of alteration remained the same: medium flows increased at the expense of peak and low flows due to extending hydrographs.

3.5 Alteration Accumulation

Several additional model scenarios were tested to understand the individual and cumulative impact impoundments have on flow alteration. These were conducted over a five-year span stretching from January 1st, 1984 to December 31st, 1989. In total, seven model runs were performed: all impoundments on, all impoundments off, all reservoirs on, all ponds on, a subset of eight impoundments on, a subset of five impoundments on, and only Lake Audubon on. Impoundments in each scenario are described in Table 5. Due to the smaller timespans, only a few flow metrics from the full suite listed in the Methods section were employed to examine alteration. Statistics like 7Q10 required more data to produce reliable estimates and were thus ignored in this analysis (Sharma et al., 2015).

Overall flow distributions are shown in Figure 25 as a difference from the null scenario. In general, the more impoundments within the model, the more flow alteration. All distributions followed the same general pattern, with extreme peak and low flows decreasing due to increasing medium sized floods. However, the magnitude of change differed between the scenarios. The highest level of alteration was seen when all impoundments were present in the model. A large portion of this alteration was attributed to reservoirs, which experienced the second largest overall alteration. The scenario with only ponds present in the model, on the other hand, experienced the smallest alteration. In fact, Lake Audubon alone contributed to significantly more flood alteration during periods of medium to high flow (greater than the 10% flow) than did small ponds. The model runs with 5 and 8 impoundments present performed very similarly, but the higher impoundment run ultimately contributed to more alteration during periods of low flow.

Despite the low alteration introduced by ponds, they seemed to have a noticeable effect on low flows. Figure 25 shows that the four modeled ponds decreased low flows up to the 20% flow, whereas all other scenarios lowered only the tenth percentile and below. The all reservoir run created more alteration in floods between 10-20% than did the all impoundments run. The presence of the ponds lowered alteration in these quantile flows. Likewise, the scenario with just Lake Audubon had significantly different flow in the lower quantiles than the pond runs. The ponds impacted peak flows similarly to the other scenarios, but played a large role in determining overall low flow alteration.

More specific trends in ponds and reservoirs may be observed in Table 6 and Figure 26 (calculated at an hourly resolution). As before, the pond scenario created different patterns in low flow metrics. Ponds increased 30Q2 while every other scenario decreased this metric. In addition, they decreased ALF and had the smallest overall alteration in the DoR and September 10% flows. Their affect in larger runs was particularly noticeable in the 10% quantile flow. The all ponds scenario decreased this metric, but the all reservoirs increased it significantly. The more ponds within a given scenario, the smaller the increase in the 10% flow. However, in general, flow alteration scaled with model impoundment rather than the number of ponds. Storm duration and average rates of rise/fall in the hydrographs was increasingly altered with impoundment. Duration in particular significantly changed, steadily increasing from 17 hours to 22 hours with more impoundments.

3.6 Uncertainty

Outlet width and impoundment storage were revealed as the two most sensitive variables in the VA Hydro framework. Even small changes in either produced notably different patterns of flow alteration, as shown in Figure 16. Several assumptions were made in modeling each of these variables for the 11 included impoundments. Outlet width scaled with stage, which in turn was determined by storage. Storage, in turn, was generated from surface area through a power regression. In this manner, both storage and outlet width were selected from a solution space entirely dependent on the uncertainty in the power regression. By using a 95% confidence interval that gave the realistic range of values for the power slope and intercepts, it was possible to create "minimum" and "maximum" values for normal/maximum storage using the surface area of each impoundment. These storages were used to develop new bathymetries representative of minimum and maximum uncertainty bounds. Based on these modified stage-storage relationships, a minimum/maximum orifice width was calculated using the available head (less freeboard). Table 7 summarizes the minimum and maximum storages associated with each impoundment, as well as the corresponding orifice widths. These values are compared to the calculated and calibrated values used in the scenarios in Table 5.

Several short, five-year (1984 – 1989) models were run to assess the influence of storage and outlet uncertainty on output flow alteration. First, separate models were created in which all impoundments were switched on and assigned either their minimum or maximum orifice width (keeping geometry constant with the calibrated runs tested in Table 5). The results of these models were compared against each other and the null run to evaluate the impact of orifice width uncertainty. For this analysis, orifice widths were not calibrated to design storms and were solely calculated from impoundment bathymetry. Unfortunately, geometry was a more complex variable within VA Hydro such that only Lake Audubon was used in the storage uncertainty analysis. Two additional five-year models were run such that Lake Audubon either had its minimum or maximum bathymetry as described in Table 7. The flow alteration from these runs were compared against each other and against scenario six, as described in Table 5. By examining how flow alteration changes within the storage solution space, this analysis determined relative error for model results.

The effect of orifice uncertainty on model flow alteration is visualized in Figure 27. The impact on low, medium, and peak flows again indicated the sensitivity of outlet width within VA Hydro. The flow duration curve of the calibrated run described in Table 5 varied from the uncertainty scenarios by 5% or less. In general, low-medium flows (around 10 – 30%) had the highest uncertainty and peak flows the lowest. This is better quantified in Figure 28 where select flow metrics have been calculated under each uncertainty and the calibrated run.

In general, the larger outlets resulted in less flow alteration. However, it should be noted that both Figure 27 and Figure 28 show an increase in low flows with larger orifices. These bigger structures also created longer storms. Without calibration, the small orifices produced significant overtopping in some downstream impoundments like Lower Timber Lake. Emergency spillways were increasingly engaged, releasing large storms more quickly from the smaller outlet scenario than the larger one. Ultimately, this caused the larger outlets to have a more significant impact on storm duration and rise rate. However, the larger orifices caused impoundment to fill less during wet periods and thus reserve less water for droughts. Without stored water to release, drought flows decreased under the maximum outlet width scenario (resulting in lower ALFs, September 10%, and 30Q2 flows). It can be noted that orifice uncertainty generally had only a small impact on overall flow alteration. Most of the flow metrics in Figure 28 all changed by less than 10% from the calibrated run and maintain similar overall distributions (shown in Figure 27).

Although it proved a rather sensitive variable within VA Hydro, changing the individual storage of Lake Audubon had little effect on downstream flow alteration. Figure 29 illustrates that the large uncertainty associated with Lake Audubon (with estimated volumes ranging from 300 to 1300 ac-ft) had little impact on flow duration. Peak flows were slightly altered, but Figure 30 demonstrates that the majority of alteration metrics remained nearly constant with the calibrated scenario described in Table 5. Low flows changed slightly, with 30Q2 fluctuating between the scenarios. The smaller geometry likely forced more rapid head change during storms due to its lower overall storage. It thus released flows more rapidly and had less stored water during periods of drought, lowering 30Q2.

Uncertainty in outlet width had the largest impact on flow alteration. Figure 29 and Figure 30 include one additional scenario that was created by assigning Lake Audubon with its minimum geometry as well as the corresponding maximum orifice. In both figures, it is clear that this model produced significantly more flow alteration than when storage alone was changed. Thus, the overall error in the VA Hydro model stems mostly from outlet width. Although this dimension is dependent on storage, it alone seems to dictate downstream flow alteration. As shown in Figure

28, model error was therefore expected to be around 10% or less. Model outputs were a decent first-order estimator of network hydraulics.

4 Discussion

4.1 Impoundment Induced Alteration

To investigate the potential impacts of impoundment networks on downstream flow alteration, a unique VA Hydro model was constructed to represent the Difficult Run watershed in Northern Virginia. Multiple catchments and channels were created to serve as a model flow network through which water could be routed from headwaters to the outlet. The Chesapeake Bay model was linked to this framework to provide the rainfall and runoff data necessary to drive hydrologic evaluation. Eleven different impoundments, including both small ponds and large reservoirs, were created throughout the modeled watershed. Despite a lack of information, impoundments were designed to the best available guidelines, regulations, and industrial practices to ensure some level of model realism. Waterbody geometry was informed by surrounding topography and NHD surface area. Outlet structures were then drafted based on design flows scaled from the USGS gauge near the watershed outlet. Finally, multiple scenarios were conducted that illustrated increasing flow alteration with impoundment.

Figure 26 shows that as impoundments were added to the model, peaks and low flows became increasingly attenuated. Medium floods (typically those between the 10-90% non-exceedance probabilities) balanced the hydrograph by increasing in magnitude. In fact, on the full 21-year runs shown in Figure 21, medium floods increased consistently by at least 5% compared to the run with no impoundments. This pattern of alteration was nearly identical across all tested scenarios. Peak and low flows were always lowered, and medium floods increased. The structure of VA Hydro allowed for some exploration into the underlying factors driving this trend. Two of the most sensitive parameters in the model were impoundment storage and orifice width. Figure 16 revealed that storm hydrographs changed dramatically with any modification to either storage or orifice width. Smaller orifices limited the amount of water that could be released from the impoundment under a given head. Peak flows thus decreased with impoundment because water was trapped behind these outlet structures and forced to release slowly over time. The null scenario passed inflow as outflow, and would therefore always produce the higher peak flows.

As high flows were stored behind the outlet structures due to limited maximum outflow, the waterbodies filled. Eventually, as storm inflow subsided, the impoundments began to release the water that had filled the waterbody. This extended storm hydrographs, creating longer rising and falling limbs and increasing average storm duration from 17.4 to 23.0 hours. Moreover, since high flows became less frequent, the releasing of these stored waters greatly increased the frequency of medium floods. In essence, the typical storm hydrograph was compressed by upstream impoundments, lowering peak flows and drawing out recessional curves. This can be seen in Figure 23, where the impounded storm reached baseflow several hours after the null run. By storing water and releasing it slowly overtime, the impoundments increased some low flows. The tenth percentile flow increased with impoundment as waterbodies released water during dry periods. Mean baseflow was augmented as well, due to the constant stream of water leaving impoundments during periods of frequent storms. As shown in the sensitivity analysis, impoundments with larger storages ultimately produce more change in downstream flow. With additional available volume, these reservoirs stored more water during storms and thus drew out recessional curves even longer.

Low flows were generally decreased by the presence of impoundments. Figure 21 illustrates that low flows became more frequent, producing smaller 7Q10 and September 10% metrics. Although impoundments stored and released water during times of otherwise low flow, they worsened extreme droughts. Without sufficient inflow to recharge lost water, impoundments would lose storage during dry, hot periods due to evaporation. Under decreased heads, less and less water would flow downstream until finally water levels dropped below the outlet structure. When this happened, no water would flow downstream and entire stream sections would run dry. Droughts became more frequent as the impoundments would then need to fill back to normal stage before releasing water. Thus, while more common low flows like the ALF increased, extreme drought flows decreased.

Clearly, even 11 impoundments in this model played a noticeable role in determining flow. The traditional modeling assumption that only large reservoirs affect downstream discharge is oversimplified. Smaller impoundments had a greater impact on low flows than did larger waterbodies. These results overall were consistent with other studies examining small impoundments. In examining a watershed in southeastern Iowa, researchers Ayalew et al. (2017) put together a hydraulic simulation of several small dams in the region. They found an inverted relationship between the number of dams in their model and peak flow, such that more small dams led to greater peak flow attenuation. They noted that medium floods experienced the greatest change in flood magnitude. Furthermore, one study demonstrating a new reservoir module for SWAT created hydraulic models of several small ponds in an agriculture watershed. They too noted significant difference in both peak and low flows, with low flows differing by as much as 25% (Liu et al., 2014). Identically, increased impoundment within this VA Hydro model produced significant changes in medium flows at the expense of peak flows.

Other models have been developed to analyze the impact of dry impoundments on streamflow. These models initialize waterbodies as empty and fill them overtime. Study periods are short enough to examine the effect of filling on flow. Models developed for California and Botswana show that these dry impoundments can significantly influence river flow, lowering even mean annual flow by up to 10% (Meigh 1995; Deitch et al., 2013). These dry impoundments are representative of those used in this study during droughts when evaporation exceeds inflow. In both instances, the impoundments significantly changed river flow while filling. Impoundments in this experiment also greatly extended storm duration, similar to the experiments Timpe et al. (2017) conducted in the Amazon. They examined gauges above and below small dams and found that their closure had a tremendous impact on flood duration and river rate-of-change. Other hydraulic models built to study the impact of dams have expressed increases in all low flow metrics, but focused on larger dams than were of interest in this experiment (Arias et al., 2014). Large dams that regulate flow through more sophisticated outlets have been previously linked to increased low flows (Williams and Wolman, 1984).

4.2 Cumulative Impact

The scenarios described in Table 5 examined cumulative flow alteration caused by impoundment. In each case, various impoundments were turned off and others were left on. Models runs were analyzed using a subset of the suite of metrics employed in the full 21-year runs. It was apparent from Figure 25 and Figure 26 that increasing the number of impoundments within the model resulted in augmented flow alteration. Added impoundments incremented medium flows by reducing peak and low flows. However, not all waterbodies affected flow in the same manner. In all scenarios with ponds, low flows became more frequent than in those without ponds. A single reservoir, Lake Audubon, decreased only the fifth percentile flow and below. On the other hand, ponds affected up to the twentieth percentile.

The sensitivity analysis conducted prior to experimentation revealed three sensitive variables within the VA Hydro framework. Impoundments with small orifices, small drainage area, and large volumes produced the most alteration. Lake Audubon was a large reservoir with a relatively small orifice, ultimately producing nearly half the alteration as all impoundments combined. Ponds created entirely different patterns of alteration than did reservoirs. They had small drainage areas and orifice lengths. Despite their small size, their presence in the headwaters and their limited outlet structures allowed them to have a noticeable impact on flow alteration. It was possible that inflow was so small to these ponds that impoundment refill after drought took more time than larger reservoirs, creating more instances of zero outflow. Indeed, pond 2 and 8 produced the most hours of zero flow within the full 21-year run after impoundments were added. This likely contributed to the pattern seen in Figure 25, where ponds caused a decrease in a much larger portion of low flows than the other scenarios.

As demonstrated in Figure 3 and many parts of the world, Difficult Run contains far more ponds than it does reservoirs (Downing, 2010). The impoundment dataset within this model was greatly simplified to include only those within the bounds of the power regression, causing reservoirs to outnumber the smaller ponds. However, the results of the various model simulations clearly depicted that flow alteration at the Difficult Run outlet was a function of cumulative upstream impoundment and dependent on volume, drainage area, and outlet width. In general, Figure 26 shows that a simulation with half of the total impoundment imparted roughly half of the peak flow, duration, and rate-of-change alteration in the system. Adding a few more impoundments increases this alteration closer to that observed under the full simulation. Thus, flow alteration can broadly be interpreted to increase linearly with impoundment. Ponds induce larger changes to the low flow regime than do reservoirs, but have preliminarily shown to impart additional alteration with each added pond (see l-10% flows in each of the simulations presented in Figure 25; more ponds results in larger decreases in extreme low flows). For this reason, it is possible to conjecture that modeling the remaining 15 possible ponds in Difficult Run would create alteration in the lower flows roughly four times larger than was observed. This would likely exasperate extreme low flow alteration, as more channels dry due to impoundment evaporation leading to decreased 30Q2 and 7Q10 values over the simulation period.

However, it was also possible that pond processes occurred below the model temporal resolution. Ponds 2 and 8, for example, had drainage areas less than 0.1 square miles. They were each well under 100 ac-ft in normal storage. It was certainly possible that runoff could be generated and travel through these catchments completely in a single hour, rather than the three hours it would take in VA Hydro (one for runoff generation, one for channel routing, and one for impoundment routing). In this sense, with model time greater than process time, it is possible the alteration induced by the presence of ponds was artificially exaggerated. Reservoirs were large enough where process time was better represented within the model framework, indicating a higher degree of realism in reservoir results.

