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Historical Streamflow Discharge Trends Considering Climate Change and Application

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16. Abstract:

Bridges and large culverts are designed using historical streamflow data. However, historical streamflow data are static and do not account for changes in precipitation, temperature, and watershed characteristics such as the percentage covered by impervious surface. This report details efforts to determine if streamflow peak discharges in Virginia have changed or remained constant for roughly the past century (1916–2015), the extent to which changes are related to physiographic factors and watershed characteristics, and efforts to develop a watershed index that identifies watersheds that may be particularly vulnerable to climate change.

The study finds that changes in precipitation may have raised peak flow discharges. For the 1941–2015 period, most streamflows increased for stream gages classified as minimally altered. This classification is most suitable for determining the effects of climate change. However, most flow increases were not statistically significant, and different results are obtained when examining a shorter period (1966–2015). However, the study does find that precipitation has not remained constant but rather increased. An increase in streamflow did not always accompany increasing trends in precipitation. For 1941 to 2015, 66.4% of stream gages had an increasing trend in precipitation but a decreasing trend in streamflow. A closer examination of the stream gage categories revealed that for minimally altered stream gages, an increase in streamflow most commonly accompanied an increase in precipitation. For regulated stream gages, a decreasing trend in streamflow usually occurred alongside an increase in precipitation. Different trend patterns between stream gage patterns could be because of variations in normalized dam storage, land use, or watershed area. For the period from 1966 to 2015, 60% of stream gages had an increasing trend in both streamflow and precipitation. In this period, most minimally altered stream gages had a nonsignificant decreasing trend alongside an increase in streamflow. Furthermore, most regulated stream gages had a decreasing trend in streamflow alongside an increase in precipitation.

The researcher developed a watershed index to identify areas of Virginia that could be particularly vulnerable to climate change. This index identified areas of Virginia with limited stream gage coverage, stream gages with shorter data records, or stream gages with significant or nonsignificant increasing trends in peak flow discharges. Most of these watersheds are in Virginia's southeastern, western, and northern regions. A recommended next step, as described in the Implementation section of this report, is to conduct an analysis to determine locations that may benefit from additional stream gages. Research from other states suggests that, for a culvert where peak flow discharge data from stream gages are available, a potential cost savings of between $74,000 and $91,000 can be realized during the lifetime of the culvert based on better design and losses avoided.

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FINAL REPORT

HISTORICAL STREAMFLOW DISCHARGE TRENDS CONSIDERING CLIMATE CHANGE AND APPLICATION

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ABSTRACT

Bridges and large culverts are designed using historical streamflow data. However, historical streamflow data are static and do not account for changes in precipitation, temperature, and watershed characteristics such as the percentage covered by impervious surface. This report details efforts to determine if streamflow peak discharges in Virginia have changed or remained constant for roughly the past century (1916–2015), the extent to which changes are related to physiographic factors and watershed characteristics, and efforts to develop a watershed index that identifies watersheds that may be particularly vulnerable to climate change.

The study finds that changes in precipitation may have raised peak flow discharges. For the 1941–2015 period, most streamflows increased for stream gages classified as minimally altered. This classification is most suitable for determining the effects of climate change. However, most flow increases were not statistically significant, and different results are obtained when examining a shorter period (1966–2015). However, the study does find that precipitation has not remained constant but rather increased. An increase in streamflow did not always accompany increasing trends in precipitation. For 1941 to 2015, 66.4% of stream gages had an increasing trend in precipitation but a decreasing trend in streamflow. A closer examination of the stream gage categories revealed that for minimally altered stream gages, an increase in streamflow most commonly accompanied an increase in precipitation. For regulated stream gages, a decreasing trend in streamflow usually occurred alongside an increase in precipitation. Different trend patterns between stream gage patterns could be because of variations in normalized dam storage, land use, or watershed area. For the period from 1966 to 2015, 60% of stream gages had an increasing trend in both streamflow and precipitation. In this period, most minimally altered stream gages had a nonsignificant decreasing trend alongside an increase in streamflow. Furthermore, most regulated stream gages had a decreasing trend in streamflow alongside an increase in precipitation.

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FINAL REPORT

HISTORICAL STREAMFLOW DISCHARGE TRENDS CONSIDERING CLIMATE CHANGE AND APPLICATION

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INTRODUCTION

The Virginia Department of Transportation (VDOT) owns and maintains more than 19,000 bridges and large culverts (VDOT, 2023). Large bridges and culverts are designed based on historical streamflow peak discharge records. Streamflow peak discharge is the maximum instantaneous rate of water passing a given point during or after a rainfall event (U.S. Department of Agriculture [USDA], 2021). However, historical streamflow records do not account for the potential effects of climate change. Climate change-driven increases in precipitation may lead to higher streamflow peak discharges. This precipitation trend has led to a focus on developing projected rainfall estimates. However, projected rainfall cannot be used to design bridges and large culverts. Higher streamflow peak discharges could stress bridges and large culverts, leading to failure if these structures are not designed to withstand potentially larger streamflow peak discharges (Hui et al., 2018).

At the same time, other impacts of climate change, such as decreased soil moisture, could also influence streamflow peak discharges by mitigating or exacerbating the effects of increased precipitation. For example, changes in soil moisture can affect water infiltration rates. At low soil moisture levels, water infiltrates quickly, whereas water infiltrates more slowly at higher soil moisture levels. Lower infiltration rates increase runoff volume and could result in higher streamflow peak discharges (USDA, 2008).

Watershed characteristics, such as drainage area and land cover, could also affect the magnitude of streamflow peak discharges (USDA, 2021). Smaller watersheds can be more sensitive to changes in precipitation because of shorter flow lengths. Larger watersheds have a longer flow length, which leads to lower streamflow peak discharges (Ganguli and Choubali, 2017). Land cover changes can also influence the magnitude of streamflow peak discharge. Watersheds with higher impervious surface coverage have higher streamflow peak discharges because of less infiltration and higher runoff volumes (USDA, 2021).

Methods to determine streamflow, such as U.S. Geological Survey (USGS) regression equations, do not account for factors like meteorological impacts of climate change or land development. Because watershed characteristics and climate changes can both influence streamflow peak discharges, it is valuable to explore how these factors may interact to influence such discharges to understand how to design infrastructure to mitigate the potential negative effects of higher streamflow peak discharges.

PURPOSE AND SCOPE

The purpose of this research is to understand the relationship between precipitation, streamflow, and watershed characteristics. The supporting objectives are to (1) determine if streamflows are increasing, (2) explore patterns in precipitation, streamflow, and watershed characteristics, and (3) identify watersheds with increasing trends in streamflow alongside a low total number of stream gages and, thus, may be more at risk for infrastructure failures because of flooding.

METHODS

The researcher completed the following three tasks to achieve this study's objectives.

1. Conducted a literature review.
2. Analyzed Virginia streamflow trend data.
3. Developed a watershed index.

Literature Review

The researcher conducted a literature review to identify three types of information: (1) methods that could be used to incorporate the effects of climate change into streamflow projections, (2) methods that state departments of transportation (DOTs) are using to incorporate the effects of climate change into hydrologic design, and (3) information on watershed indices.

Sources were found primarily through Google Scholar using various combinations of the following keywords: climate change, streamflow, resiliency, watershed index, projections, trends, and precipitation. The researcher reviewed drainage manuals and searched for key terms such as rainfall, projected, climate change, and resilience to find information on how DOTs incorporate climate change into hydrologic design practices.

Streamflow Trend Data Analysis

The researcher analyzed a dataset from the study *Effects of Climate, Regulation, and Urbanization on Historical Flood Trends in the United States* (Hodgkins et al., 2019). This dataset contains drainage basin characteristics, peak-streamflow trend, and change-point results for 2,683 USGS stream gages across the conterminous United States.

Streamflow Trend Dataset Background

To create the dataset, Hodgkins et al. (2019) retrieved streamflow records through the water year 2015 (ending September 30, 2015) from the USGS National Water Information System for the conterminous United States. Stream gages were subject to a length and completeness criterion. Gages were required to have instantaneous peak data from 1966 to 2015 (50 years) and have values for at least 8 of the 10 years (80%) for each decade. The 80% decadal completeness criterion was applied to allow for long-term data to have minor amounts of missing data but no large blocks for any one decade. An 80% decadal completeness criterion was also applied to the years from 1941 to 2015 (75 years) and from 1916 to 2015 (100 years).

Stream gages were classified based on watershed characteristics to determine if trends were related to climatic changes or because of a combination of climate changes and watershed alterations. The authors obtained watershed characteristics from the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES II) dataset (Falcone, 2011; Falcone et al., 2010). GAGES II contains climatological, geological, land cover, water use, hydraulic infrastructure, and watershed characteristics for 9,000 USGS gages. Each stream gage was classified as one of the following four categories, when a gage's category did not change by time period.

- *Minimally altered*. These gages were designated as part of the Hydroclimatic Data Network-2009 (HCDN-2009) (Lins, 2012) and in watersheds with minimal human disturbance. To be designated as part of the HCDN-2009, a stream gage had to meet the following criteria: be identified as a reference gage in the GAGES II database, have at least 20 years of complete and continuous data, have less than 5% impervious surface area as measured using the National Land Cover Database 2006, and not be eliminated during a review by participating USGS Water Science Centers. Reference stream gages have a hydrologic disturbance of less than 75%, have no "regulated" flows identified in the USGS Annual Water Data Reports, and have passed a visual screening using satellite imagery for the presence of human activities that may influence natural streamflows. Minimally altered stream gages may be influenced primarily by climatic changes and variability instead of human disturbance or alteration. These gages were used to understand how climate influences streamflow trends.
- *Regulated*. Such gages had normalized dam storage in the top 25% of normalized dam storage and less than 10% of developed area. Regulated gages were used to understand how basin alterations influence streamflow trends.
- *Urbanized*. These stream gages had more than 20% of developed area and were in the lowest 25% of normalized dam storage (Hodgkins et al., 2019). Urban gages were used to understand how land development influences streamflow trends.
- *Unclassified*. Such stream gages did not meet the criteria for the other three categories.

Normalized dam storage was calculated by multiplying dam storage (volume units per unit drainage area) by basin drainage area and then dividing by the mean annual flow for the period from 1966 to 2015. The 1966–2015 period was used to calculate normalized dam storage because it is the longest record that all study basins have in common.