Nonetheless, the addition of impoundments had a clear impact on downstream flow. Indeed, the effect of impoundments accumulated throughout the network to produce larger changes than each individually. Lake Audubon alone produced nearly half the alteration in the network due to its large size and small orifice. However, to develop a full understanding of flow alteration, it was necessary to examine the entire impoundment network. Ponds played a large role in determining the degree of low flow alteration, but reservoirs more greatly impacted medium and peak floods. Previous studies have emphasized the need to analyze dam design and construction from a cumulative perspective (Winemiller et al., 2017). By directly connecting alteration to impoundment, this study has quantified the differences between analyzing a network of impoundments versus just a single waterbody. Further, the noticeable impact of both reservoirs and ponds stresses the need to evaluate standard hydraulic assumptions. Watershed-scale models should attempt to model all impoundments within the region or risk missing their effect on storm duration and magnitude. With limited resources, water resource managers interested in assessing peak flows should concentrate on larger reservoirs, but will need to evaluate the impact of ponds when addressing drought flows or low-flow habitat.

4.3 Flow Metric Temporal Resolution

While examining flow alteration, this study had the unique opportunity to evaluate the performance of traditional water regulation metrics calculated at daily resolutions. All statistics employed in data analysis were calculated from both an hourly and daily perspective. The hourly statistics of course better matched model hydrograph patterns as they were determined at the same temporal resolution as the data itself. The daily flow values were averaged over 24 hours and thus expressed more muted values. However, as seen in Table 4, not all daily metrics were capable of predicting the same scale of alteration as hourly statistics. In general, as shown in Figure 22, the daily flow metrics performed decently when predicting alteration in extreme drought (7Q10, 30Q2, September 10%) or medium floods (Q25, Q50). Nonetheless, they failed to capture any changes in storm duration and low-medium flows. Storm duration increased nearly 30% when calculated at an hourly level, but only by 3% at a daily level, a whole magnitude lower. The rate of rise and fall of storm hydrographs, too, were over predicted by daily metrics (causing lower overall durations). The daily flow data simply expressed less variation than the hourly data, causing small storm surges to meld artificially into lumped, larger storms. In doing so, the daily flows concealed changes in storm duration or rate-of-change. This led to under prediction of baseflow alteration as well as ALF, which depends more on more middle-sized storms.

These results suggest that standard daily metrics like 7Q10 may be useful in evaluating changes to extreme droughts or median flow where variation in flow is limited. However, they cannot properly assess how impoundment affects the flow regime itself. Without analyzing river hydrographs at an hourly perspective, it was difficult to capture how peak and low flow magnitude were impaired by longer storm durations. Medium flows became more frequent as a result of the longer recessional hydrograph limbs, increasing some monthly flows like the ALF. The daily metrics failed to capture this pattern due to their less variable hydrographs. In areas where duration and rate of change matter (e.g. floodplain management), particular attention should be paid to hourly flow whenever possible. Traditional metrics may be able to examine alteration in extreme droughts, but they completely miss larger low flows and changes to the base flow regime.

5 Conclusions

The proliferation of small impoundments has brought to question many previously basic assumptions about hydrologic modeling. Studies are increasingly showing a need to examine downstream flow as a function of cumulative upstream impoundment (Winemiller et al., 2017). Unfortunately, information regarding the volume and discharge control structures within these smaller impoundments is limited. Previous studies have relied on extensive bathymetrical surveys or otherwise private information to model small ponds and reservoirs and were limited to the scale of their data (Ayalew et al., 2017). This experiment sought to better understand how impoundment impacted streamflow. A unique modeling framework was created to model impoundments based on readily accessible information as well as current design standards, industrial practices, and published guidelines. By combining hydraulic routing with a published rainfall-runoff model, multiple simulations were conducted to examine the role of impoundment in river flow alteration.

Increasing impoundment led to increased flow alteration. Medium floods became more frequent as peak flows were clipped and storms extended. Average rates of hydrograph fall and rise decreased, leading to longer storm durations that increased baseflow and some low flows. Extreme droughts were decreased significantly by the presence of small impoundments. Evaporation from reservoirs dropped water levels below orifices to create periods of zero flow in upstream catchments, greatly diminishing outlet flow. Reservoirs had a larger impact on flow alteration than small ponds due to their large volumes and often small outlets. Ponds changed patterns in resulting low flows, but were so small that they may have violated model assumptions. Nonetheless, it was clear that impoundments cumulatively played a large role in determining flow.

Model structure will ultimately be improved when version 6.0 of the Chesapeake Bay Model is introduced. This update extends the model time period up to 2015. In Difficult Run, there are two gauges in the headwaters regions that were opened in 2007 and collect data at an hourly level. A new VA Hydro model could be created to interface with version 6.0 of the Bay model and be validated against hourly observed data. In this manner, more gauges in the area could be used to guide the impoundment design process. With upstream and downstream gauges available for comparison, impoundment modeling strategies could be validated against upstream gauges and refined based on their impact on the outlet. In addition, this model performed extremely well despite significant downscaling from the original river segment in the Chesapeake Bay model. It may be possible to interpolate between hourly Bay model data to create 15-minute intervals that are more useful for modeling pond processes. The model could be validated against available 15-miunte gauge to ensure proper function. Additional outlet structure algorithms could also be added to the VA Hydro framework to better represent the designs seen in field visits. This would improve model realism and give a more comprehensive analysis of the impact impoundments have on flow alteration. Finally, future field visits and bathymetry surveys may be needed to validate modeling strategies and lower overall uncertainty.

Small impoundments ultimately served as sources of major flow alteration within this VA Hydro model. This study highlighted the need to examine all upstream impounded waters when studying flow. Both ponds and reservoirs had a tremendous impact on flow magnitude, duration, frequency, and rate of change. Furthermore, their effects accumulated traveling down the network, with additional impoundments further altering flow. When possible, future water resource managers must give attention to impoundment even if available information is lacking. Estimated bathymetry and outlet designs can be generated from readily available satellite and aerial imagery, making it entirely possible to assess the impact of impoundment in any given routing model. By better understanding how a river or lake flow regime has been shaped by impoundment, informed decisions can be made regarding future dam and stormwater control design. In addition, with careful modeling, useful inferences can be made from impoundment networks to better predict water availability during periods of drought, medium, or high flow by improving model storm duration. Any model should be validated at a sub-daily temporal resolution whenever possible to examine changes to the flow regime that extend beyond flood magnitude.

Appendix

Table 1. Impoundment terminology used in distinguishing different sized impoundments.

Limnetic Term	Description	Source
Waterbody	"A body of water forming a physiographical feature" including all of the following terms	*Oxford Dictionary, 2017*
Impoundment	Any artificially created water body regardless of its size	*Renwick et al., 2005*
Pond	A small impoundment created by a dam that fails to meet NID criteria i.e. below 6 feet in height and store less than 25 ac-ft or below 25 feet in height and store less than 15 ac-ft	*Renwick et al., 2005* *ACE, 2016*
Reservoir	A large impoundment created by a dam that meets NID criteria i.e. 6 feet or above in height and store more than 25 ac-ft or 25 feet or above in height and store more than 15 ac-ft	*Renwick et al., 2005* *ACE, 2016*

Table 2. Impoundment dataset and VA Hydro catchment properties (label IDs in Figure 5).

ID	Catchment	Parent	Normal/ Max Stage (ft)	Normal/ Max Storage (ac-ft)	Drainage Area (mi^2)	Channel Length (ft)	10-yr Design Flow (cfs)	Orifice Width (ft)
5	Outlet	N/A	N/A	N/A	58.30	50050	4819	N/A
6	Lake Anne	Lake Fairfax	15.4/28.3	363/745	0.91	2201	75.87	2.6
9	Lake Audubon	Outlet	15.8/45.6	410/1364	2.37	14206	195.09	4.0
7	Lake Fairfax	Outlet	10.6/24.5	182/487	4.22	12792	351.84	11.2
8	Lake Thoreau	Lake Audubon	32.6/48.8	813/1406	0.57	2306	47.52	1.4
10	Lower Timber	Outlet	12.8/16.1	38/50	2.42	14288	201.76	73.1
12	Martins Lake	Outlet	5.7/10.9	45/93	0.51	1296	42.52	3.1
3	Piney Run	Outlet	7.1/17.3	58/167	4.05	21138	337.66	13.0
4	Pond 2	Outlet	6.3/14.6	34/89	0.05	1401	4.54	0.3
11	Pond 8	Lower Timber	6.8/15.6	52/137	0.09	1253	7.46	0.4
1	Pond 27	Pond 32	5.2/10.5	10/25	0.15	3524	12.51	0.9
2	Pond 32	Outlet	5.7/12.5	18/56	1.13	10256	94.21	8.8

Table 3. Experimental design diagram defining constants, variables, and projected outcomes.

Title	The effect of impoundments on Difficult Run low flow regime
Hypothesis	Increasing presence stream impoundments within a VA Hydro analysis will result in lower magnitude and more frequent low flows in Difficult Run
Independent Variable *Levels of the Independent Variable*	The presence of modeled impoundments 0: Control Group --- VA Hydro run with no impoundments (21 years) 1: Treatment Group --- VA Hydro run with all impoundments (21 years) 2: Treatment Group --- VA Hydro run with only reservoirs (5 years) 3: Treatment Group --- VA Hydro run with only ponds (5 years) 4: Treatment Group --- VA Hydro run with 8 impoundments (5 years) 5: Treatment Group --- VA Hydro run with 5 impoundments (5 years)
Repeated Trials	11 headwater waterbodies across Difficult Run
Dependent Variable	August Low Flows (ALF), September 10%, Drought of Record (DoR), 7q10, 30q2, 10/25/50/75/90/99% flow, mean flow, rising/falling limb rate of change, storm duration, mean baseflow, number of zero flows, and flow duration (tested statistically with KS test),
Constants	Flow network, background climate/channel data, time period, Chesapeake Bay inflow data, routing and outlet algorithms

Table 4. Results of impounded and null scenario at Difficult Run outlet.

Metric	Impounded		Null		% Change	
	Hourly	Daily	Hourly	Daily	Hourly	Daily
ALF	2.2 cfs	3.2 cfs	2.0 cfs	3.2 cfs	6.6 %	2.1 %
DoR	9.8 cfs	9.8 cfs	9.8 cfs	9.9 cfs	0.0 %	-1.3 %
September 10%	0.9 cfs	1.0 cfs	1.0 cfs	1.1 cfs	-11.7 %	-11.4 %
7q10	0.1 cfs	0.1 cfs	0.2 cfs	0.2 cfs	-24.9 %	-25.6 %
30q2	4.5 cfs	4.7 cfs	4.7 cfs	4.8 cfs	-4.3 %	-3.6 %
Rise	1.2 hr^{-1}	2.9 d^{-1}	1.4 hr^{-1}	2.9 d^{-1}	-13.2 %	-0.4 %
Fall	-0.1 hr^{-1}	-0.9 d^{-1}	-0.2 hr^{-1}	-1.0 d^{-1}	-9.9 %	-7.2 %
Duration	23.0 hrs	5.9 d	17.4 hr	5.8 d	32.3 %	2.3 %
Mean Baseflow	35.6 cfs	16.8 cfs	33.4 cfs	16.2 cfs	6.6 %	3.6 %
Q10	3.5 cfs	3.8 cfs	3.4 cfs	3.6 cfs	3.2 %	4.0 %
Q25	9.6 cfs	10.4 cfs	8.8 cfs	9.5 cfs	9.1 %	8.6 %
Q50	25.6 cfs	27.9 cfs	23.8 cfs	26.1 cfs	7.6 %	6.7 %
Q75	59.3 cfs	64.2 cfs	56.1 cfs	62.7 cfs	5.6 %	2.4 %
Q90	139.5 cfs	149.0 cfs	136.3 cfs	149.4 cfs	2.3 %	-0.2 %
Q99	627.7 cfs	580.1 cfs	659.3 cfs	590.3 cfs	-4.8 %	-1.7 %
Zero	1.0 hours	0.0 days	1.0 hours	0.0 days	0.0 %	0.0 %
Mean	63.9 cfs	63.9 cfs	63.7 cfs	63.7 cfs	0.3 %	0.3 %

Table 5. Model scenarios to analyze cumulative impact on alteration.

Scenario	Impoundments Included	Intention
Null	None	Provide a baseline for analyzing flow alteration
All Impoundments	Lake Anne Lake Audubon Lake Fairfax Lake Thoreau Lower Timber Martins Lake Piney Run Pond 2 Pond 8 Pond 27 Pond 32	Serve as a scenario of maximum alteration
Reservoirs Only	Lake Anne Lake Audubon Lake Fairfax Lake Thoreau Lower Timber Martins Lake Piney Run	Demonstrate the benefits of including all reservoirs in flow models
Subset of 8 Impoundments	Lake Audubon Lake Fairfax Lake Thoreau Lower Timber Martins Lake Pond 2 Pond 27 Pond 32	Show how alteration changes with fewer impoundments
Subset of 5 Impoundments	Lake Audubon Lake Fairfax Lake Thoreau Pond 2 Pond 32	Show how alteration changes with fewer impoundments
Ponds Only	Pond 2 Pond 8 Pond 27 Pond 32	Evaluate the role of small ponds in flow alteration
Lake Audubon	Lake Audubon	Illustrate how large impoundments can play significant roles in alteration

Table 6. Cumulative impact of impoundment on alteration at the Difficult Run outlet. See Table 5 for scenario descriptions.

Metric	Scenario						
	Null	All imps	Reservoirs only	8 imps	5 imps	Lake Audubon	Ponds only
ALF (cfs)	1.12	1.27	1.28	1.26	1.27	1.19	1.12
DoR (cfs)	12.33	11.98	12.01	12.08	12.13	12.25	12.30
September 10% (cfs)	0.65	0.56	0.57	0.59	0.61	0.68	0.64
30Q2 (cfs)	5.42	4.82	4.80	4.74	4.96	5.42	5.68
Rise (hr^{-1})	1.52	1.37	1.41	1.44	1.47	1.47	1.48
Fall (hr^{-1})	-0.16	-0.14	-0.14	-0.15	-0.15	-0.16	-0.16
Duration (hr)	17.06	22.97	21.92	20.94	20.03	17.07	17.17
Mean Baseflow (cfs)	25.67	27.56	27.49	27.16	27.08	26.43	25.75
Q10 (cfs)	2.89	3.02	3.04	3.02	3.05	3.01	2.87
Q50 (cfs)	18.54	20.38	20.31	19.98	19.91	19.31	18.60
Q90 (cfs)	105.81	109.01	108.64	108.14	107.90	106.76	106.16
Q99 (cfs)	520.33	498.03	500.95	505.73	507.48	513.21	519.41

Table 7. Minimum and maximum storage/outlet width used in uncertainty analysis. Calibrated, final values as used in 21-year scenarios included as the "used" values.