Hodgkins et al. (2019) used a Mann-Kendall test to assess if a trend occurs in annual instantaneous peak flows over time. A Mann-Kendall test is a nonparametric linear regression analysis that statistically assesses if a monotonic increasing or decreasing trend is present in a variable of interest over time. A nonsignificant trend indicates that a nonmonotonic trend occurred in the data ($p > 0.05$). A significant trend demonstrates that a monotonic trend was present in the data ($p < 0.05$). Figure 1 provides an example of a monotonic and a nonmonotonic trend.

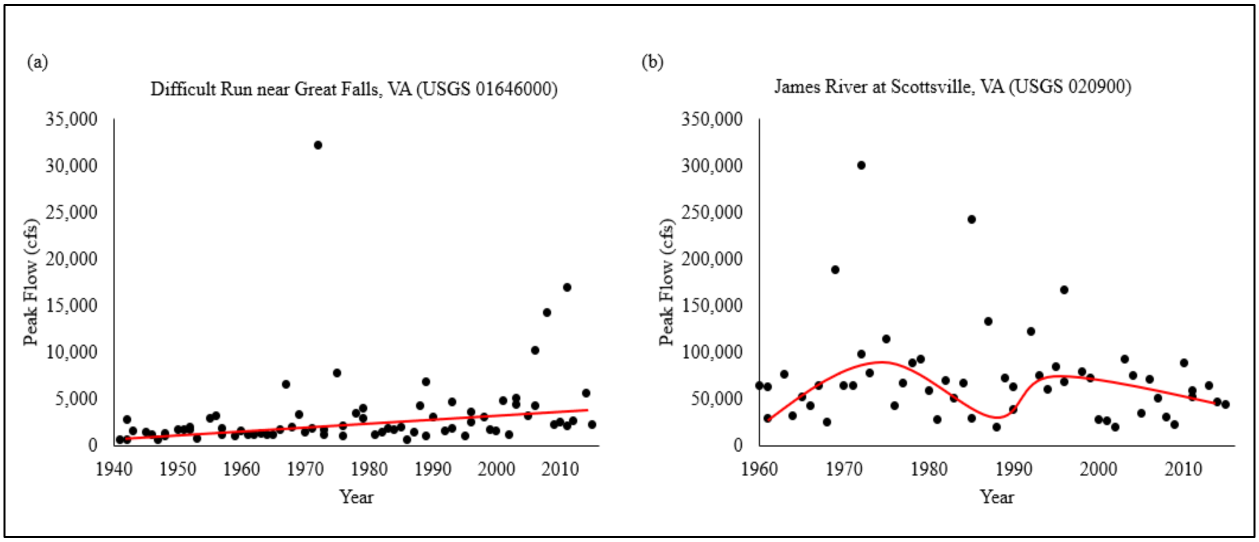

Figure 1. (a) A Statistically Significant (Monotonic) Increasing Trend; (b) A Nonsignificant (Nonmonotonic) Decreasing Trend. The researcher added red lines for illustrative purposes (USGS, 2024a, 2024b). cfs = cubic feet per second; USGS = U.S. Geological Survey.

Stream Gage Data Analysis

The researcher extracted Virginia stream gage data from the Hodgkins et al. (2019) dataset. To identify patterns in streamflow trends and stream gage characteristics, the percentage of stream gages in each trend and stream gage category was calculated for each period. Stream gage locations and trend category maps for each period were created. For each period, stream gages were categorized by size. Size categories were determined by using the 33rd and 66th percentiles of the drainage area for the stream gages in each period.

Precipitation Data Analysis

To examine precipitation trends alongside streamflow trends, historical precipitation data for each period were obtained from the PRISM climate group at Oregon State University for the stream gages included in this study. A linear trendline was fit to the time and precipitation data using the MATLAB computing platform for each stream gage. Each stream gage was classified as increasing or decreasing based on the slope value. Then the stream gages were categorized based on their streamflow and precipitation trend. To determine the relationship between precipitation trend and streamflow, each stream gage was assigned to a group based on its streamflow trend and precipitation trend.

Watershed Index

The researcher used a watershed index to identify Virginia watersheds that could benefit from having more stream gages or additional analyses. When creating this index, factors considered included the number of stream gages in a watershed, years of available data, and streamflow trends. A watershed may benefit from the addition of stream gages or more analyses if a low number of stream gages are available with many years of data or many stream gages with increasing trends.

Stream Gage Dataset Background

Stream gage data were retrieved from the USGS National Water Information database using the USGS Site Service tool. This tool searches for USGS sites using various filters, such as location, period, or data types. The Site Service tool was used to search for stream gages in Virginia with peak streamflow data for 1966 through 2015.

Stream Gage Data Processing

The researcher uploaded the stream gage data to ArcGIS Pro along with a map of Virginia's Hydrologic Unit Code 8-digit (HUC8) watersheds. They used the counting tool to determine the number of stream gages per HUC8 watershed. For each stream gage, the number of years of available data was calculated in Microsoft Excel. Then the number of each stream gage within each data record timeframe was counted. The researcher considered the data record timeframes ranging from 0 to 19 years, 20 to 41 years, 42 to 71 years, 72 to 112 years, and 112 to 161 years.

The streamflow trend data were also used to help develop the watershed identification system (Hodgkins et al., 2019). The number of stream gages in each streamflow trend category (e.g., significant increasing, nonsignificant increasing, nonsignificant decreasing, or significant decreasing) was determined for each HUC 8 watershed. Not all the stream gages retrieved from USGS for the development of the watershed index had streamflow trend data.

A score was calculated for each of the 10 variables for each watershed: (1) the total number of stream gages, (2 to 6) number of stream gages per data record timeframe (0 to 19 years, 20 to 41 years, 42 to 71 years, 72 to 112 years, and 112 to 161 years), and (7 to 10) number of stream gages per streamflow trend category (significant increasing trend, nonsignificant increasing trend, significant decreasing trend, and nonsignificant decreasing trend).

The score for three variables—the number of gages with 0 to 19 years of data and the number of increasing trends (significant and nonsignificant separately)—was calculated using Equation 1 (Ghosh, 2022). This equation determines a score with a positive influence. A positive score means that watersheds with higher numbers of stream gages in the 0- to 19-years category or stream gages with increasing trends will have a larger value.

$$p = \left(\frac{v - min}{max - min}\right) * w$$

Where:
p = site score for positive influence. (Equation 1)
v = variable value for the site.
min = minimum variable value for the site.
max = maximum variable value for the site.
w = variable weight.

Equation 2 calculates the score for seven variables—the remaining data record timeframes (20 to 41, 42 to 71, 72 to 112, or 112 to 161 years), total number of stream gages, and number of decreasing trends (significant and nonsignificant).

$$s = \left(\frac{max - v}{max - min}\right) * \ w \qquad \text{(Equation 2)}$$

Where:
s = site score for inverse influence.
v = variable value for site.
min = minimum variable value for site.
max = maximum variable value for the site.
w = variable weight.

Equation 2 determines a score with an inverse influence. An inverse influence means that watersheds with few gages that have long periods of record, lower total number of stream gages, or fewer decreasing trends will also have a larger value.

For both equations, each variable was initially weighted the same. Ten variables were considered, so each variable was weighted 10% (w = 0.10). The scores for each variable were totaled across watersheds and mapped in ArcGIS. Watersheds with a larger score should be prioritized for future analyses. Maps showing the distribution of stream gages across watersheds and years of data per stream gage were also created.

To understand the sensitivity of the watershed index to changes in variable weights, the weights assigned to each variable were incrementally adjusted, and changes in the resulting score were documented. Weights were adjusted so that a given variable group (e.g., data records) had higher weights. The prioritized variable group was adjusted in the following order: data record timeframes and streamflow trends, total number of stream gages, data record timeframes only, and trend data only. Multiple iterations were performed within each variable group, with the weights within the prioritized variable group increasing in each iteration. In contrast, the weights for the other variable groups decreased with each iteration. Weights were evenly distributed within a variable group.

RESULTS AND DISCUSSION

Literature Review

The literature review first examined how other states incorporate climate change into hydrologic design, including using distributed rainfall-runoff modeling (DRRM) to incorporate climate change impacts and methods in states' DOT drainage manuals. The review concluded with an examination of the development of watershed indices.

Incorporating Climate Change into Hydrologic Design

Climate models and assessments are often used to help incorporate climate change into infrastructure design. The results of these climate models and assessments can have significant cost implications. Overestimates of peak flow could result in costly oversizing of drainage infrastructure, whereas underestimates might leave infrastructure vulnerable. Accounting for climate change in hydrologic design is complicated by additional nonstationary processes due to urbanization and other land cover changes.

To help guide practitioners, the National Cooperative Highway Research Program (NCHRP) produced report NCHRP 15-61 that describes tools and methods to incorporate climate change into hydrologic and coastal design (Kilgore et al., 2019). Alongside the report, researchers developed a design guide to provide more information and examples of incorporating climate change into design. These documents describe several methods to incorporate climate change into streamflow projections. Table 1 summarizes these methods.

Table 1. Summary of Streamflow Projection Methods (Kilgore et al., 2019)

Method	Notes
Identify and estimate a historical time-varying mean	This method is appropriate when annual peak discharges at a gauging station are nonstationary or varying with time because of land use or climate changes. It can result in flood estimates indicative of current land use or climate conditions. Trends in mean values should be projected only if the trend can be attributed to some hydrologically meaningful covariate, like land use change.
Adjust annual maximum discharges to current land use conditions (Index Adjustment Method)	This method is more time consuming than the time-varying mean approach. It can result in a significant reduction in variance such that adjusted discharges provide lower estimates of the extreme annual exceedance probabilities than using the unadjusted data.
Use a homogeneous subperiod of the historical record	This approach is the simplest for adjusting for nonstationary, but the homogeneous subperiod may not include major floods that have occurred on the watershed. It may be appropriate regardless of whether urbanization or climate change caused the trend. It requires a short period of data and may exclude some extreme flood data points.
USGS regression equations	Equations can be used if a precipitation variable is present. However, the precipitation values should stay within the range of precipitation values used to create the equation. It is recommended to project precipitation values by adjusting historical values by multiplying them by the ratio of modeled GCM future to modeled GCM baseline conditions. Note that the use of future precipitation may reduce the reliability of the equation to an unknown degree because other watershed or climatic changes may affect streamflows.
Index Flood Method	This method estimates flood frequency curves on ungauged sites by aggregating information on the slopes of curves obtained from stream gage sites. Estimates from a discharge quantile, like a 10-year flood event, may provide a better estimate for design.
Multiple or Panel Regression	Panel regression pools multidimensional data across several watersheds and through time. This tool allows for simultaneous analysis of the effects of climate and land use changes across several watersheds. The panel regression is a complex statistical tool and may involve more time and effort than other methods.