Impoundment	Normal Storage (ac-ft)			Max Storage (ac-ft)			Outlet Width (ft)		
Name	Used	Min	Max	Used	Min	Max	Used	Min	Max
Lake Fairfax	182	81	234	487	204	679	11.2	9.2	20.5
Lake Anne	363	117	360	745	294	1059	2.6	1.9	4.3
Lake Audubon	410	130	407	1364	326	1201	4.0	4.6	10.7
Lake Thoreau	813	133	420	1406	335	1241	1.4	1.2	2.7
Piney Run	58	36	89	167	90	251	13.0	10.5	21.8
Martins Lake	45	34	83	93	85	234	3.1	1.4	2.9
Lower Timber	38	13	26	50	32	71	73.1	8.3	15.9
Pond 8	52	33	81	137	83	228	0.4	0.3	0.5
Pond 27	10	7	13	25	18	35	0.9	0.7	1.3
Pond 32	18	12	26	46	31	69	8.8	3.9	7.4
Pond 2	34	22	51	89	56	142	0.3	0.2	0.4

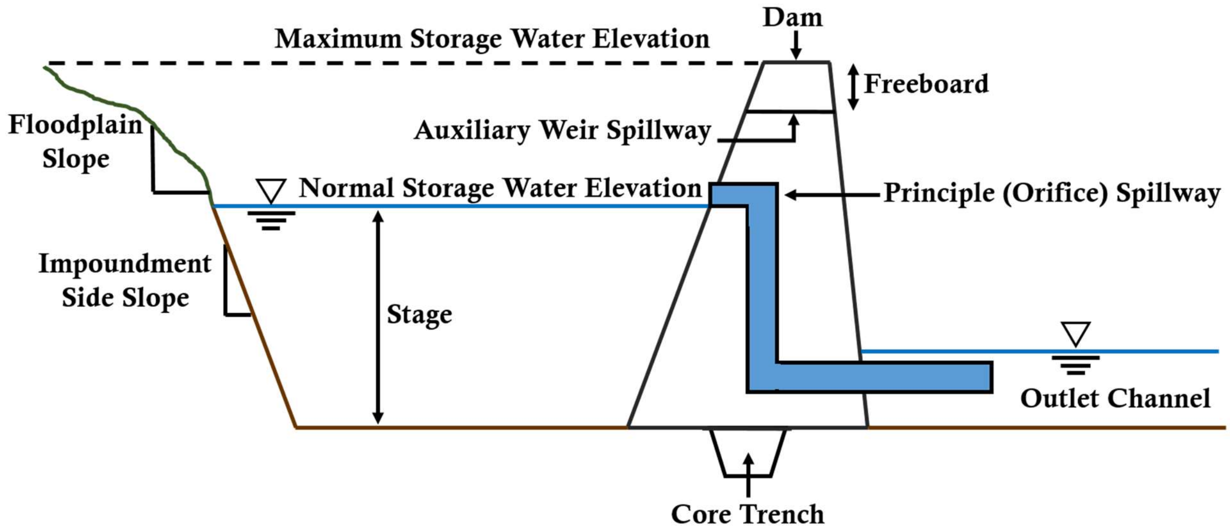

Figure 1. A side-view diagram of an impoundment.

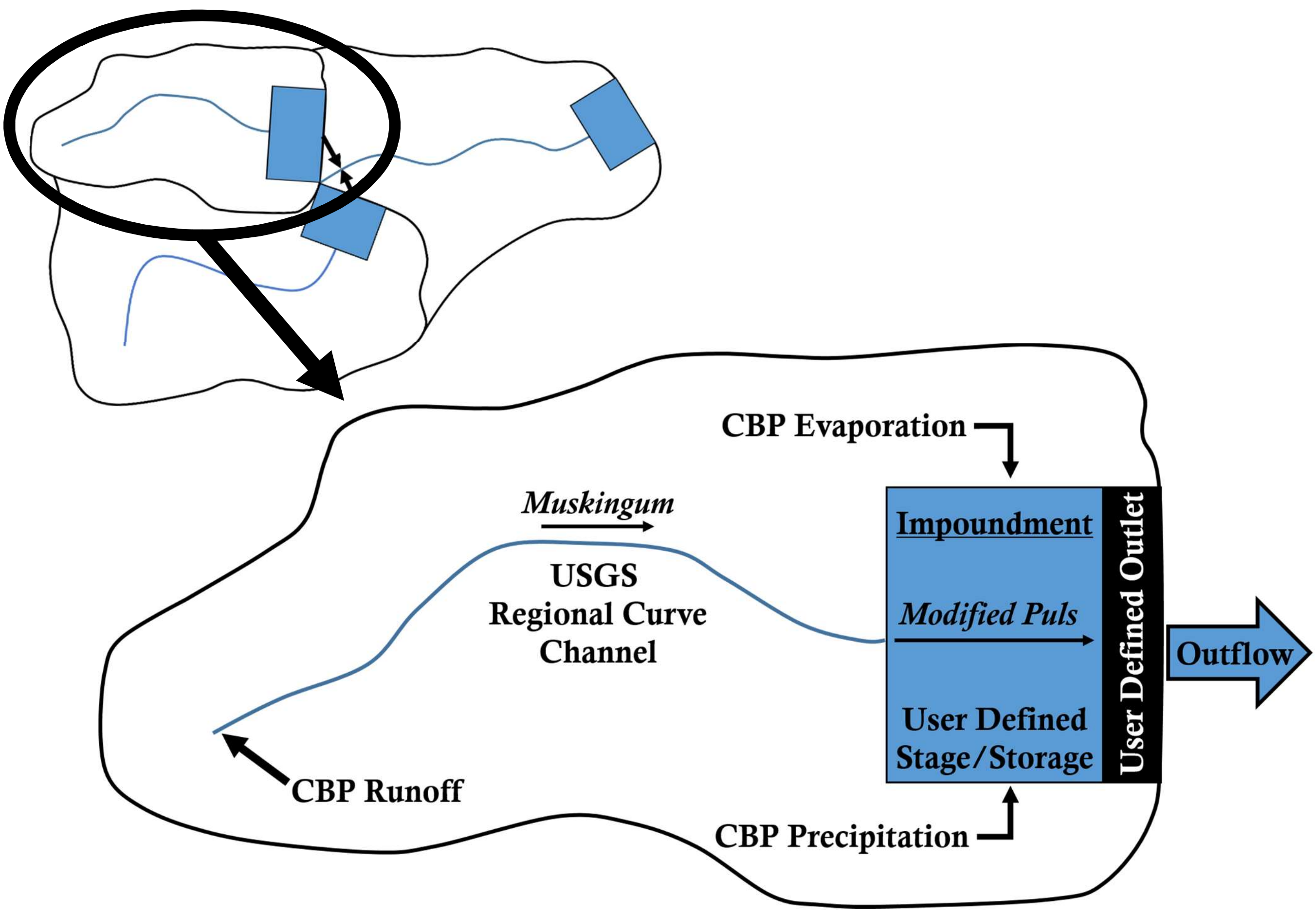

Figure 2. A conceptual diagram of a VA Hydro watershed model and individual catchment.

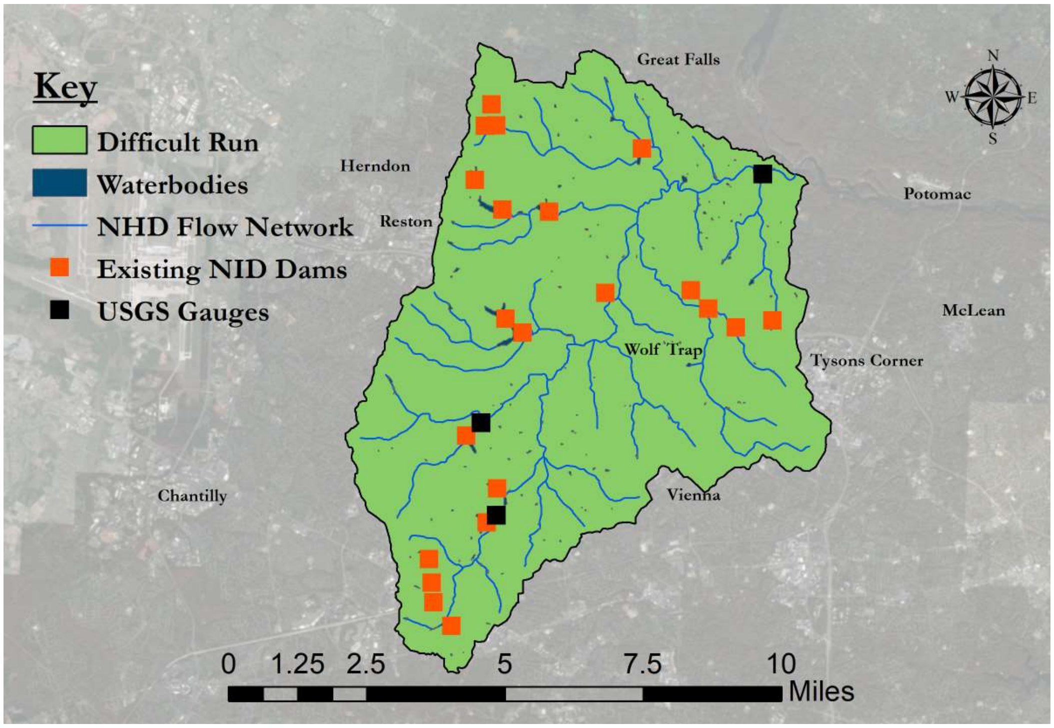

Figure 3. Difficult Run with all waterbodies in the area shown.

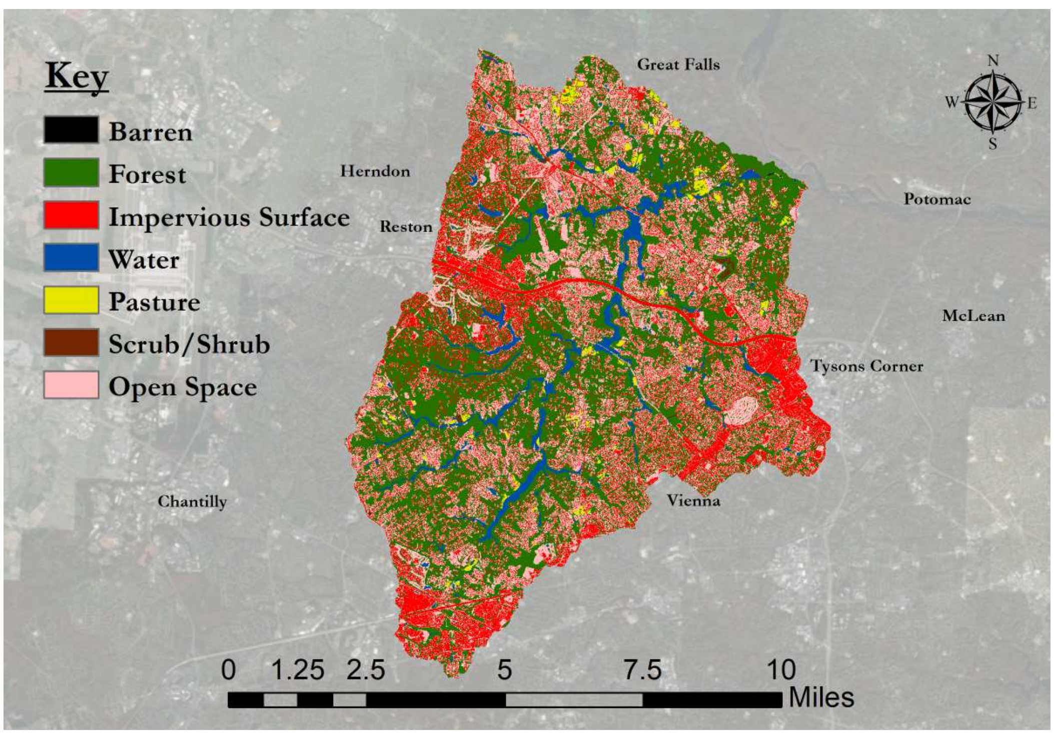

Figure 4. Difficult Run 1-m land cover.

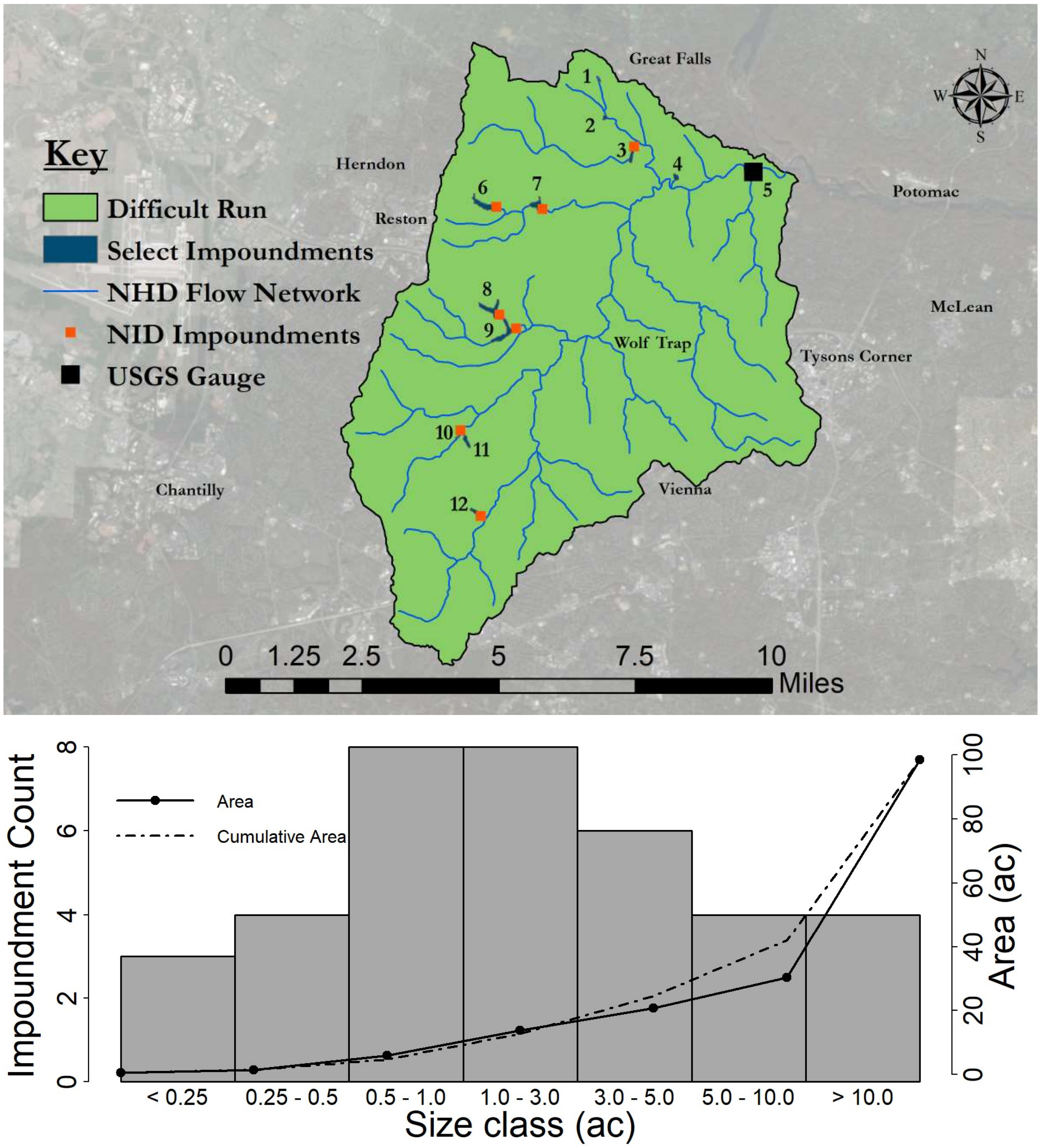

Figure 5. Difficult Run with final impoundment dataset (top) and waterbody breakdown (bottom).

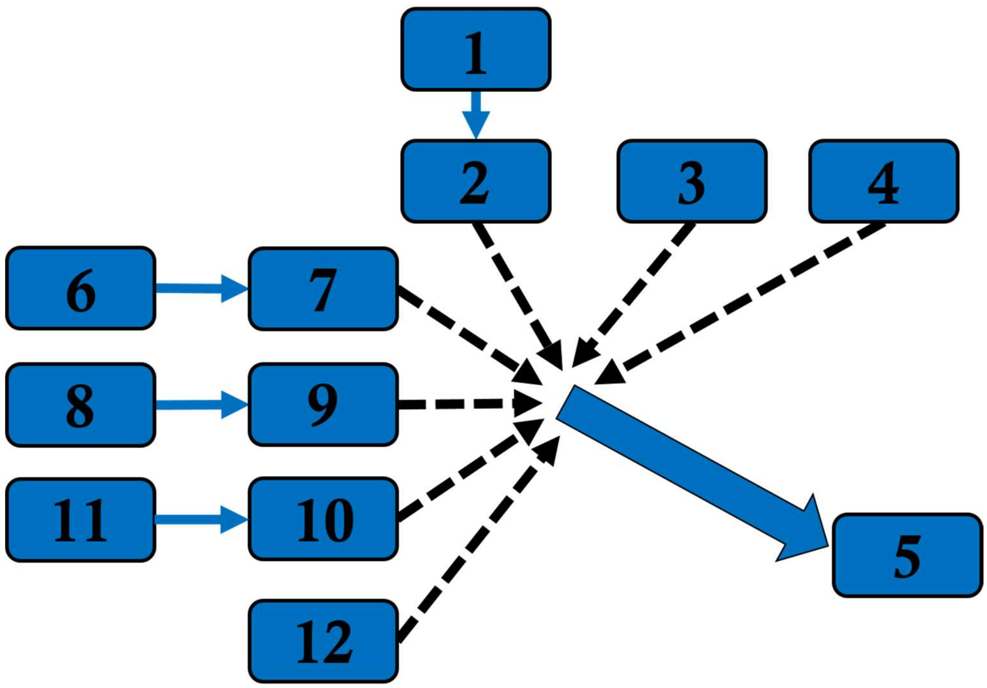

Figure 6. Final VA Hydro model (labels in Table 2 and Figure 5). Black lines are artificial flow paths such that water from outlets in 2, 3, 4, 7, 9, 10, and 12 is instantly routed to the upstream point in catchment 5. Blue arrows show routed water fed from one impoundment to the most upstream point in the next catchment through estimated channels.

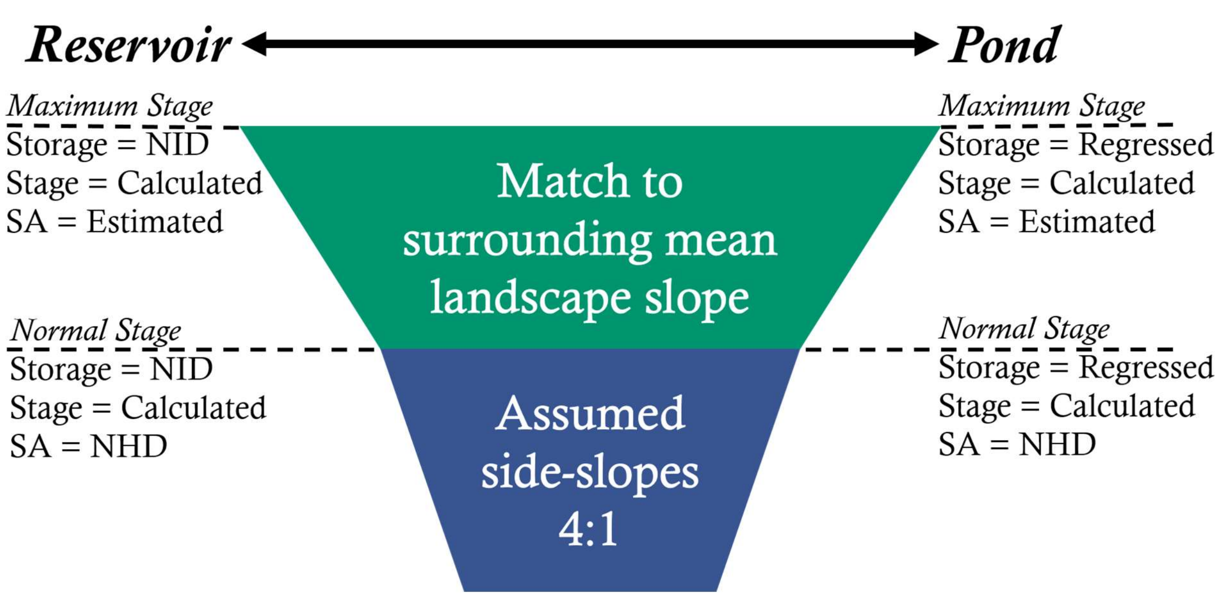

Figure 7. Impoundment bathymetry model showing procedure differences in pond and reservoir model generation.

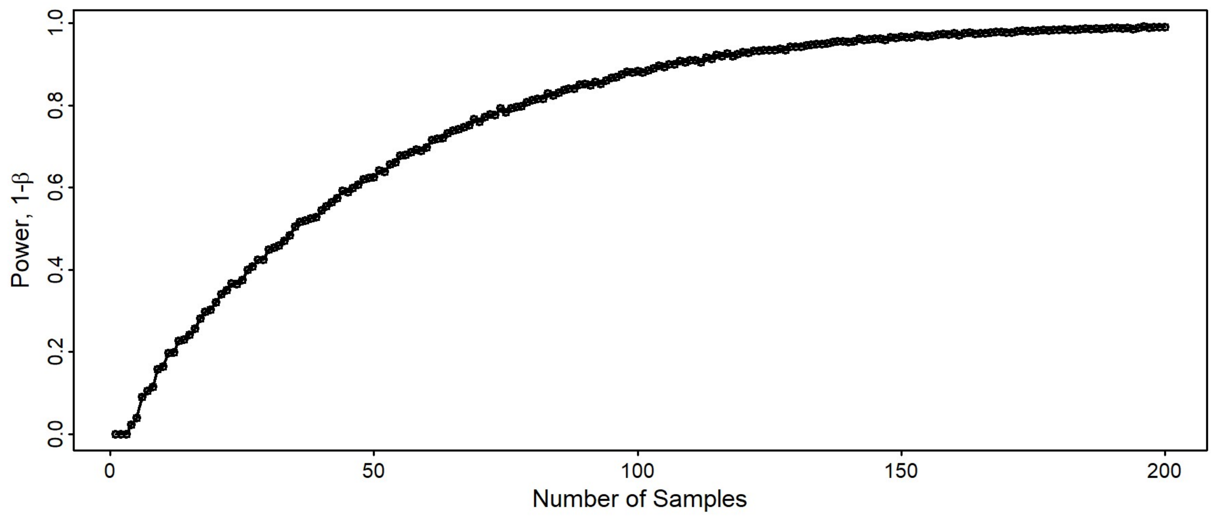

Figure 8. Low-flow metric power analysis to determine necessary number of samples in statistical testing.

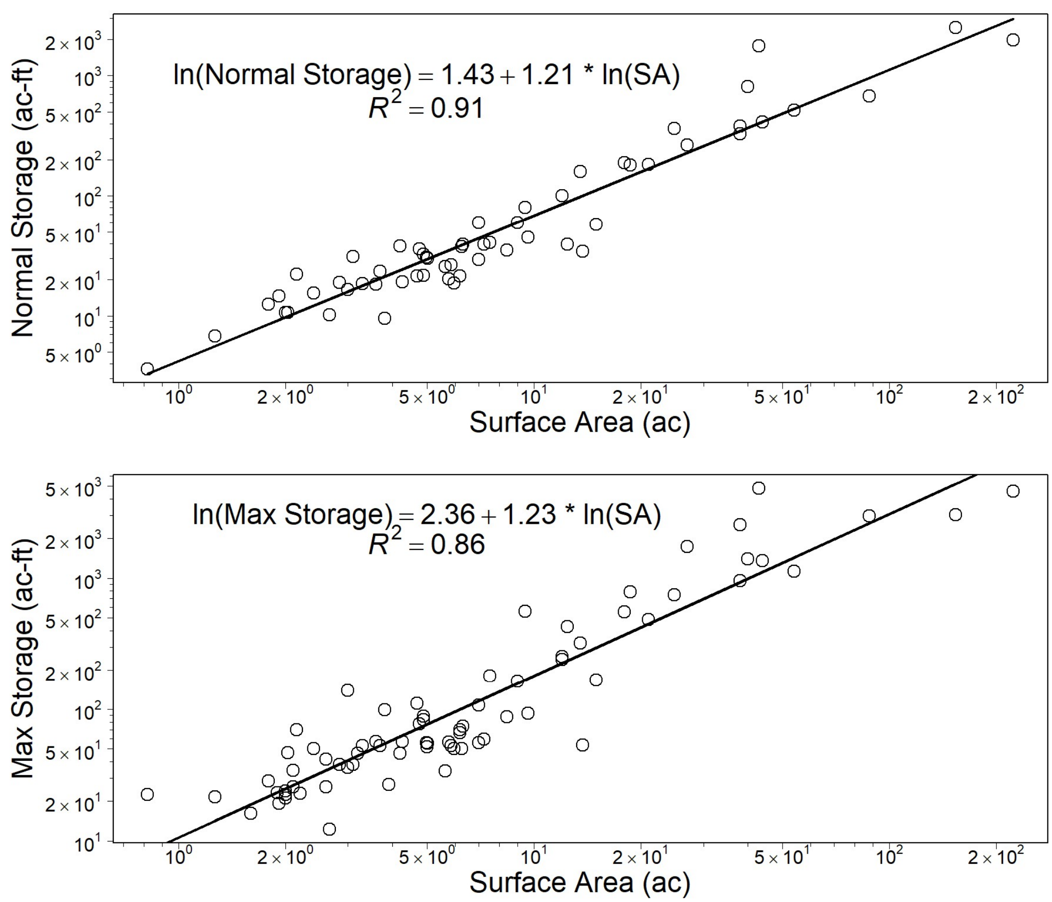

Figure 9. Power regressions of surface area and normal (top) and maximum storage (bottom).

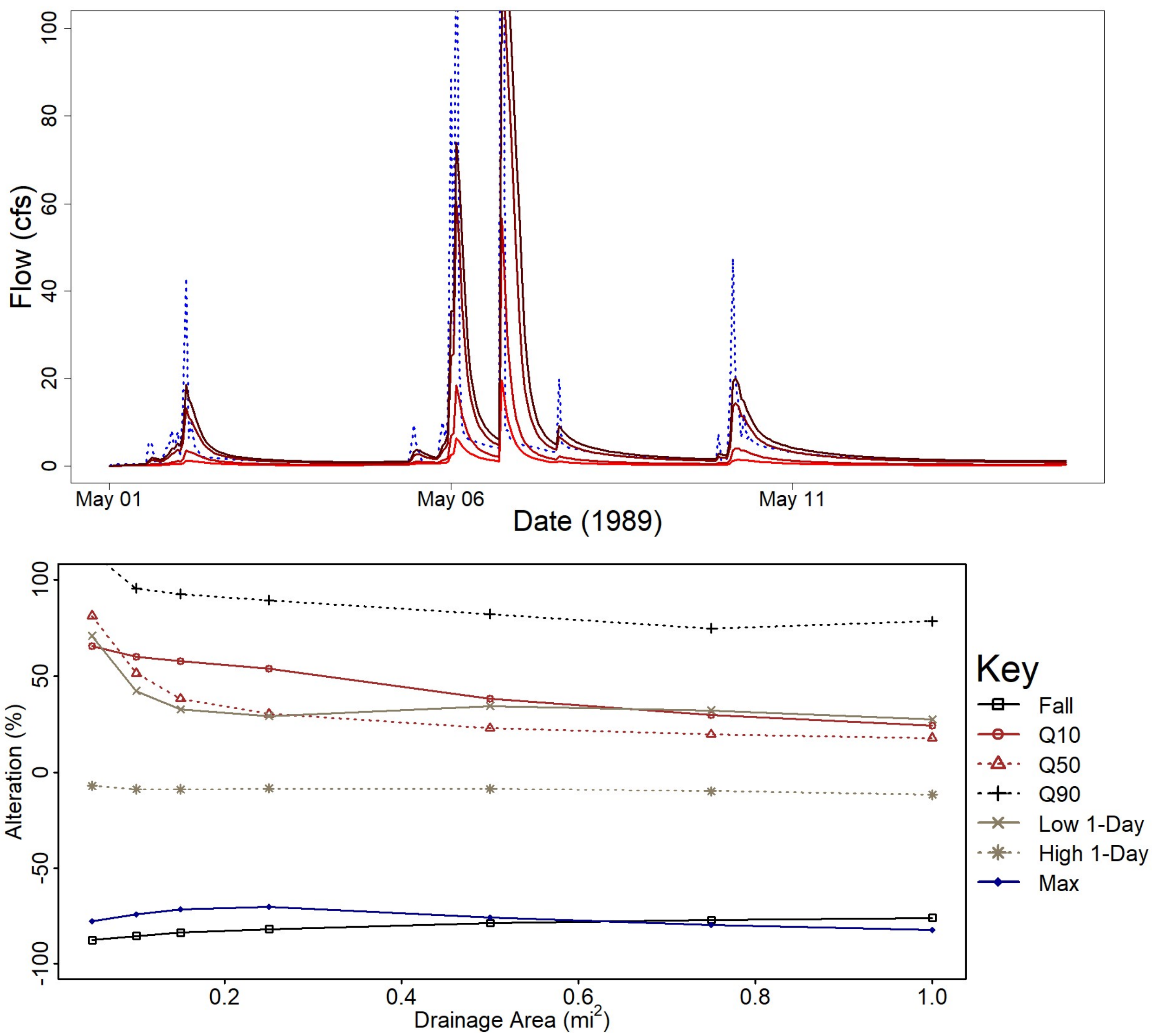

Figure 10. Drainage area sensitivity analysis. The hydrograph (top) was created under multiple simulations with increasing drainage area (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with increasing drainage area. Other variables held constant.

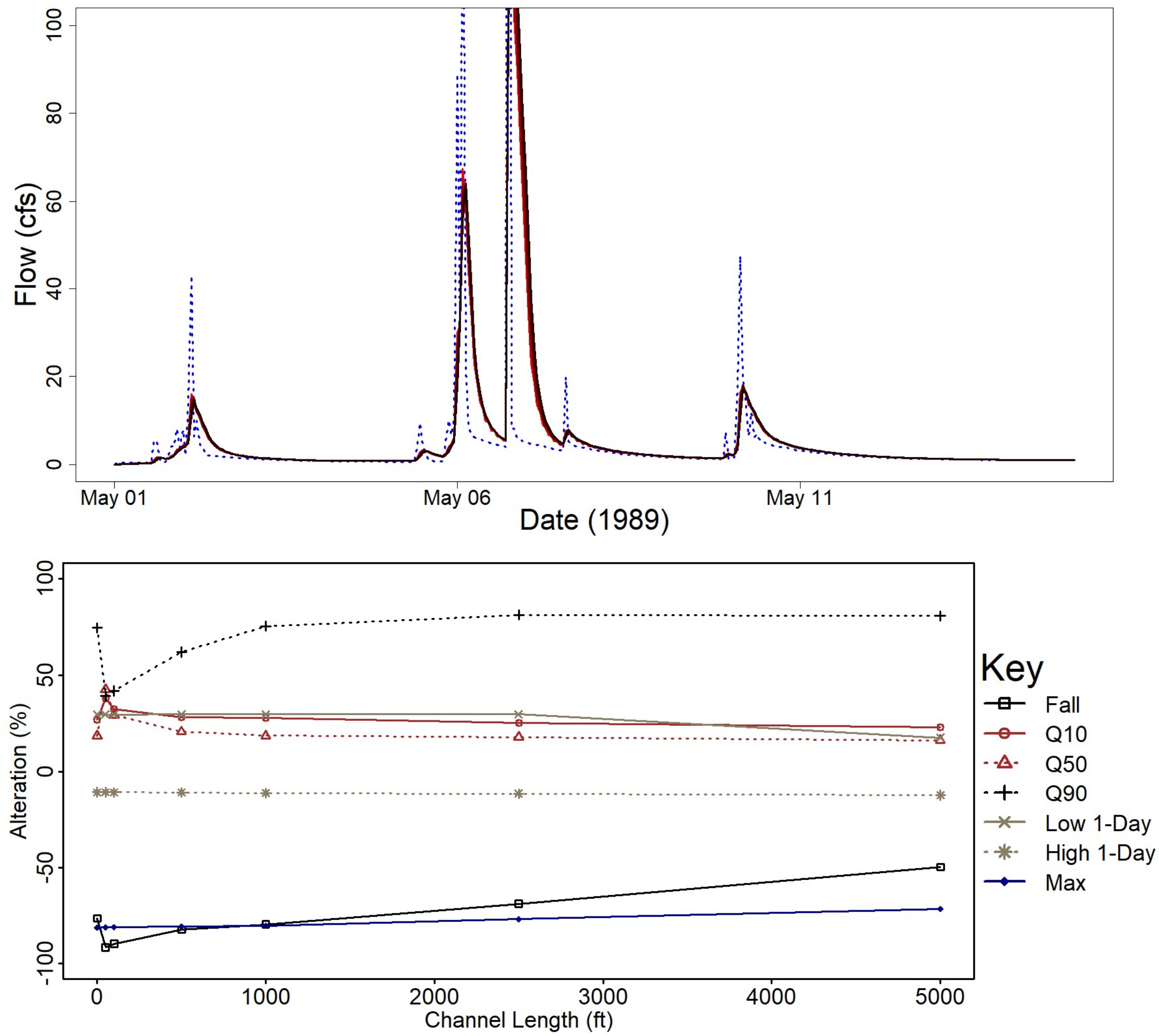

Figure 11. Channel length sensitivity analysis. The hydrograph (top) was created under multiple simulations with increasing channel length (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with increasing channel length. Other variables held constant.