GCM = Global Circulation Model; USGS = U.S. Geological Survey.

As a followup to NCHRP 15-61, Dewberry LLC and AEM Corporation conducted an additional NCHRP study, *Pilot Test of Climate Change Design Practices Guide for Hydrology and Hydraulics* (NCHRP 20-44(23)), to evaluate and improve the NCHRP 15-61 products.

NCHRP 20-44(23) involved coordinating a group of state DOTs to apply NCHRP 15-61 to existing and planned infrastructure projects. The projects included in the study evaluated many of the approaches outlined in the NCHRP 15-61 report (Dewberry Consultants LLC and AEM Corporation, 2022; Kilgore et al., 2019). Table 2 lists the pilot projects and methods for incorporating climate change into hydrologic design.

As a part of this project, participants provided feedback through level-of-effort surveys, post-pilot interviews, and a final workshop. State DOTs answered survey questions about the time and effort spent implementing their pilot projects. On average, DOTs and their implementing partners spent 136 staff hours on each pilot project. The authors observed a significant variation in the amount of effort across the pilot projects as they varied in size and scope. Some projects required 50 hours of work, whereas others needed more than 250 hours. Coastal projects were more complex, with an average of 231 hours, whereas inland hydrology projects had an average of 89 hours. Participants suggested that the number of staff hours needed to implement NCHRP 15-61 would decrease over time as experience using the guide increased (Dewberry Consultants LLC and AEM Corporation, 2022; Kilgore et al., 2019).

To facilitate the implementation of NCHRP 15-61, an active NCHRP project (NCHRP 20-44(44)) focuses on enhancing and expanding the implementation of the NCHRP 15-61 design practice guide. This project concentrates only on inland hydrology and hydraulics. The goal of this study is to understand ways that state DOTs may already be implementing the guide and develop methods to help DOTs implement it into their design methods (Transportation Research Board, 2024).

In terms of considering policy measures, VDOT contracted with a private firm to review administrative or policy measures adopted by others to evaluate VDOT’s preparedness and responsibilities, as well as which options might be within the authority of the Commonwealth Transportation Board or VDOT to implement. As a part of this study, Dewberry Engineers, Inc. (2024a) conducted a survey to gather information about other transportation agencies and allied organizations. Nine organizations responded to the survey, and four of the organizations were state DOTs. Five respondents said their agency “plans, designs, constructs, operates, or maintains at-risk infrastructure and assets differently to reduce risk.” Some popular strategies included elevating at-risk infrastructure and designing to higher standards. Agencies responded that the main challenges in implementing resilience strategies are funding and budget constraints, insufficient data or information, or regulatory barriers (Dewberry Engineers Inc., 2024a).

Table 2. Summary of Pilot Projects Included in the Dewberry Consultants LLC and AEM Corporation (2022) Report

DOT	Project Summary	Project Type	Method to Project Precipitation/SLR	Method to Project Design Discharge/SLR	Methods to Calculate Design Impacts	Notes
AZ	Bridge renovation project considering temperature and precipitation	Inland hydrology	10-step procedure	N/A	Soil and erosion testing services for bridge scour and Bayesian Belief Network	Resulted in design recommendations to improve bridge resiliency.
CO	Evaluation of bridge scour at Colorado River bridge and Chacuaco Cheek bridge	Inland hydrology	10-step procedure	Trends in historic discharge, HEC-HMS rainfall-runoff model, regression equations	Bridge scour design equations	Projected discharge under existing and future conditions is sensitive to method.
FL	Evaluation of design for two bridges considering SLR	Coastal hydrology	USACE Sea Level Calculator, deterministic equations, probabilistic modeling	+ 1.12 m SLR	Monte Carlo simulation of SLR and ADCIRC/SWAN modeling	Guide can yield consistent results when used by different engineering teams.
IA	Evaluate level of service for two bridges under climate change	Inland hydrology	10-step procedure	HEC-1 rainfall-runoff model; index approach	Flood frequency analysis	Modified the index approach by calculating and applying a separate projected baseline ratio for return intervals up to 10 years. Developed a set of gridded rasters with precipitation change factors for the state to reduce potential for miscalculations in the 10-step method.
MD	Evaluation of inland urban reconstruction project	Inland hydrology	10-step procedure	TR-20	Various models and design equations	Used climate change indicator to determine if a level 2 or 3 analysis was needed.
ME	Evaluate culvert design under projected precipitation	Inland hydrology	10-step procedure	Rational method	Design equations	
NC	Interstate widening and resiliency project	Inland hydrology	10-step procedure	HEC-RAS rain-on-grid model	HEC-RAS rain-on-grid model	
NC	Evaluate effects of SLR on coastal bridges	Coastal hydrology	MIKE 21 coastal hydrodynamic modeling	+ 4.4 ft SLR	Monte Carlo simulation	
OR	Evaluate scour and flood exposure to coast	Coastal and inland hydrology	10-step procedure	USGS regression equations	HEC-RAS modeling of scour and flood levels	

ADCIRC = ADvanced CIRCulation; DOT = Department of Transportation; HEC-HMS = Hydrological Engineering Center Hydrological Modeling System; HEC-RAS = Hydrological Engineering Center River Analysis System; N/A = not applicable; SLR = sea level rise; SWAN = Simulating WAves Nearshore; USACE = U.S. Army Corps of Engineers; USGS = U.S. Geological Survey.

Using Distributed Rainfall-Runoff Modeling to Incorporate Climate Change Impacts

Historically, lumped hydrologic modeling techniques have been used to quantify the stress of extreme rainfall events. These techniques provide rapid and convenient estimates of peak flows or simplified hydrographs for design storms. However, lumped hydrologic models use past hydrologic data, which may not represent the effects of climate change.

Lumped hydrologic models can also combine watershed characteristics, which may affect the accuracy of hydrologic predictions. In large watersheds, lumped hydrologic models can also be challenging to implement because of a longer time to concentration and non-uniformity in rainfall, land use, and soil characteristics. Lakes and reservoirs can also complicate modeling runoff in large watersheds (Westphal, 2001).

DRRM techniques may be an alternative to lumped hydrologic modeling. DRRM techniques divide watersheds into smaller spatial elements. Different hydrological processes can be represented within each element, which may provide a more detailed and accurate representation of runoff formation, transport, and accumulation. These tools may support effective decision making regarding hydrologic risks.

As a part of the NCHRP synthesis program, Vasconcelos et al. (2023) conducted a literature review and a survey to document state DOTs' use of DRRM techniques. Forty-seven states responded to the survey. The authors learned that using DRRM is less widespread than lumped hydrologic approaches. Lumped hydrologic models may be preferred because they have lower data requirements, require less training, and have fewer data inputs. Most DOT hydraulic and hydrologic guidelines (98%) reference the rational method and USGS regression equations (lumped modeling approaches). States that use the rational method or regression curves use these methods primarily because of economic feasibility, lower input data requirements, and familiarity with techniques (Vasconcelos et al., 2023).

About one-half of DOTs (54%) mention DRRM in their guidelines. However, only 16 states say that they actively use DRRM, which is fewer than the number of states that mention them in their guidelines. DRRM is used primarily because DRRM can more precisely consider the effects of rain events, diagnose causes of flooding, reduce hydrologic uncertainty, and account for the effects of previous conditions (e.g., recent rainfall). Some state DOTs indicated that using DRRM is project specific, and the decision to use DRRM is not motivated by contributing drainage area (Vasconcelos et al., 2023). State DOTs responded that they use in-house engineers and private consultants to conduct projects involving DRRM.

State DOTs have used DRRM to assess and inform design decisions in roadways likely to be affected by extreme hydrological events, determine causes for roadway flooding and potential solutions, reduce the uncertainty in hydrological estimates, and enable higher accuracy in hydraulic computations of bridge scour. Consulting firms typically develop DRRM. Most states using DRRM use design rainfall amounts in the models. Only North Carolina responded that they use projected rainfall from the Global Circulation Model (Vasconcelos et al., 2023).

State DOTs noted that the primary barriers to using DRRM were a “lack of training opportunities,” “insufficient in-house expertise for creation or reviewing model results,” and “lack of data for model setup.” Some state DOTs added that “unfamiliarity with the process” and “time it takes to set up and run models” were also barriers to using DRRM. The authors recommend that future research related to DRRM focus on lowering barriers to using DRRM, such as developing guidance documents related to best practices regarding data requirements and developing models.

Drainage Manuals and Climate Change

State DOT drainage manuals were reviewed to determine how climate change is incorporated into hydrologic and hydraulic design. The researcher found this information by conducting a Google Search using the keywords: state name and drainage manual. They searched drainage manuals using the terms rainfall, projected, climate change, and resilience. Table 3 summarizes this information, which was obtained between December 2022 and December 2024.

Table 3. Summary of Guidance from State DOT Drainage Manuals Related to Climate Change

State	Notes	Source
Maryland	Uses change factors obtained using the Mid-Atlantic Projected IDF Curve Data Tool to adjust precipitation. They are used to design new drainage infrastructure and evaluate existing infrastructure. They are required along with Federal Emergency Management Agency hurricane evacuation routes.	Maryland DOT (2008)
New York	Increases design discharge for culverts. Uses a multiplier to change the design discharge. The multipliers are county specific.	New York State DOT (2021)
Delaware	Applies a confidence interval to increase the flow values obtained from the regression equations to ensure that the design flow envelopes the actual flow value.	Delaware DOT (2024)
North Carolina	Uses guidance from Federal Highway Administration publications (Douglass and Krolak, 2008; Kilgore et al., 2016).	North Carolina DOT (2022)
Rhode Island	Considers rainfall projections during the design. Rhode Island DOT provides a list of acceptable sources for climate projections. The proposed design must pass the future design storm according to span and highway functional classification. A climate change check storm is used during the design phase that applies to road-stream crossings.	Vanasse Hangen Brustlin, Inc. (2021)
Tennessee	Uses U.S. Geological Survey regression equations for rural areas containing a climate factor.	Tennessee DOT (2012)
Minnesota	May consider a design flow adjusted for climate change for larger design projects that may occur in situations such as long highway routes having no practical detour, critical routes, deep fills, sites where watershed changes are likely, or when designing the repair or replacement of a flood-damaged flooding feature. Bridges and culverts with a span or diameter greater than 48 inches require a risk assessment. The risk assessment evaluates the structure and encroachment design over a range of design frequencies. The results are used to make decisions regarding implementation of adaptation strategies to reduce flood risk.	Minnesota DOT (2024)
New Hampshire	Uses National Weather Service and Northeast Regional Climate Center’s precipitation data, which should be compared with National Oceanic and Atmospheric Administration Atlas 14.	New Hampshire DOT (2014)

State	Notes	Source
	Documents the precipitation data used and the reasoning behind that decision.	
Virginia	Uses a 200-year flood event for the design scour, water velocity, and buoyancy to incorporate resiliency into bridge design. In Virginia, the location and design guidance for designing culverts should be referenced.	VDOT (2024)

DOT = Department of Transportation; IDF = intensity-duration-frequency.