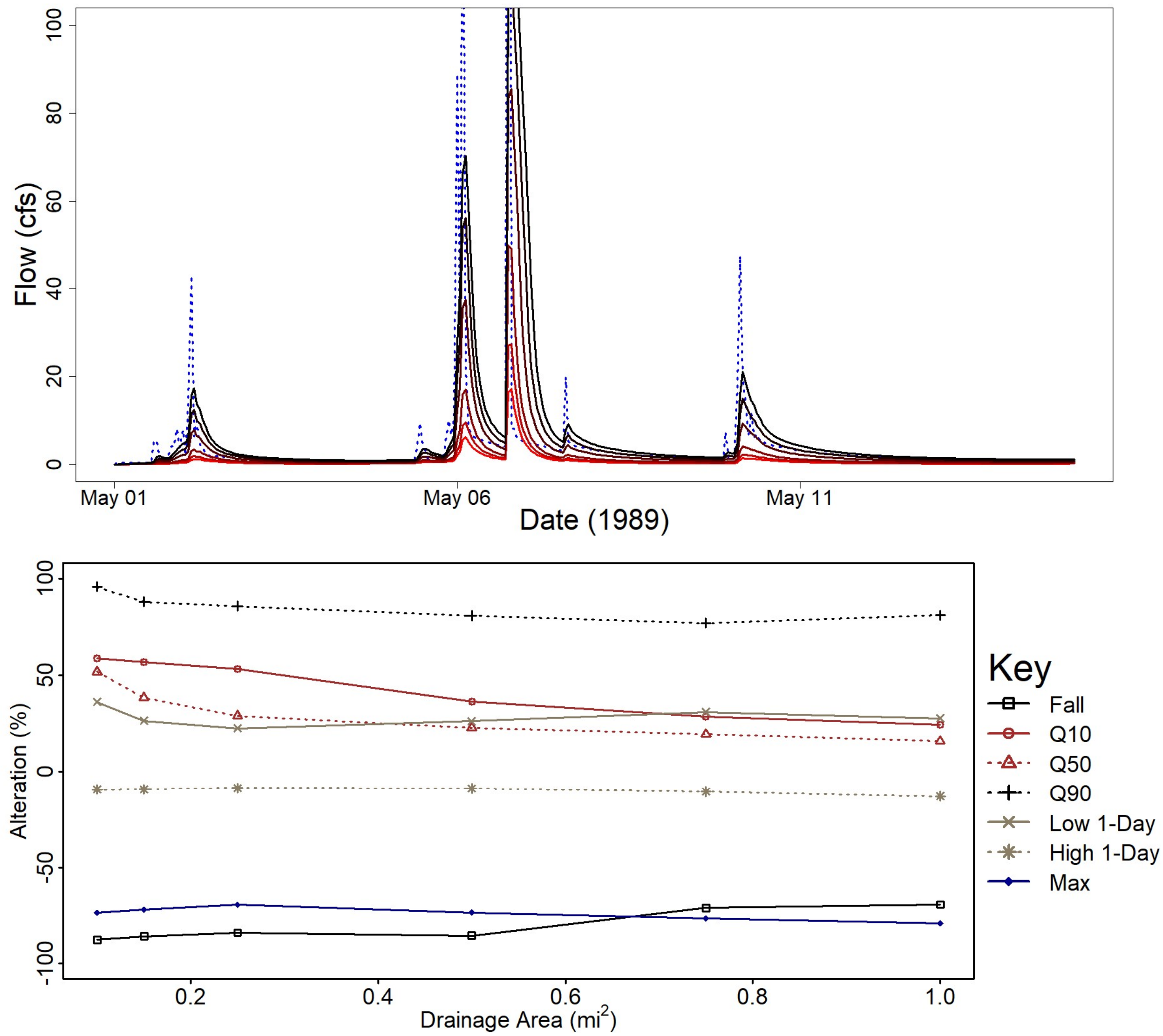

Figure 12. Drainage area and channel length sensitivity analysis. The hydrograph (top) was created under multiple simulations in which channel length increased proportionally with larger drainage areas (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with increasing drainage area and channel length. Other variables held constant.

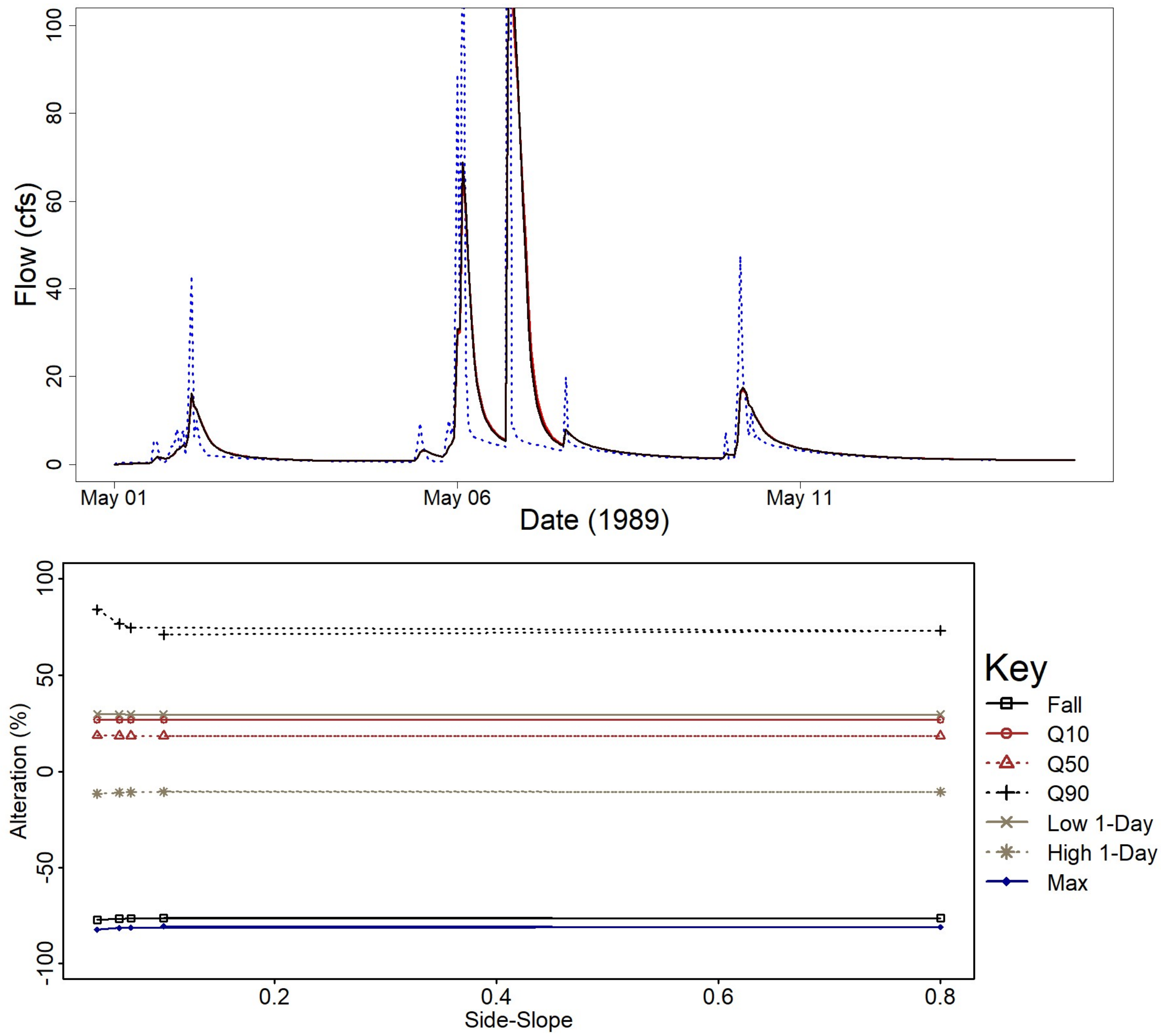

Figure 13. Side slope sensitivity analysis. The hydrograph (top) was created under multiple simulations with increasing side slope (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with increasing side slope. Other variables held constant.

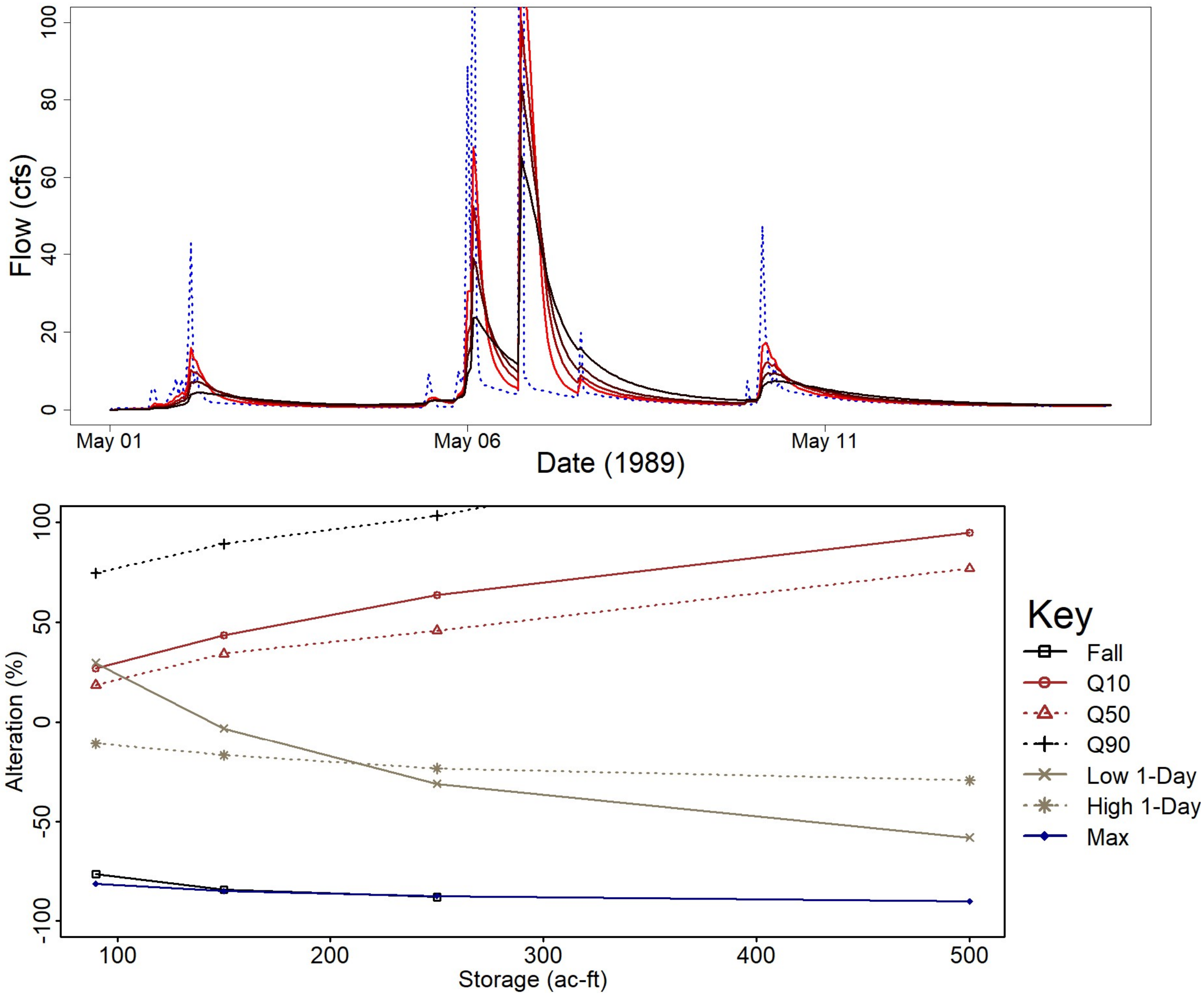

Figure 14. Storage sensitivity analysis. The hydrograph (top) was created under multiple simulations with increasing storage (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with increasing storage. Other variables held constant.

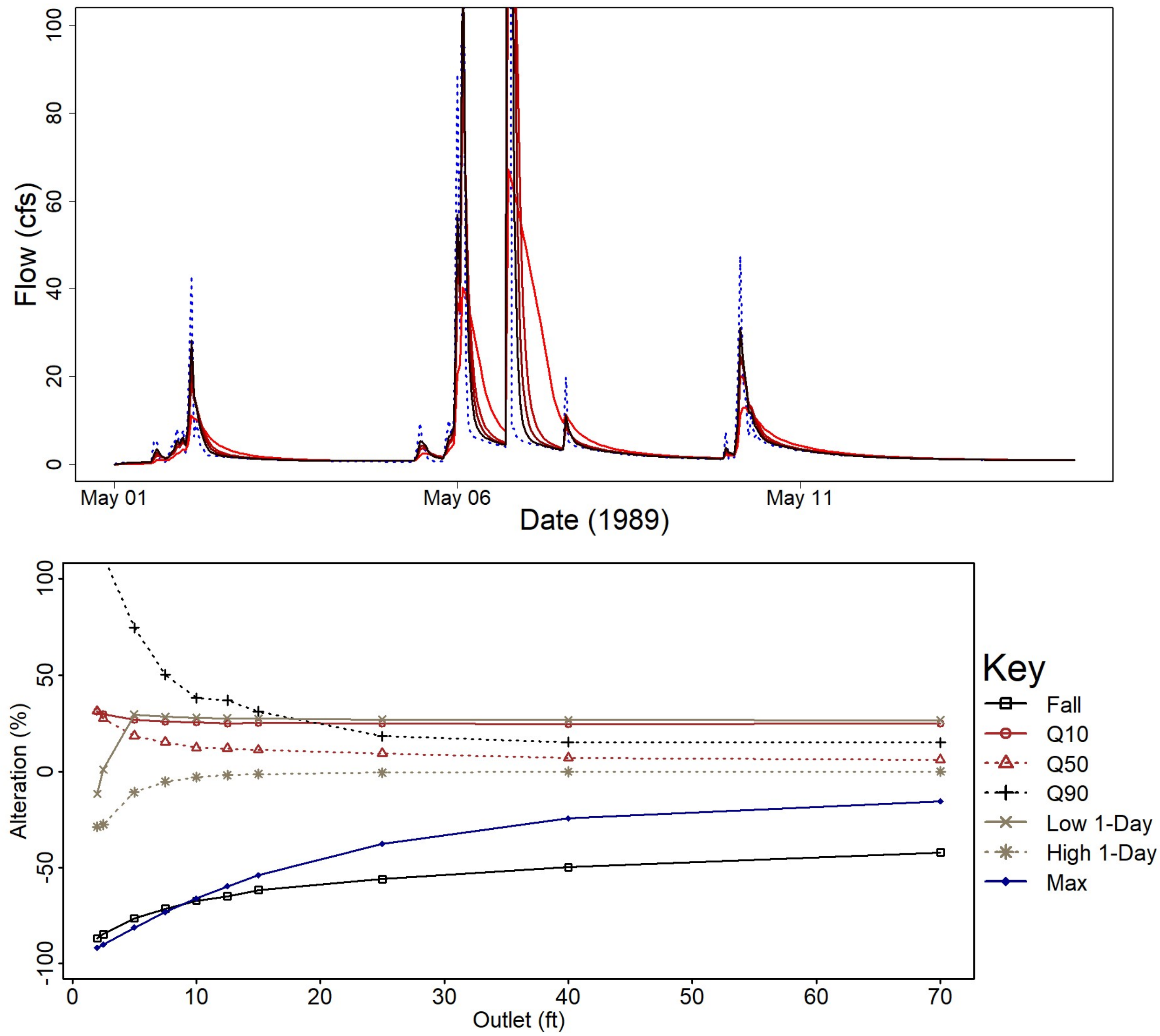

Figure 15. Outlet width sensitivity analysis. The hydrograph (top) was created under multiple simulations with increasing outlet width (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with increasing outlet width. Other variables held constant.