Watershed Index

Factors such as years of record, spatial distribution, effects of climate change, and modeling assumptions can lead to increased uncertainty in calculations or models made using streamflow data (Arbit et al., 2024). Areas with limited spatial or temporal distribution of stream gage are potentially vulnerable to the effects of flooding because of increased uncertainty in calculations and models (Kiang et al., 2013). Areas with increasing trends in streamflow because of climate change may have increased vulnerability to flooding.

A suitability index could identify areas that meet these characteristics. A suitability index uses scores and ranking to identify sites based on weighted criteria (Ghosh, 2022). In this case, watersheds with low total numbers of gages, gages with shorter periods of record, and with increasing trends in streamflow would be identified as being particularly vulnerable to the impacts of climate change.

Summary of Key Lessons from the Literature Review

The literature review provided two key lessons that influenced the analysis of Virginia streamflow trend data and the subsequent development of a watershed index.

First, changes in design practices, especially when such design practices are new to the agency, increase the cost of project development. For instance, explicit consideration of changes in temperature, precipitation, sea level rise, and climate was a component of the pilot projects in Table 2. The techniques for implementing these considerations, such as estimating a time-varying mean for peak discharges or modifying USGS regression equations, may require additional time beyond conventional design practices. The additional effort required for DRRM is striking. Although mentioned in design manuals for about one-half the states, only about one-third (16 states) reported using DRRM, and of those that do, nearly all (88%) will utilize consultants in addition to in-house staff.

Second, creating a watershed index has the potential to support the development of design recommendations by highlighting areas of Virginia that may be vulnerable to climate change. Logically, these areas will be watersheds known to have increasing peak flow discharges over time. These watersheds may also have no data, limited stream gage coverage, or stream gages with limited records. Such watersheds may be locations that could benefit from additional stream gages if such gages could inform the design or management of VDOT’s transportation infrastructure.

Streamflow Trend Data Analysis

The streamflow trend data analysis was divided into three parts: a dataset overview, a trend analysis (by time, geography, stream gage category, and size), and an analysis of precipitation effects on streamflow.

Stream Gage Dataset

One hundred seven gages met the 80% decadal completion criteria for 1966 to 2015, 70 gages for 1941 to 2015, and 7 gages for 1916 to 2015. For each period, most gages were categorized as unclassified. The second largest category was minimally altered, followed by regulated, and then urban. Table 4 presents stream gage characteristics, and Table 5 lists the number of stream gages in each basin category. Supplemental File 1 presents stream gage identification numbers, names, latitude, longitude, and more detailed characteristics. Supplemental File 2 contains a map of stream gages categorized by data record and maps showing stream gage locations and categories.

Table 4. Stream Gage Characteristics and Categories for Each Time Period

Characteristic	Time Period		
	1916–2015	1941–2015	1966–2015
Average Area (km^2)	7,333.4	2,503	1,806.2
Minimum Area (km^2)	994.6	90.9	19.7
Maximum Area (km^2)	16,192.6	17,490.2	17,490.2
Average Percent Urban	8.3%	7.6%	8.3%
Minimum Percent Urban	4.6%	2.3%	1.8%
Maximum Percent Urban	19.0%	50.5%	77.8%
Average Dam Storage (days)	68	51	48
Min. Dam Storage (days)	17	0	0
Max. Dam Storage (days)	225	481	577

Table 5. Number of Stream Gages in Each Basin Category per Time Period

Stream Gage Category	Time Period		
	1916–2015	1941–2015	1966–2015
Regulated	1	6	9
Urban	0	0	1
Unclassified	6	41	59
Minimally Altered Stream	0	23	38
Total Number	7	70	107

Trend Analysis

The researcher observed a mix of streamflow trends across Virginia. Proportions of increasing and decreasing trends varied based on time periods and when considering stream gage type. The researcher considered four types of trends:

- Temporal trends in streamflow.
- Geographical trends in streamflow.
- Streamflow trends by stream gage category.
- Streamflow trends by size.

Temporal Trends in Streamflow

The researcher considered streamflow trends for all three time periods. For 1916 to 2015, 85.7% of stream gages had an increasing trend in streamflow, and 14.3% had a decreasing trend (Figure 2). All increasing trends were nonsignificant ($p > 0.05$), and the decreasing trend was significant ($p < 0.05$). However, only seven gages met the 80% decadal completion criteria for 1916 to 2015, and most stream gages were in Virginia's western portion. As such, these gages may not be representative of streamflow trends across the state.

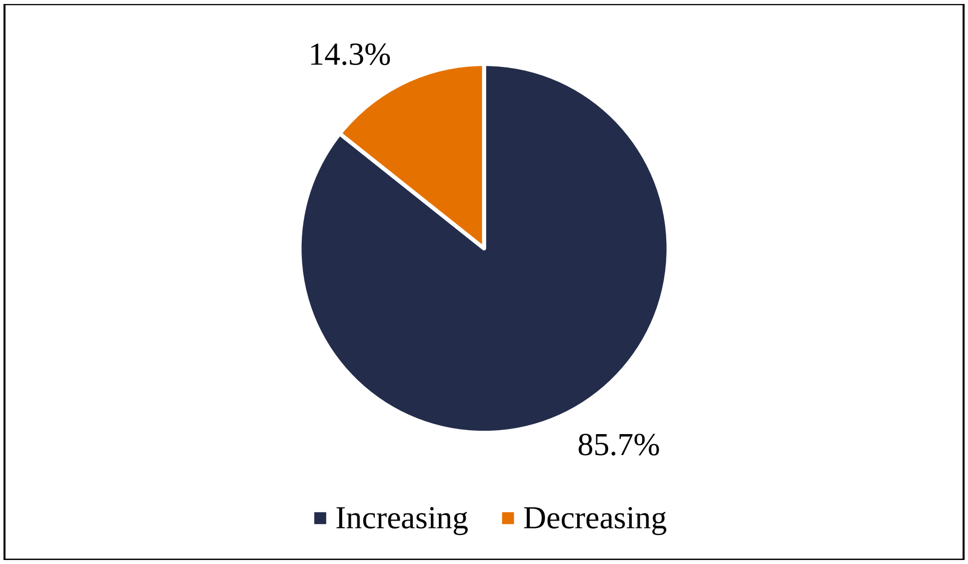

Figure 2. Percentage of Stream Gages with Increasing and Decreasing Streamflow Trends for 1916–2015. Seven gages met the 80% decadal completion criteria for 1916–2015. All increasing trends were nonsignificant, and the decreasing trends were statistically significant.

For 1941 to 2015, most stream gages had increasing trends in streamflow. Nearly 63% (62.9%) of stream gages had an increasing trend in streamflow, and 37.1% had a decreasing trend in streamflow. Both increasing and decreasing trends were primarily nonsignificant ($p > 0.05$) (Figure 3).

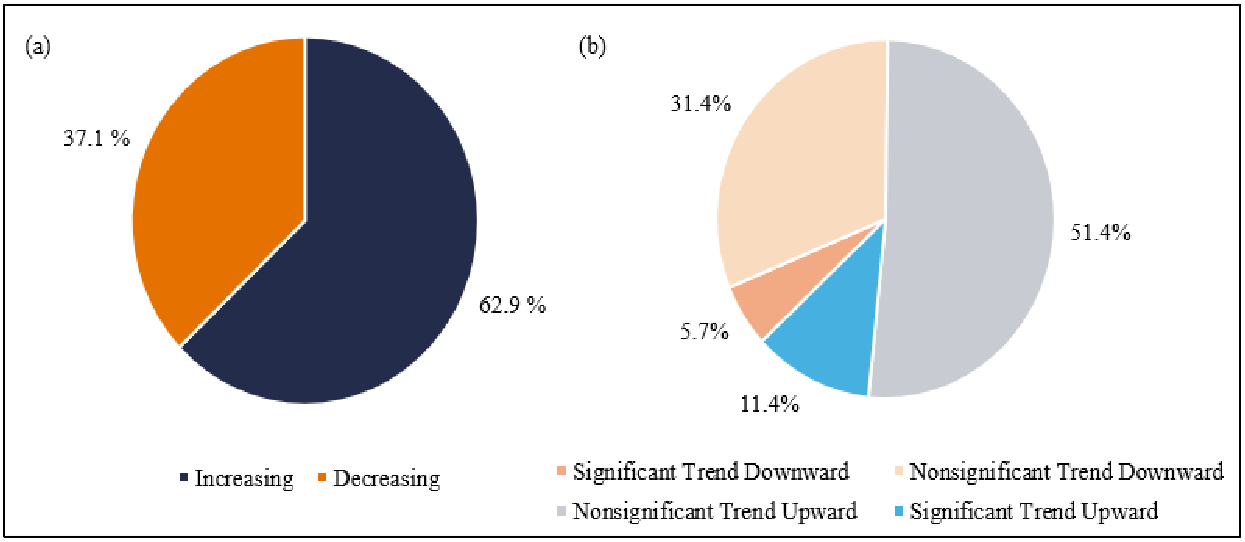

Figure 3. (a) Percentage of Stream Gages with Increasing or Decreasing Streamflow Trends; (b) Percentage of Stream Gages with Significant and Nonsignificant Increasing or Decreasing Trends in Streamflow. Seventy gages met the 80% decadal completion criteria for 1941–2015.

For 1966 to 2015, most stream gages (71.96%) experienced a decreasing trend in streamflow. Nearly 72% (71.96%) of increasing trends and 28.04% of decreasing trends were nonsignificant ($p > 0.05$) (Figure 4).

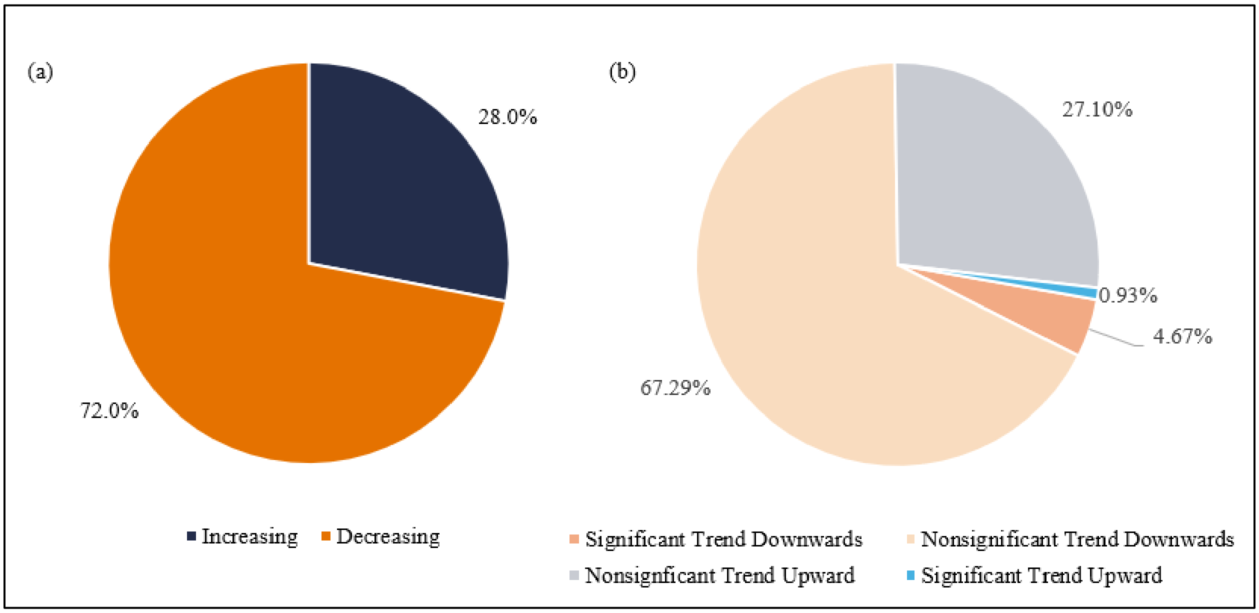

Figure 4. (a) Percentage of Stream Gages with Increasing and Decreasing Streamflow Trends for 1966–2015; (b) Percentage of Stream Gages with Significant and Nonsignificant Trends in Streamflow for 1966–2015. One-hundred seven gages met the 80% decadal completion rate for 1966–2015.

Geographical Trends in Streamflow

Streamflow trends varied geographically and with the time period. For 1941 to 2015, stream gages with increasing streamflow trends were spread across the state, and most stream gages with decreasing streamflow trends were in Virginia's western region. Figure 5 shows stream gage locations categorized by trend for 1941 to 2015. Figures 5 through 11 and 13 and 14 were created using ArcGIS® software by Esri. ArcGIS and ArcMap™ are the intellectual property of Esri and are used herein under license.

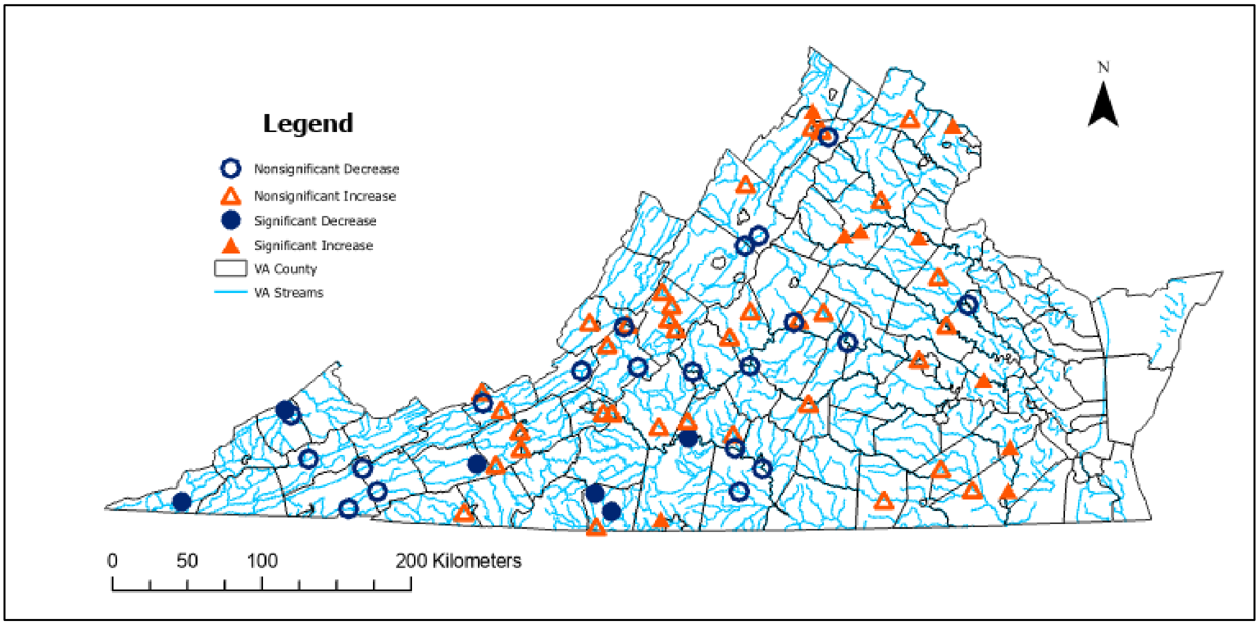

Figure 5. Virginia Stream Gage Locations Categorized by Trend for 1941–2015

For 1966 to 2015, nonsignificant decreasing streamflow trends were widespread across the state. Only two watersheds had significant increasing streamflow trends. Most gages with nonsignificant increases were in Virginia's eastern region. Figure 6 shows stream gage locations categorized by trends in the period from 1966 to 2015.

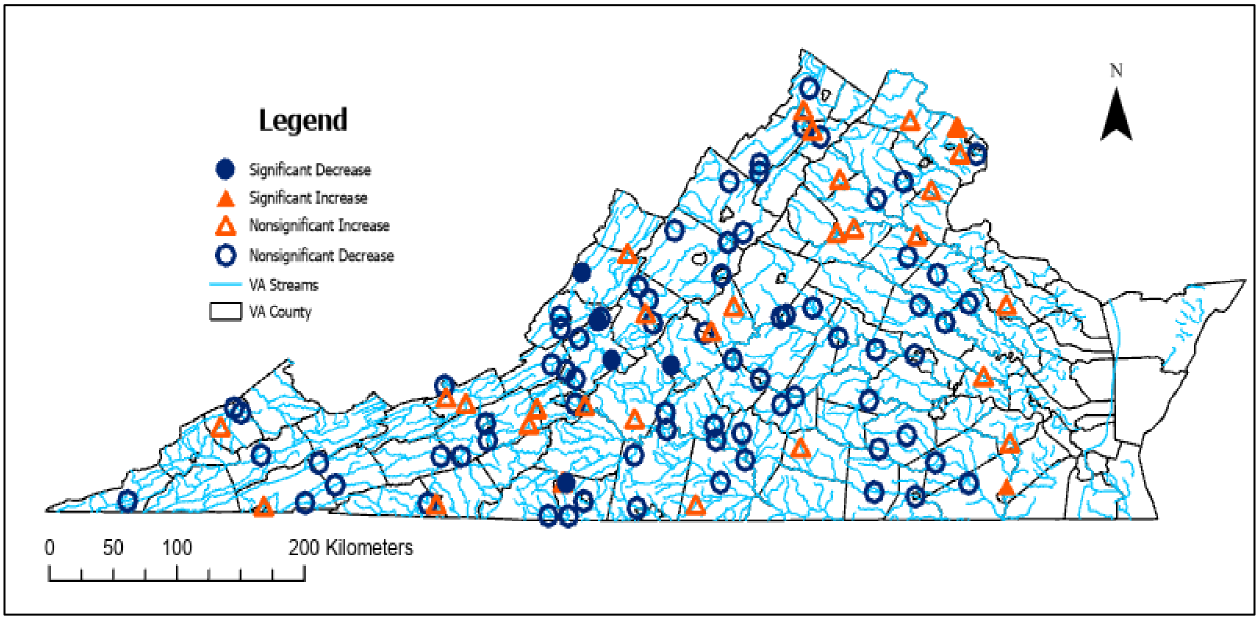

Figure 6. Virginia Stream Gage Locations Categorized by Trend for 1966–2015

Streamflow Trends by Stream Gage Category

Minimally altered watersheds were identified as being relatively free of human disturbance and alteration, so these stream gages are likely affected primarily by climatic changes and variability. Figures 7 and 8 show the locations and trends for the minimally altered watersheds for 1941 to 2015 and 1966 to 2015, respectively. For 1941 to 2015, most minimally altered watersheds had nonsignificant increasing or significant increasing trends. Nearly all minimally altered watersheds were in Virginia's eastern region. For 1966 to 2015, more minimally altered watersheds had nonsignificant decreasing trends. The difference could be because of more gages meeting the decadal completion criteria for 1966 to 2015 than for 1941 to 2015, or the number of years included in the analysis.