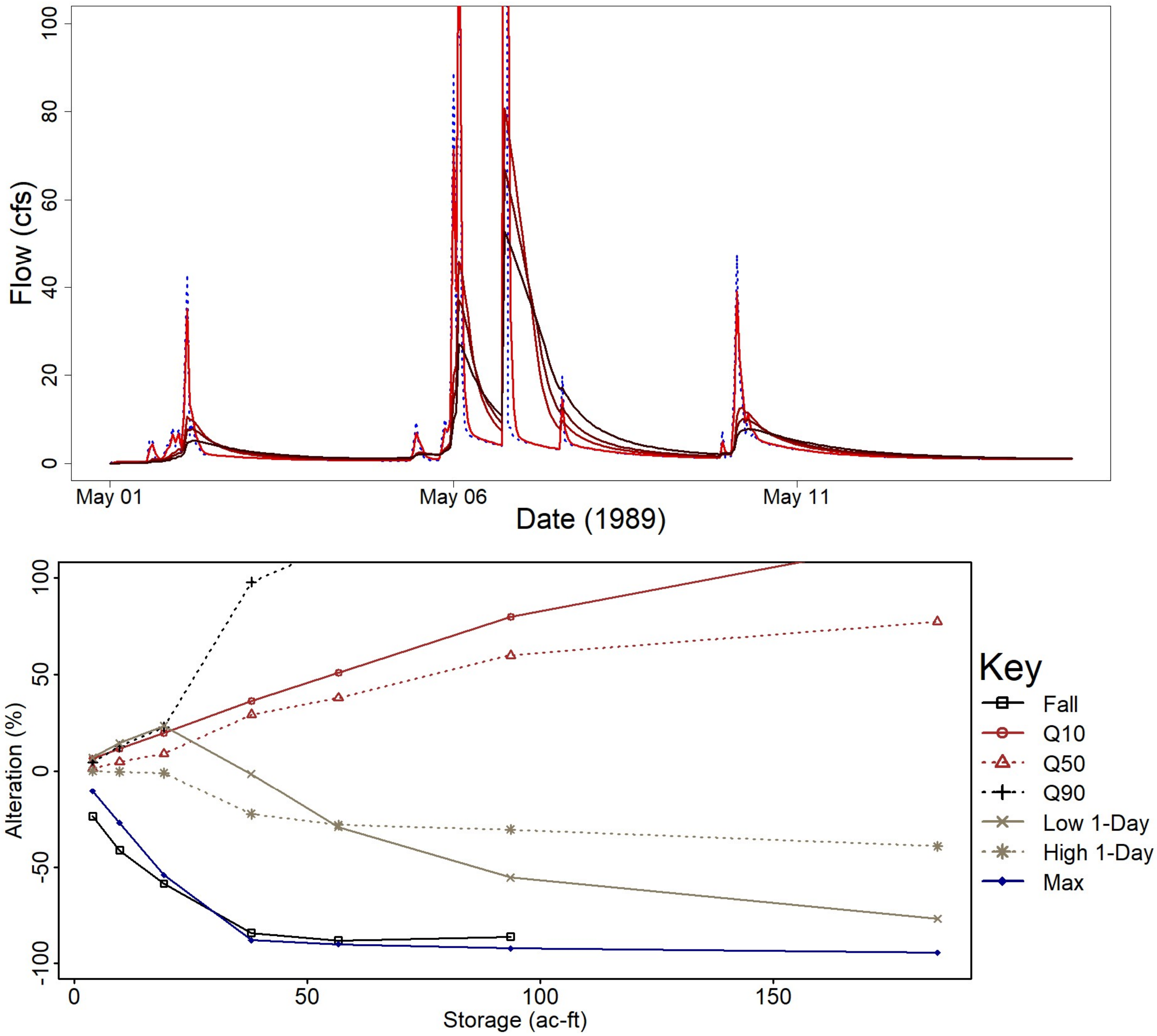

Figure 16. Storage and outlet width sensitivity analysis. The hydrograph (top) was created under multiple simulations in which outlet width decreased proportionally to increasing storage (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with decreasing outlet width and increasing storage. Other variables held constant.

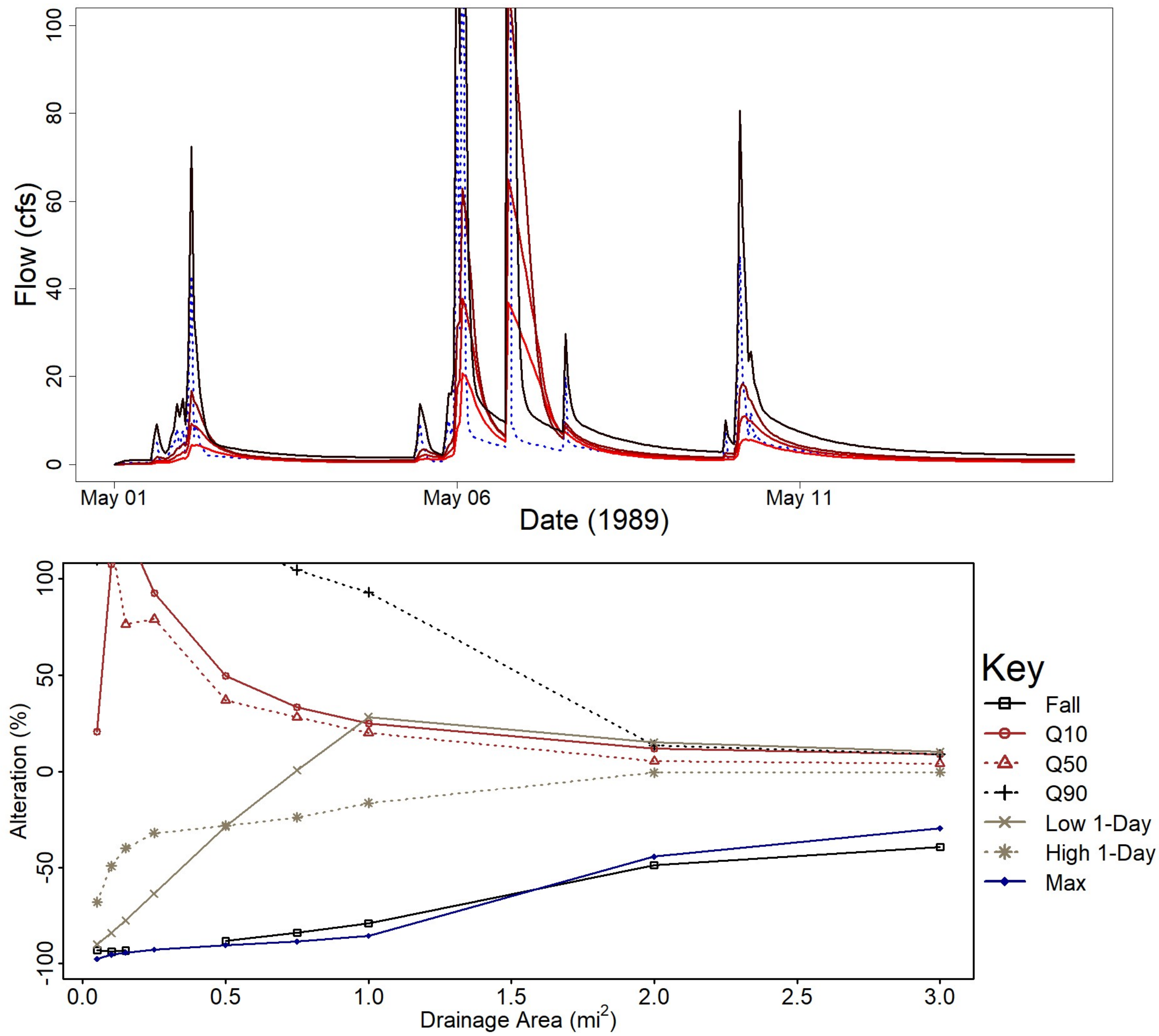

Figure 17. Drainage area and outlet width sensitivity analysis. The hydrograph (top) was created under multiple simulations in which outlet width increased proportionally with larger drainage areas (darker lines). The blue dashed line indicates inflow. The alteration graph (bottom) shows how metrics vary with increasing drainage area and outlet width. Other variables held constant.

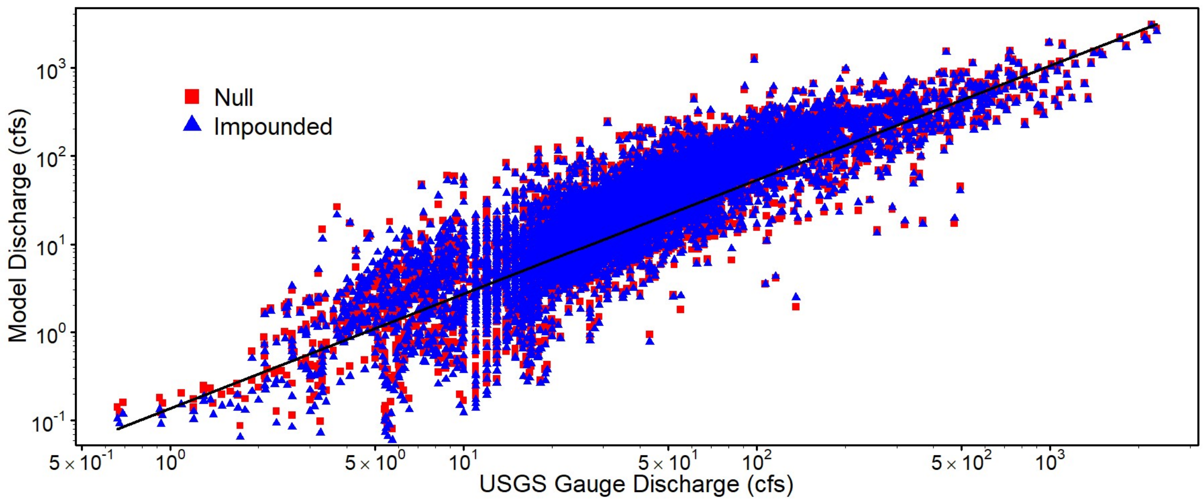

Figure 18. Model validation to outlet USGS flow record for 21-year study period under null and impounded scenarios.

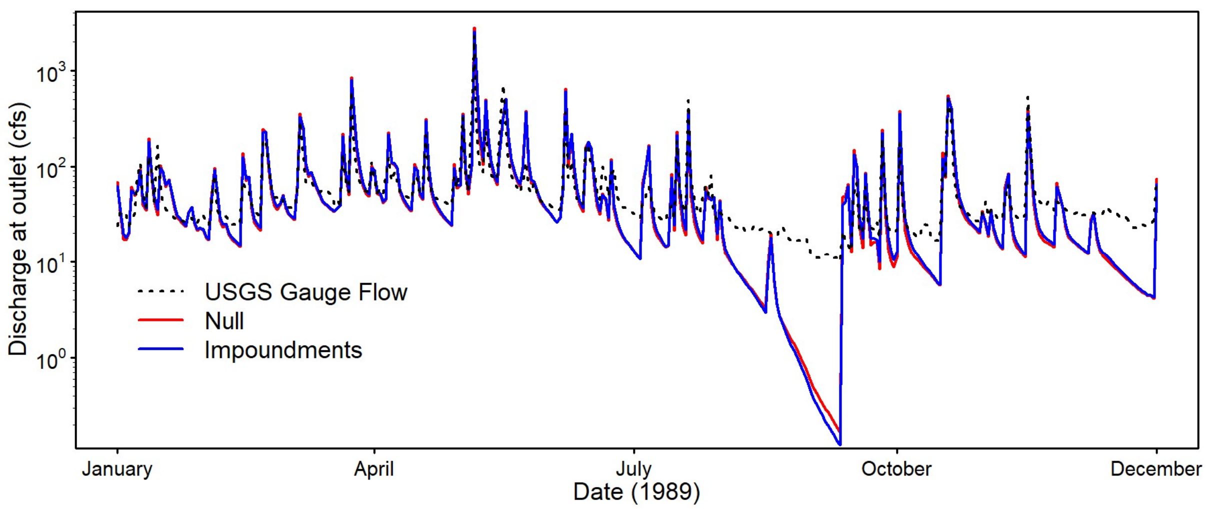

Figure 19. Model performance over a single year, 1989.

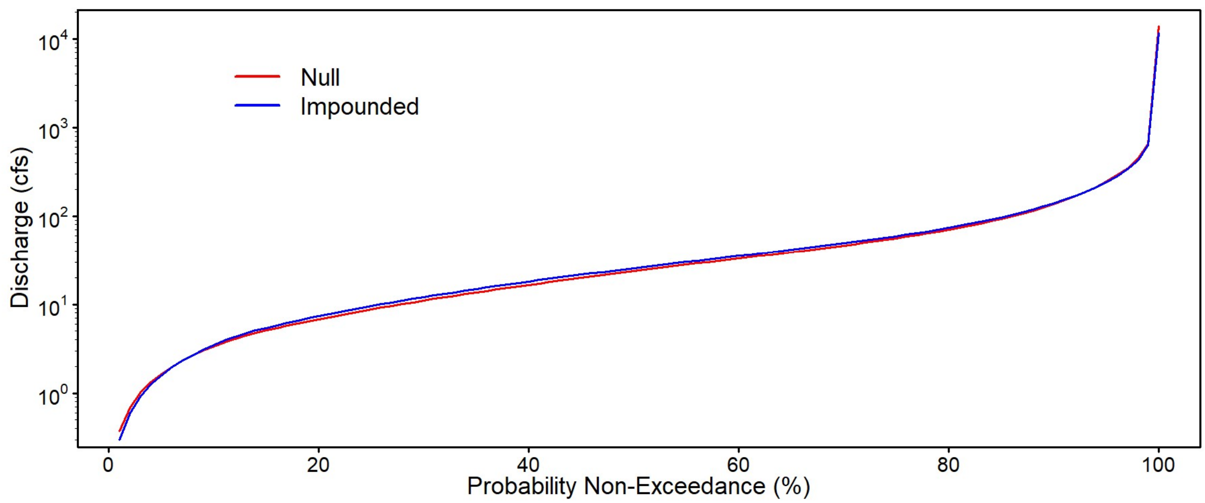

Figure 20. Flow duration curves of 21-year impounded and null scenarios.