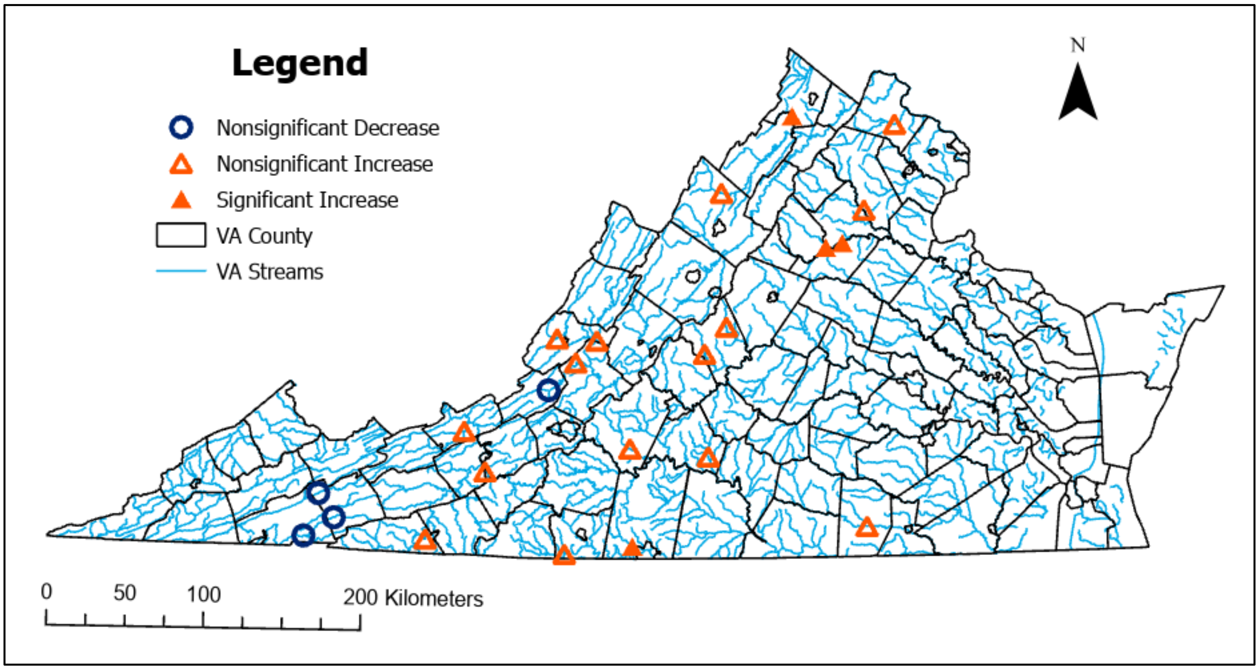

Figure 7. Locations and Trends for 1941-2015 for Minimally Altered Watersheds in Virginia

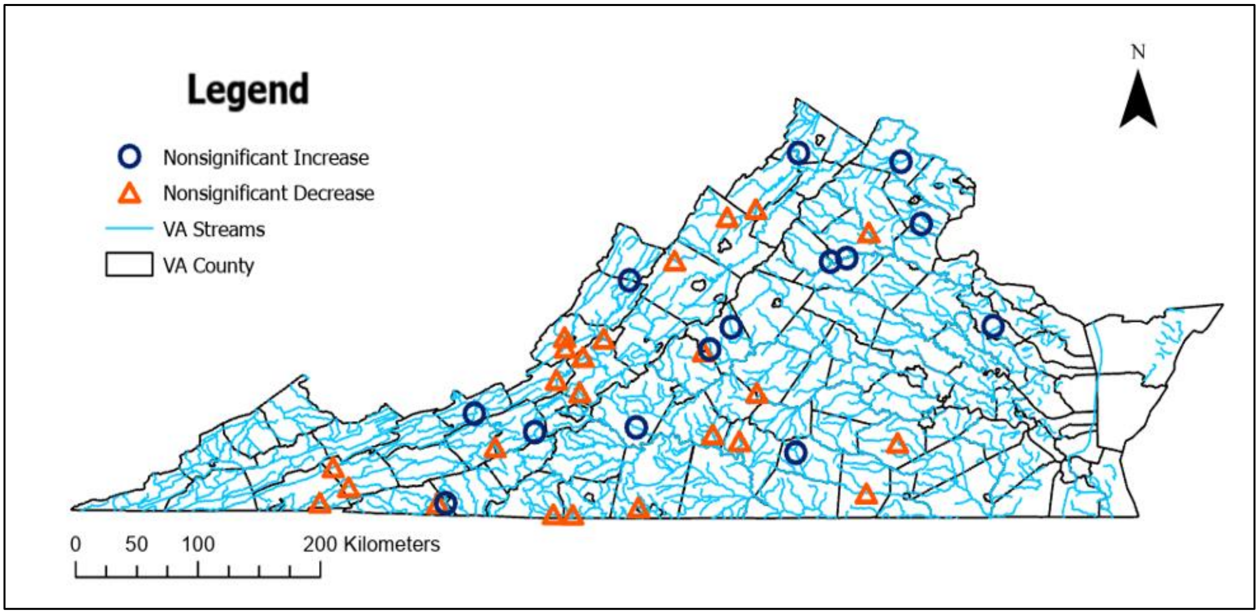

Figure 8. Locations and Trends for 1966–2015 for Minimally Altered Watersheds in Virginia

For all three time periods, most regulated stream gages had a decreasing trend in streamflow. This trend is expected for watersheds with large amounts of normalized dam storage (Table 6).

Table 6. Trends for Regulated Stream Gages

Time Period	Number of Regulated Stream Gages	Increasing Trend	Decreasing Trend
1916–2015	1	0	1
1941–2015	6	1	5
1966–2015	9	1	8

Only one watershed was classified as urban. Its drainage area was 61.9 km^2 and 72.1% urban. The watershed showed a nonsignificant increasing trend in streamflow. The urban watershed met the 80% decadal completion criteria for 1966 to 2015.

Streamflow Trends by Size

Stream gages were categorized based on size for each period to better understand the relationship between size and streamflow trends. Table 7 lists the boundaries of the size categories for each period.

Table 7. Size Category Boundary (km^2)

Time Period	Small	Medium	Large
1916–2015	995–5,344	5,345–7,661	7,662–16,193
1941–2015	91–670	671–913	914–16,193
1966–2015	20–293	293–981	982–17,490

For 1916 to 2015, an equal amount of each size category had a nonsignificant increase in streamflow. One large watershed had a significant decreasing trend. Large watersheds can result in runoff being more dispersed and, thus, in lower streamflows. For 1941 to 2015, more smaller watersheds (17) had an increasing trend compared with medium (14) and large (13) watersheds. For 1966 to 2015, the only watershed with a significant increasing trend was categorized as large. More medium (27) and large (31) watersheds had a decreasing trend. Small watersheds had similar numbers of nonsignificant increasing trends (16) and nonsignificant decreasing trends (19). Table 8 summarizes the stream gages per size category and streamflow trend.

Table 8. Number of Stream Gages per Size Category and Streamflow Trend

Period	Size Category	Significant Increase	Nonsignificant Increase	Nonsignificant Decrease	Significant Decrease	Total Increasing	Total Decreasing
1916–2015	Small	0	2	0	0	2	0
	Medium	0	2	0	0	2	0
	Large	0	2	0	1	2	1
1941–2015	Small	5	12	5	1	17	6
	Medium	2	12	7	2	14	9
	Large	2	11	10	1	13	11
1966–2015	Small	0	16	19	0	16	19
	Medium	0	9	25	2	9	27
	Large	1	4	28	3	5	31

Precipitation Impacts

For all three time periods, most stream gages experienced an increasing trend in precipitation. The few stream gages with a decreasing precipitation trend were in Virginia’s western region. Table 9 summarizes the number of stream gages per precipitation trend. Figures 9, 10, and 11 show precipitation trends for the periods of 1916 to 2015, 1941 to 2015, and 1966 to 2015, respectively.