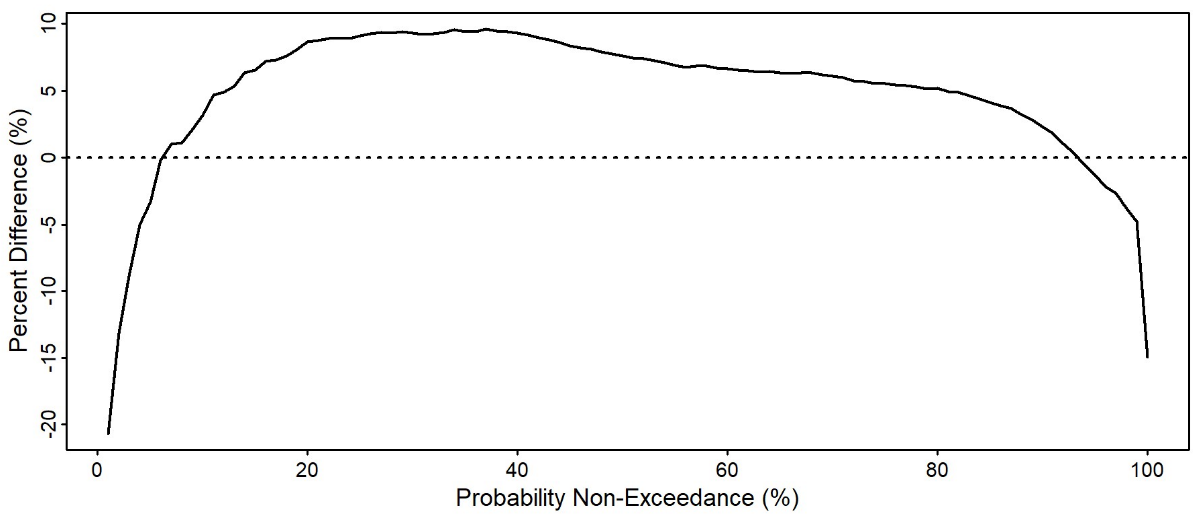

Figure 21. Hourly percent difference in flow duration between impounded and null runs in full 21-year model simulations.

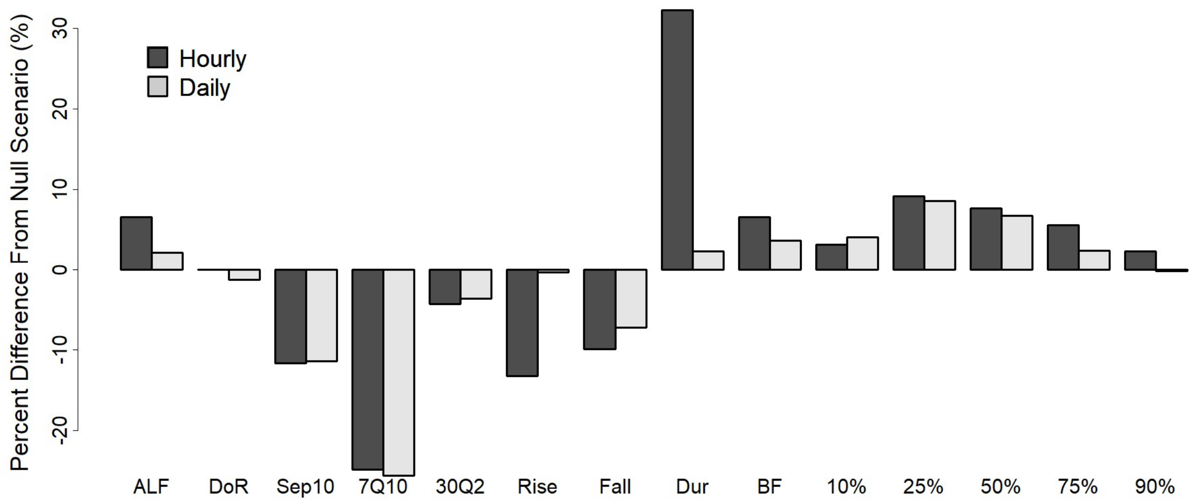

Figure 22. Select alteration metrics at the Difficult Run model outlet calculation from percent differences of the 21-year impounded simulation with that of the null scenario.

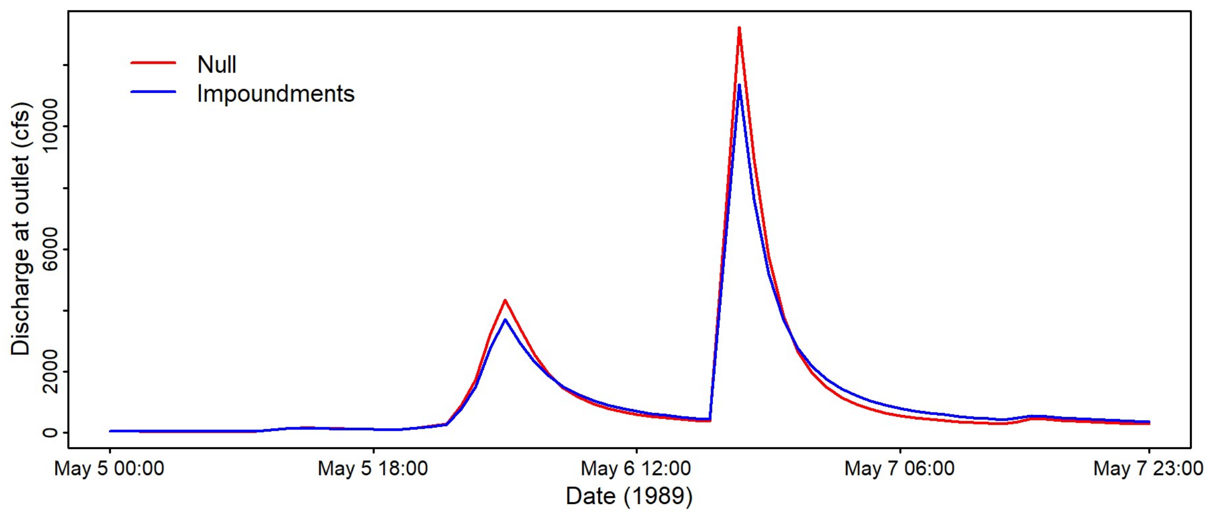

Figure 23. A storm showing lowered peaks and longer duration after impoundment.

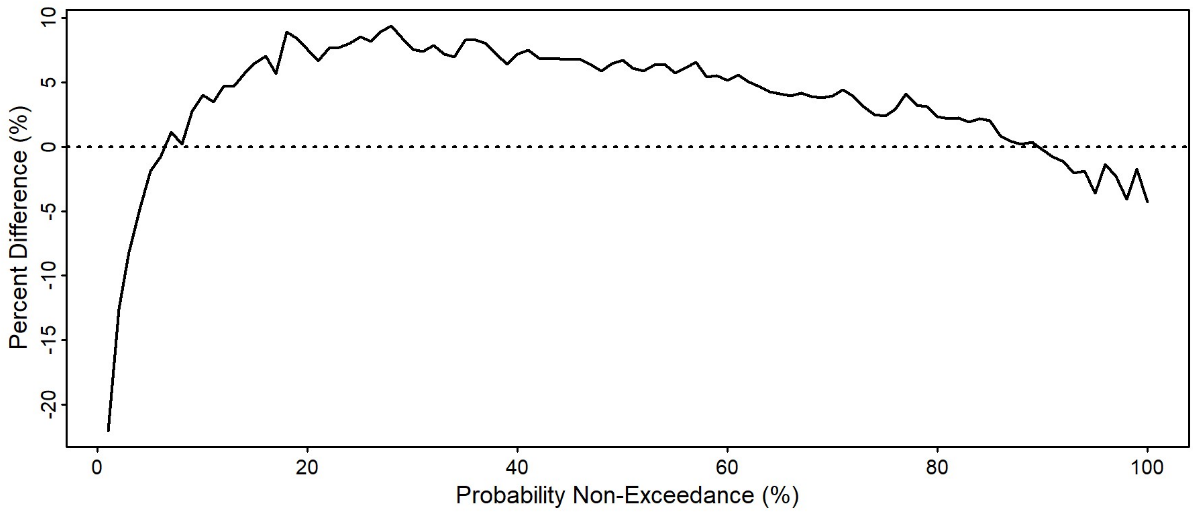

Figure 24. Daily percent difference in flow duration between impounded and null runs in full 21-year model simulations.

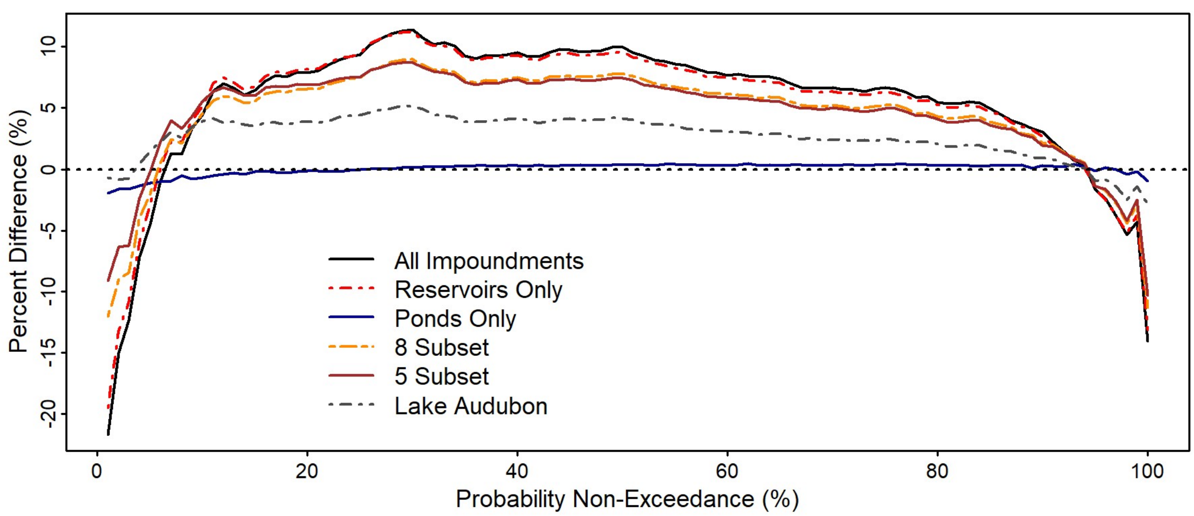

Figure 25. Cumulative impact of impoundment on alteration. Scenarios described in Table 5.

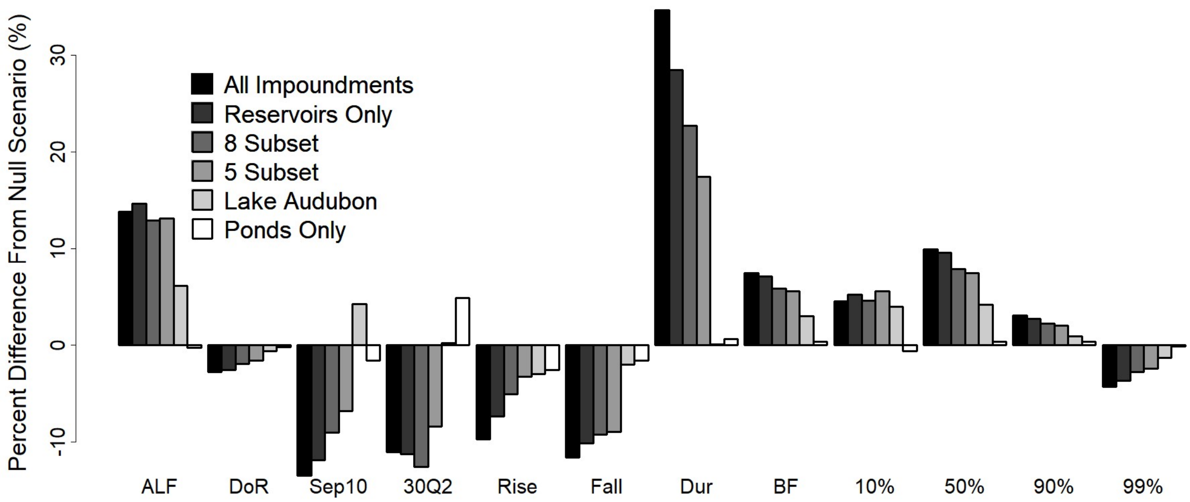

Figure 26. Percent difference from null scenario under different model runs.

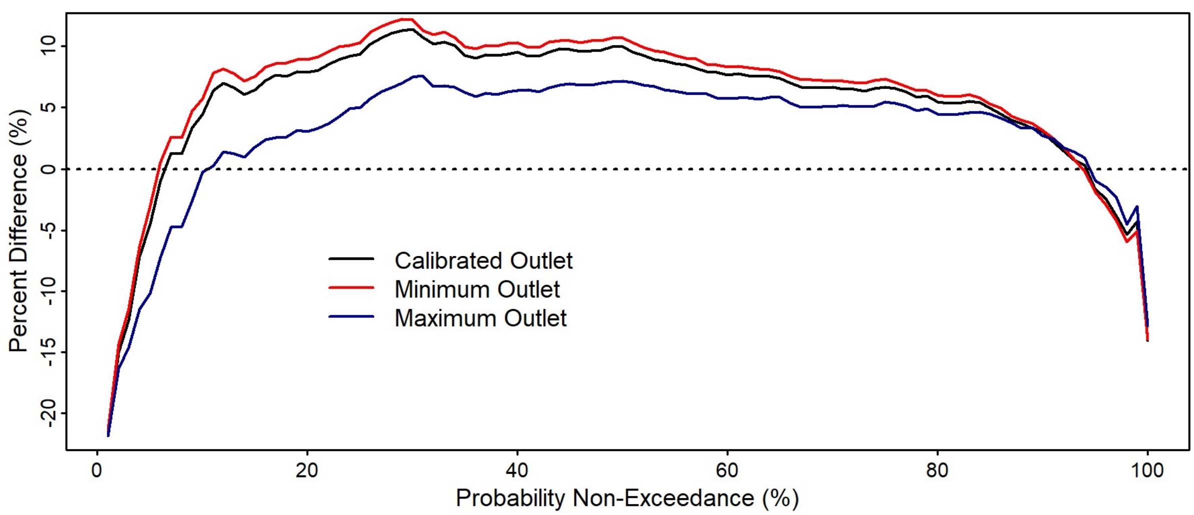

Figure 27. Orifice uncertainty compared to calibrated model run in percent difference from null.

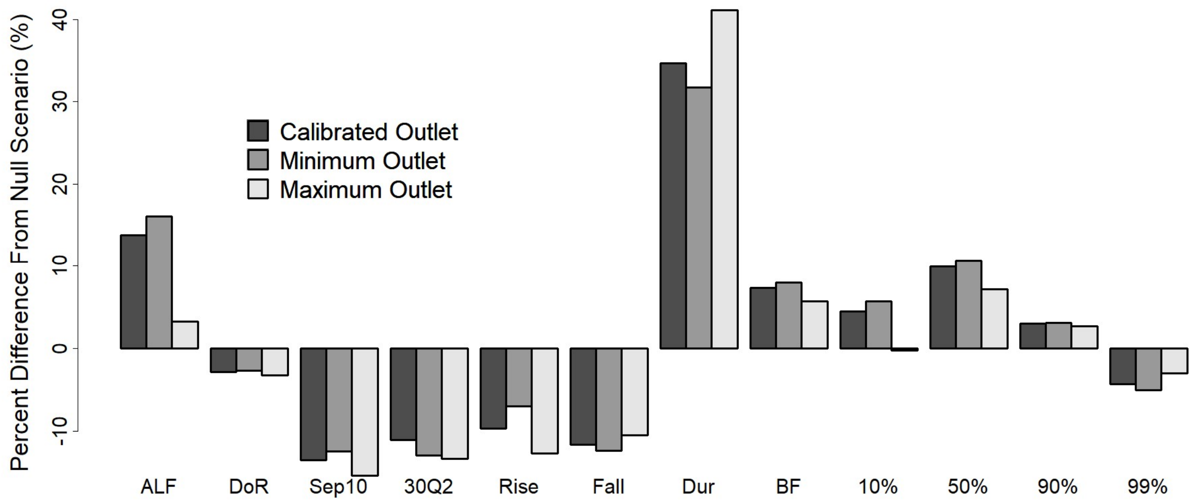

Figure 28. Impact of orifice uncertainty on select flow metrics (in percent difference from null).

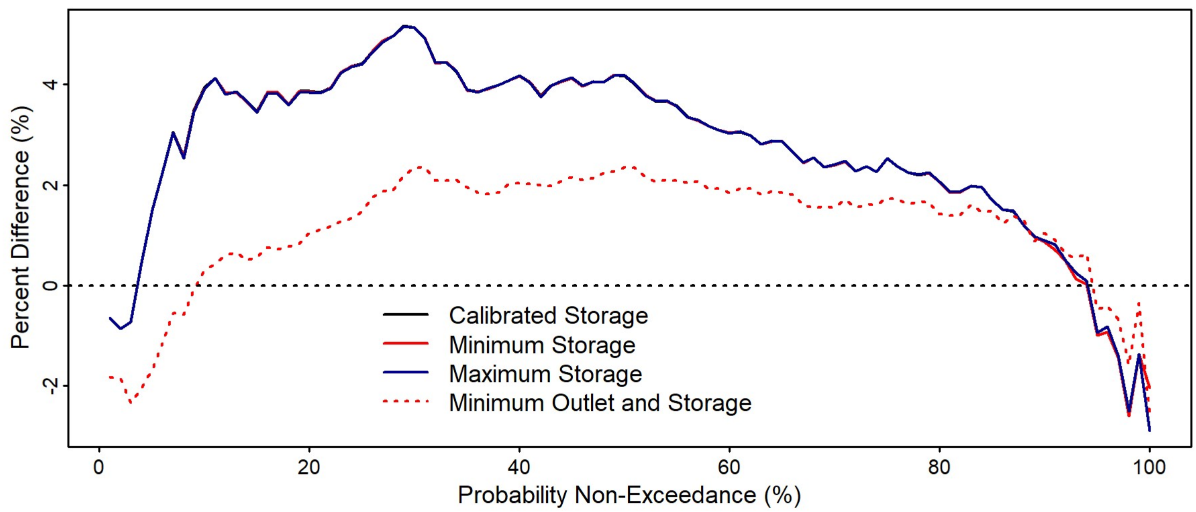

Figure 29. Storage uncertainty compared to calibrated model run in percent difference from null.

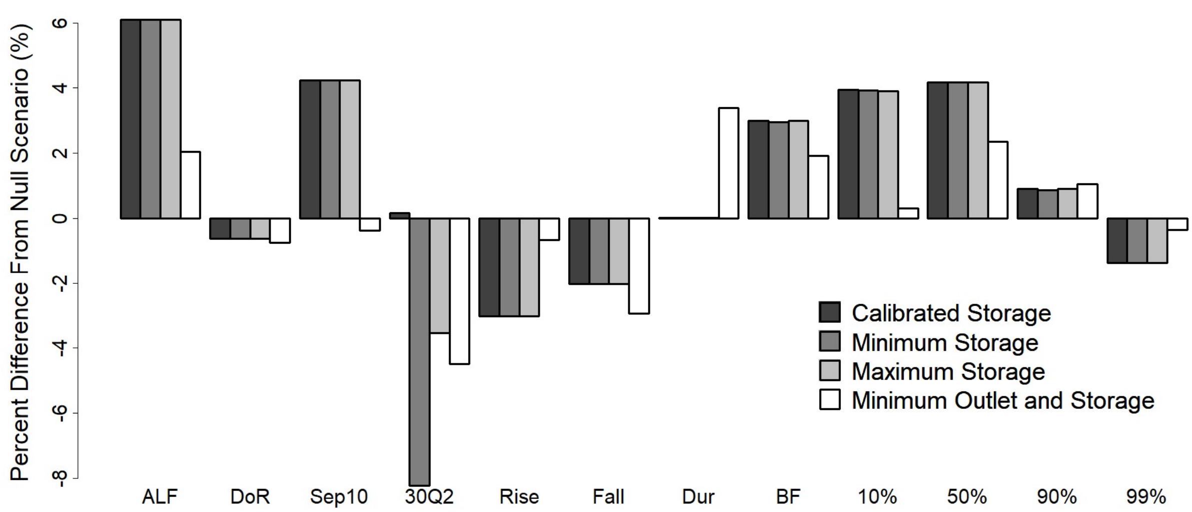

Figure 30. Impact of storage uncertainty on select flow metrics (in percent difference from null).

References

Alexander, R. B., Boyer, E. W., Smith, R. A., Schwarz, G. E., & Moore, R. B. (2007). The role of headwater streams in downstream water quality. *Journal of the American Water Resources Association*, *43*(1), 41–59. https://doi.org/10.1111/j.1752-1688.2007.00005.x

Arias, M. E., Piman, T., Lauri, H., Cochrane, T. A., & Kummu, M. (2014). Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia. *Hydrology and Earth System Sciences*, *18*(12), 5303–5315. https://doi.org/10.5194/hess-18-5303-2014

Austin, S. H., Krstolic, J. L., & Wiegand, U. (2011a). Low-Flow Characteristics of Virginia Streams. *Scientific Investigations Report 2011 – 5144*. Reston, Virginia.

Austin, S. H., Krstolic, J. L., & Wiegand, U. (2011b). Peak-Flow Characteristics of Virginia Streams. *Scientific Investigations Report 2011 – 5144*. Reston, Virginia.

Ayalew, T. B., Krajewski, W. F., Mantilla, R., Wright, D. B., and Small, S. J. (2017). Effect of spatially distributed small dams on flood frequency: Insights from the Soap Creek Watershed. *Journal of Hydrologic Engineering.* 22(7): -1--1. DOI: 10.1061/(ASCE)HE.1943-5584.0001513

Batalla, R. J., Gómez, C. N., and Kondolf, G. M. (2004). Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*. 290: 117-136. DOI: 10.1016/j.jhydrol.2003.12.002

Becker, M. and Klößner, S. (2017). Package 'PearsonDS'. *The comprehensive R archive network.* Accessed at https://cran.r-project.org/web/packages/PearsonDS/PearsonDS.pdf

Berg, M. D., Poescu, S. C., Wilcox, B. P., Angerer, J. P., Rhodes, E. C., McAlister, J., and Fox, W. E. (2016). Small farm ponds: Overlooked features with important impacts on watershed sediment transport. *Journal of the American Water Resource Association*. 52(1): 67-76. DOI: 10.1111/1752-1688.12369

Brinkman, W. L. F. (1985). Urban stormwater pollutants: Sources and loadings. *GeoJounal*, 11(3), 277-283.

Chow, V. T. (1959). *Open Channel Hydraulics*. New York City, NY: McGraw-Hill Book Company.

Chumchal, M. M., Drenner, R. W., and Adams, K. J. (2016). Abundance and size distribution of permanent and temporary farm ponds in the southeastern Great Plains. *Inland Waters*. 6: 258-264. DOI: 10.5268/IW-6.2.954

Cohen, J. E. (2003). Human Population: The Next Half Century. *Science*. 302 (5648): 1172-1175. DOI: 10.1126/science.1088665.

Deitch, M. J., Merenlender, A. M., & Feirer, S. (2013). Cumulative Effects of Small Reservoirs on Streamflow in Northern Coastal California Catchments. *Water Resources Management*, *27*(15), 5101–5118. https://doi.org/10.1007/s11269-013-0455-4

Döll, P., Fiedler, K., and Zhang, J. (2009). Global-scale analysis of river flow alterations due to water withdrawals and reservoirs. *Hydrology and Earth System Sciences.* 6: 4773-4812.

Downing, J. A. (2010). Emerging global role of small lakes and ponds: Little things mean a lot. *Limnetica*. 29(1): 9-24.

Downing, J. A., Praire, Y. T., Cole, J. J., Duarte, C. M., Tranvik, L. J., McDowell, W. H., … Middleburg, J. J. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography.* 51(5): 2388-2397.

Fairchild, G., Robinson, C., and Brainard, A. (2012). Historical Changes in the Distribution and Abundance of Constructed Ponds in Response to Changing Population Density and Land Use. *Landscape Research.* 37: 1–14. DOI:10.1080/01426397.2012.672640

Fairfax County. (2018). Building a farm or amenity pond. *Northern Virginia Soil and Water Conservation District*. Accessed at https://www.fairfaxcounty.gov/soil-water-conservation/building-farm-or-amenity-pond

Fuka, D.R., Walter, M.T., Archibald, J.A., Steenhius, T.S., and Z. M. Easton. (2015). Package 'EcoHydRology'. *The comprehensive R archive network.* Accessed at https://cran.r-project.org/web/packages/EcoHydRology/EcoHydRology.pdf

Grill, M. A. (1978). Flood routing by the Muskingum Method. *Journal of Hydrology*. 36: 353-363.

Heathcote, A. J., del Giorgio, P. A., Prairie, Y. T., & Brickman, D. (2015). Predicting bathymetric features of lakes from the topography of their surrounding landscape. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(5), 643–650. https://doi.org/10.1139/cjfas-2014-0392

Holgerson, M. A., & Raymond, P. A. (2016). Large contribution to inland water CO2and CH4emissions from very small ponds. *Nature Geoscience*, *9*(3), 222–226. https://doi.org/10.1038/ngeo2654

Hollister, J., Milstead, B. (2010). Using GIS to estimate lake volume from limited data. *Lake Reservoir Management*. 26: 194-199. DOI: 10.1080/07438141.2010.504321

Hupp, C. R., Noe, G. B., Schenk, E. R., and Benthem, A. J. (2012). Recent and historic sediment dynamics along Difficult Run, a suburban Virginia Piedmont stream. *Geomorphology*. 180-181: 156-169. DOI: https://doi.org/10.1016/j.geomorph.2012.10.007

Liu, Y., Yang, W., Yu, Z., Lung, I., Yarotski, J., Elliott, J., and Tiessen, K. (2014). Assessing effects of small dams on stream flow and water quality in an agricultural watershed.

Journal of Hydrologic Engineering. 19(10): -1—1. DOI: 10.1061/(ASCE)HE.1943-5584.0001005

Liu, Z., Chunyang, H., Zhou, Y., and Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape Ecol.* DOI: 10.1007/s10980-014- 0034-y

Lotspeich, R. R. (2009). Regional curves for bankfull geometry for non-urban streams in the Piedmont physiographic province, Virginia. United States Geological Survey. Accessed at https://pubs.usgs.gov/sir/2009/5206/pdf/sir2009-5206.pdf

Mays, L. W. (2011). *Water Resources Engineering* (2nd ed.). Hoboken, NJ: John Wiley & Sons Inc.

Meigh, J. (1995). The impacts of small farm reservoirs on urban water supplies in Botswana. *Natural Resource Forum*. 19(1): 71-83.

Mogollón, B., Frimpong, E. A., Hoegh, A. B., and Angermeier, P. L. (2016). Recent changes in stream flashiness and flooding, and effects of flood management in North Carolina and Virginia. *Journal of the American Water Resource Association*. 52(3): 561-577. DOI: 10.1111/1752-1688.12408

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE.* 50(3): 885-900.

National Centers for Environmental Information (NCEI). (2016). National Centers for Environmental Information. National Oceanic and Atmospheric Administration. Accessed at https://www.ncei.noaa.gov/

National Resources Conservation Service: Conservation Practice Standard (NRCS). (2011). Pond: code 378. District of Colombia, Washington D.C: NRCS

Organization for Economic Co-operation and Development (OECD). (2012). OECD Environmental Outlook to 2050. OECD Publishing. Accessed at https://read.oecd-ilibrary.org/environment/oecd-environmental-outlook-to-2050_9789264122246-en#page1

Oxford Dictionary. (2017). Waterbody. Accessed at https://en.oxforddictionaries.com/definition/waterbody

Poff, N. L., Allan, J. D., Bain, M. B., Karr, K. R., Prestegaard, K. L., Richter, B. D., …Stromberg, J. C. (1997). The natural flow regime. *BioScience*. 47(11): 769-784.

Poff, N. L., and Hart, D. D. (2002). How dams vary and why it matters for the emerging science of dam removal. *BioScience*. 52(8): 659-668.

Renwick, W. H., Sleezer, R. O., Buddemeier, R. W., and Smith, S. V. (2006). Small artificial ponds in the United States: Impacts on sedimentation and carbon budget. *Proceedings of the. 8th Federal Interagency Sedimentation Conference.* pp.738-744. Reno, NV: USGS.

Sahagian, D. (2000). Global physical effects of anthropogenic hydrological alterations: Sea level and water redistribution. *Global Planet Change*. 25: 39-48.

Saunders III, J. F., Murphy, M., Clark, M., & Lewis, W. M. (2004). The influence of climate variation on the estimation of low flows used to protect water quality: A nationwide assessment, *40*, 1339–1349.

Sharma, S., Khanal, K., and Marucci, T.A. (2015). Stream low flows and regulatory low flows estimation for national pollutant discharge elimination systems (NPDES) permitting in changing climate. *Journal of Water Resource and Hydraulic Engineering.* 4(4): 432–449. doi:10.5963/JWRHE0404018

Smith, S. V., Renwick, W. H., Bartley, J. D., and Buddemeier, R. W. (2002). Distribution and significance of small, artificial water bodies across the United States landscape. *Science of the Total Environment*. 299: 21-36.

Timpe, K., & Kaplan, D. (2017). The changing hydrology of a dammed Amazon. *Science Advances*, *3*(11), 1–14. https://doi.org/10.1126/sciadv.1700611

United States Army Corps of Engineers (ACE). (2016). National Inventory of Dams. *CorpsMap*. Accessed at nid.usace.army.mil/

United States Department of Agriculture (USDA). (1982). Agriculture handbook number 590. Ponds-planning, design, and construction. District of Colombia, Washington, D.C.: USDA.

United States Environmental Protection Agency (EPA). (2012) NHDPlus. *Horizon Systems*. Accessed at http://www.horizon-systems.com/nhdplus/

United States Environmental Protection Agency (USEPA). 2010. Chesapeake Bay Phase 5.3 Community Watershed Model. EPA 903S10002 - CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis MD. December 2010.

USEPA. (2017). Storm water management model reference manual: Volume II – Hydraulics. *Storm water management model (SWMM).* Accessed at https://www.epa.gov/water-research/storm-water-management-model-swmm#documents

USGSa. (2017). National Elevation Dataset (NED). *The National Map*. Accessed at https://nationalmap.gov/elevation.html

USGSb. (2017). StreamStats Services. *StreamStats Service Documentation.* Accessed at https://streamstats.usgs.gov/streamstatsservices/#/

USGS. (2018). National Hydrography Dataset (NHD). *The National Map.* Accessed at https://nhd.usgs.gov/

Virginia Department of Environmental Quality (DEQ). 1999. Virginia Stormwater Management Handbook. Richmond, Virginia: VA DEQ.

Virginia Department of Transportation (VDOT). 2016. Chapter 11 – Stormwater Managment. Richmond, Virginia: VDOT.

Virginia Standard. (2017). 4VAC50-20-40: Hazard potential classifications of impounding structures. Richmond, VA: Virginia General Assembly.

Virginia Standard. (2017). 4VAC50-20-50: Performance standards required for impounding structures. Richmond, VA: Virginia General Assembly.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P.,…, and Davies, P.M. (2010). Global threats to human water security and river biodiversity. *Nature.* 468: 334–334. DOI:10.1038/nature09549

Vörösmarty, C.J., Sharma, K.P., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., and Lough, J.A. (1997). The storage and aging of continental runoff in large reservoir systems of the world. *Ambio*. 26(4): 210-219.

Williams, G. P., and Wolman, M. G. (1984). Professional paper 1286: Downstream effects of dams on alluvial rivers. District of Colombia, Washington D. C.: United States Department of the Interior.

Winemiller, K. O. et al. (2017). Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science.* 351(6269): 128-129.

Yang, X., and Lu, X. X. (2014). Drastic change in China's lakes and reservoirs over the past decades. *Nature*. 4(6041): 1-10. DOI: 10.1038/srep06041