Table 9. Number of Stream Gages per Precipitation Trend

	Decreasing Trend	Increasing Trend
1916–2015	1	6
1941–2015	3	67
1966–2015	9	98

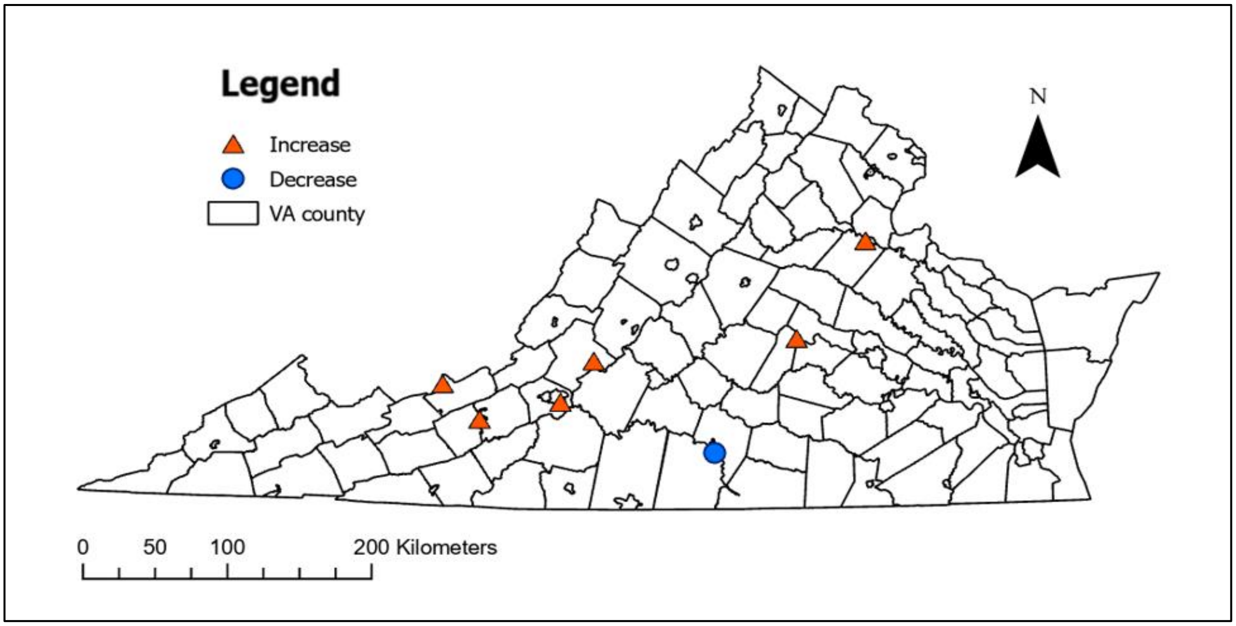

Figure 9. Trends in Precipitation for 1916–2015 in Virginia

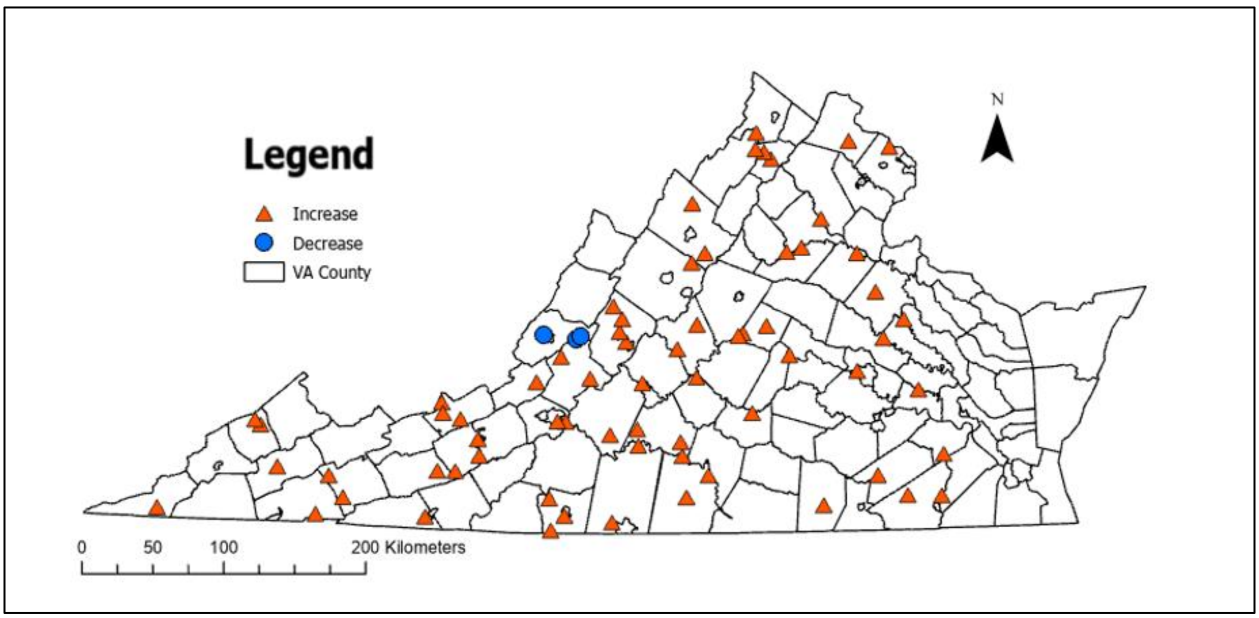

Figure 10. Trends in Precipitation for 1941–2015 in Virginia

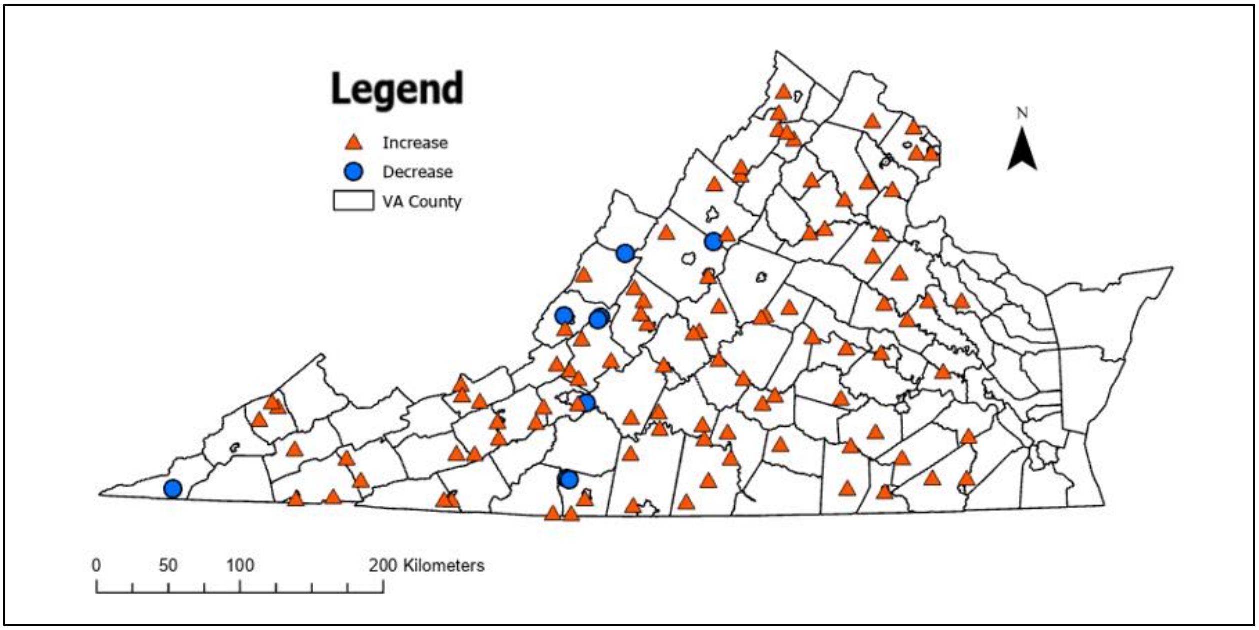

Figure 11. Trends in Precipitation for 1966–2015 in Virginia

For 1916 to 2015, precipitation and streamflow trends varied. One gage had a decrease in precipitation accompanied by a nonsignificant increase in streamflow. As expected, the regulated stream gage had an increase in precipitation and a significant decrease in streamflow. This result is most likely because of the amount of reservoir storage in this watershed. Stream gage VA 02066000 (Roanoke (Staunton) River at Randolph, Virginia) has 225.4 days of normalized dam storage. Table 10 lists the number of stream gages per precipitation, streamflow, and stream gage category for 1916 to 2015.

Table 10. Precipitation and Streamflow Trend Categories for 1916–2015

Precipitation Trend	Streamflow Trend	Regulated	Unclassified
Increase	Nonsignificant Increase	0	5
	Significant Decrease	1	0
Decrease	Nonsignificant Increase	0	1

For 1941 to 2015, the researcher observed a mix of precipitation and streamflow trends. Most stream gages underwent an increase in precipitation during this period, and very few gages had a decrease in precipitation (Table 11). Most minimally altered watersheds experienced increased precipitation alongside either a nonsignificant or significant increase in streamflow, which could indicate that climate change may be affecting streamflow at these gages.

Table 11. Number of Stream Gages per Category, 1941–2015

Precipitation Trend	Streamflow Trend	Regulated	Minimally Altered	Unclassified
Increase	Significant Increase		4	5
	Nonsignificant Increase	1	15	17
	Nonsignificant Decrease	2	3	14
	Significant Decrease	3		3
Decrease	Nonsignificant Increase			2
	Nonsignificant Decrease		1	

In addition, most unclassified gages experienced a similar trend of increases in streamflow. Notably, several regulated gages experience an increase in precipitation and either a nonsignificant or a significant decrease in streamflow, which is expected for watersheds with a fair amount of normalized dam storage.

Stream gages for 1966 to 2015 were also classified based on streamflow trend and precipitation (Table 12). Similarly, researchers observed a mix of streamflow and precipitation trends for 1966 to 2015. Twenty-six stream gages experienced an increase in precipitation and a nonsignificant increase in streamflow, with one-half of these gages (13) classified as minimally altered. As expected, the one urban stream gage experienced an increase in both precipitation and streamflow. Most of the regulated stream gages had a decrease in streamflow alongside an increase in precipitation, and most gages with a decrease in precipitation also had a decrease in streamflow. Supplemental File 3 summarizes stream gages and their streamflow and precipitation trends.

Table 12. Precipitation, Streamflow, and Stream Gage Category, 1966‒2015

Precipitation Trend	Streamflow Trend	Regulated	Minimally Altered	Unclassified	Urban	Total
Increase	Significant Increase			1		1
	Nonsignificant Increase		13	12	1	26
	Nonsignificant Decrease	5	22	41		68
	Significant Decrease	1		2		3
Decrease	Nonsignificant Increase	1	1	1		3
	Nonsignificant Decrease		2	2		4
	Significant Decrease	2				2

For 1941 to 2015, an increase in precipitation was not always accompanied by an increase in streamflow. Nearly two-thirds (66.4%) of stream gages for the period had a decreasing streamflow trend but also experienced an increase in precipitation. This outcome suggests that for these stream gages, other factors, such as watershed size or water use, may influence how these watersheds respond to increased precipitation. Interestingly, for the period from 1966 to 2015, 60% of stream gages experienced an increasing trend in streamflow and precipitation (Figure 12). Differences in trends between periods may be because of differences in the number of gages in the dataset or the years in the analysis.

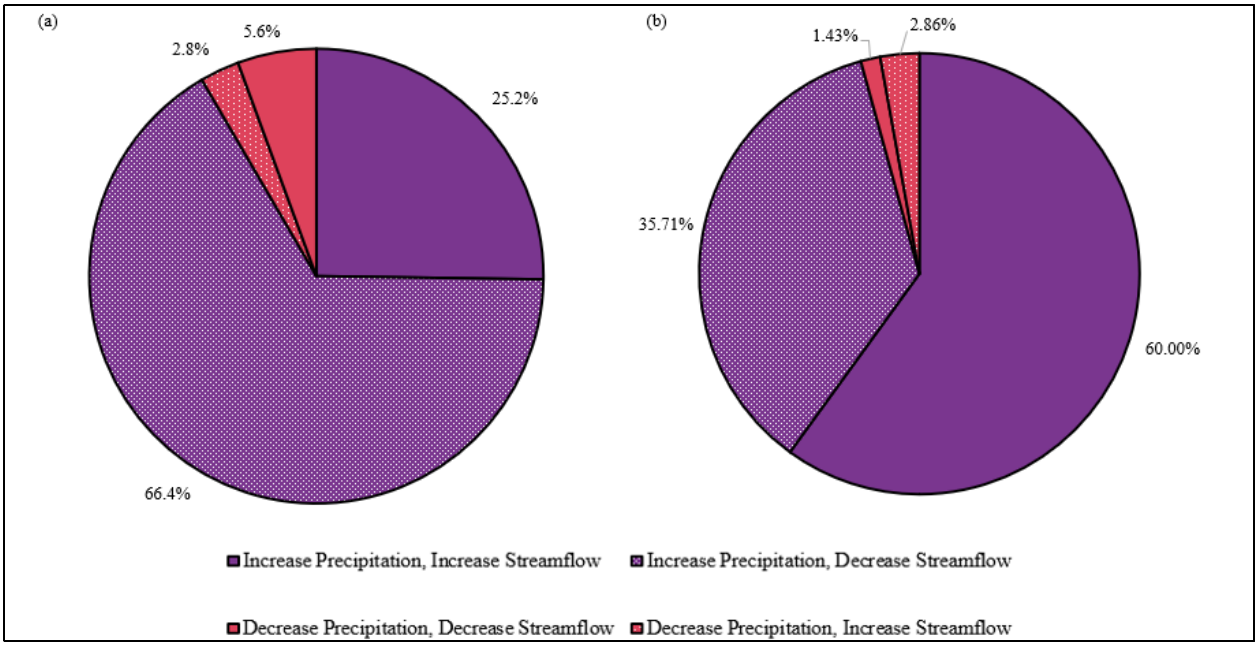

Figure 12. Stream Gages Categorized Based on Precipitation and Streamflow Trends for (a) 1941–1966 and (b) 1966–2015

Summary of Stream Gage Analysis

On balance, the stream gage analysis presented here does not prove that climate change has led to increased flow, but it opens the door to this possibility. This possibility is best raised by the observation that for the best type of stream gage for determining if climate change alone has raised streamflows, minimally altered, most (19 of 23 gages) showed some increase in flow for the 1941–2015 period (Table 10). However, two observations temper this possibility. First, most of these increases in flow (15 of 19 gages) were not statistically significant. Second, one obtains different results than those listed previously for the 1966–2015 period (Table 11), with only 14 of 38 gages showing some increase, all of which were insignificant. Thus, the question of whether climate change alone has led to an increase in flow over time depends partly on the time period: 1941 to 2015 yields substantially different results than 1966 to 2015. This discrepancy is exacerbated when considering the effect of precipitation. For the 1941–2015 period, the increase in streamflow (nonsignificant and significant) aligns with an increase in precipitation. For the later time period, 1966 to 2015, no clear association between increased precipitation and increased streamflow is observed.

Because minimally altered gages have experienced minimal anthropogenic disturbance, they are useful for determining the effects of climate change on streamflow. However, they are not the majority of gages in this study. Considering just the latter two time periods (1941 to 2015 and 1966 to 2015), such gages are slightly more than one-third (61 of 177) considered, with most other gages unclassified (100) and a few that are regulated (15) and just one that is urban. With one exception, all regulated gages showed a decrease of some type (nonsignificant or significant). The one exception was that for both time periods, when one regulated gage showed a nonsignificant increase. Unclassified gages also performed differently than minimally altered gages. For the earlier time period, 37% of unclassified gages showed some increase compared with 83% for minimally altered gages, and for the later period, 24% of gages showed some increase compared with 59% for minimally altered gages. Thus, streamflow discharges vary by gage type, with the latter two categories—regulated and unclassified—being most likely to show a significant or nonsignificant decrease compared with minimally altered stream gages.

Watershed Index

Watersheds in Virginia's eastern region have few stream gages. Other watersheds along the state's western and southern borders also had a low number of stream gages. Watersheds in central Virginia have more stream gages, with the greatest number in Northern Virginia (Figure 13). Areas with insufficient stream gages may affect the accuracy of flood predictions because of the lack of data for that area. Most stream gages have short periods of record. Northern Virginia has the highest number of stream gages with less than 20 years of data. Efforts to add stream gages across the Commonwealth should prioritize watersheds with a low total number of stream gages. Supplemental File 4 contains the number of stream gages per data timeframe, streamflow trend category, and number of stream gages per watershed. Note that the red areas near the coast primarily have tidal gages instead of stream gages.

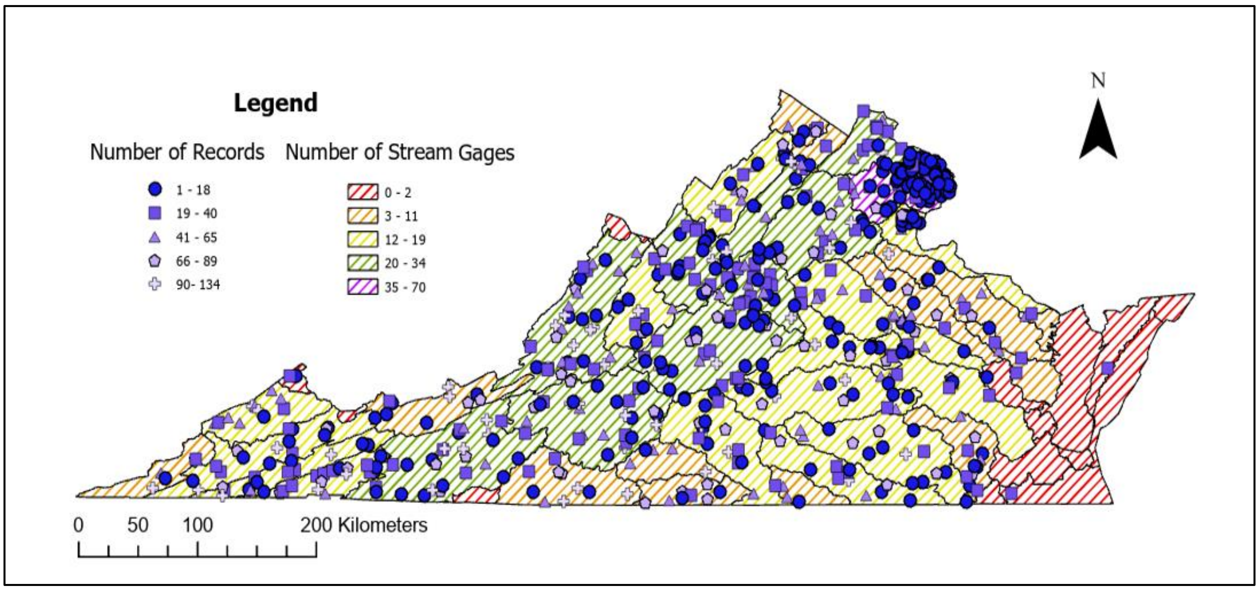

Figure 13. Number of Records per Stream Gage and Number of Stream Gages per Hydrologic Unit Code 8-Digit Watershed in Virginia

The watershed index identifies areas in eastern Virginia and along the state's northern and southern borders that would benefit from further analyses (Figure 14). Additional analyses could include a more in-depth spatial analysis to identify areas that need more stream gages or more in-depth streamflow trend analyses. These watersheds had low totals of stream gages and a low number of stream gages with long records of data. Furthermore, these watersheds had stream gages with either nonsignificant or significant increasing trends, as Hodgkins et al. (2019) identified.

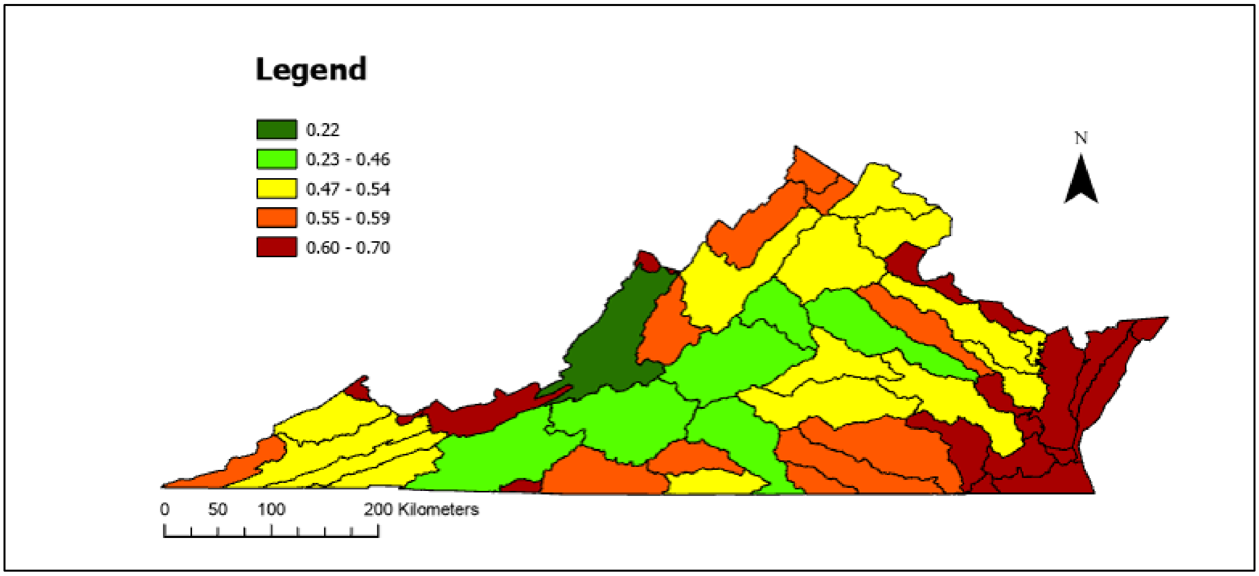

Figure 14. Watershed Index for Virginia. The highest scoring watersheds (red) should be prioritized for future analyses, or more stream gages could be added.

Sensitivity Analysis

Figures 13 and 14 were created based on all 10 variables that comprise the watershed index, having a weight of 0.10. For instance, when weighting all variables equally, the Lower Potomac watershed index needs a medium high, given a nonsignificant increasing trend and most of its gages being in the 0- to 19-year category. However, the weights naturally influence the final classification that results from the index. The Lower Potomac watershed had 12 gages. Only 21 of the 52 watersheds had more stream gages. If one changes the weight for the variable for the total number of gages from 0.10 to 0.90 (and reduces the weights for the other variables such that total weights sum to 1.0), then one would expect that the Lower Potomac watershed does not have a strong need for additional gages compared with other watersheds—and indeed that is the case, with the index dropping compared with other watersheds such that the Lower Potomac's need for additional gages changes from medium-high priority to medium priority.

Figure 15 shows the results of a sensitivity analysis. For instance, under iteration 1 (all weights are equal), the Lower Potomac watershed has a medium-high priority (orange color in Figure 15). Under iteration 10 (90% of the index is based on the number of gages), the Lower Potomac has a priority of medium (yellow color in Figure 15).

The sensitivity analysis showed that 6 of the 52 watersheds were very sensitive to changes in variable weights (Figure 15). These watersheds changed into opposite score categories, either from low priority to high priority or from high priority to low priority, when the variable weights were adjusted. These 6 watersheds shifted in ranking when streamflow trend categories were weighted higher. Scores for each iteration and the weights are included in Supplemental File 4.

HUC8	Watershed Name	Iteration																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
02070003	Cacapon-Town																			
02040303	Chincoteague																			
03010203	Chowan																			
02040304	Eastern Lower Delmarva																			
05050003	Greenbrier																			
02080208	Hampton Roads																			
06010104	Holston																			
02080101	Lower Chesapeake Bay																			
02080108	Lynnhaven-Poquoson																			
05100201	North Fork Kentucky																			
02080111	Pokomoke-Western Lower Delmarva																			
02070001	South Branch Potomac																			
05130101	Upper Cumberland																			
03040101	Upper Yadkin																			
02080107	York																			
03010202	Blackwater																			
03010205	Albemarle																			
05070201	Tug																			
02070011	Lower Potomac																			
03010106	Roanoke Rapids																			
02070007	Shenandoah																			
05050002	Middle New																			
03010105	Banister																			
02070004	Conococheague-Opequon																			
02080105	Mattaponi																			
03010204	Meherrin																			
06010206	Powell																			
02080202	Maury																			

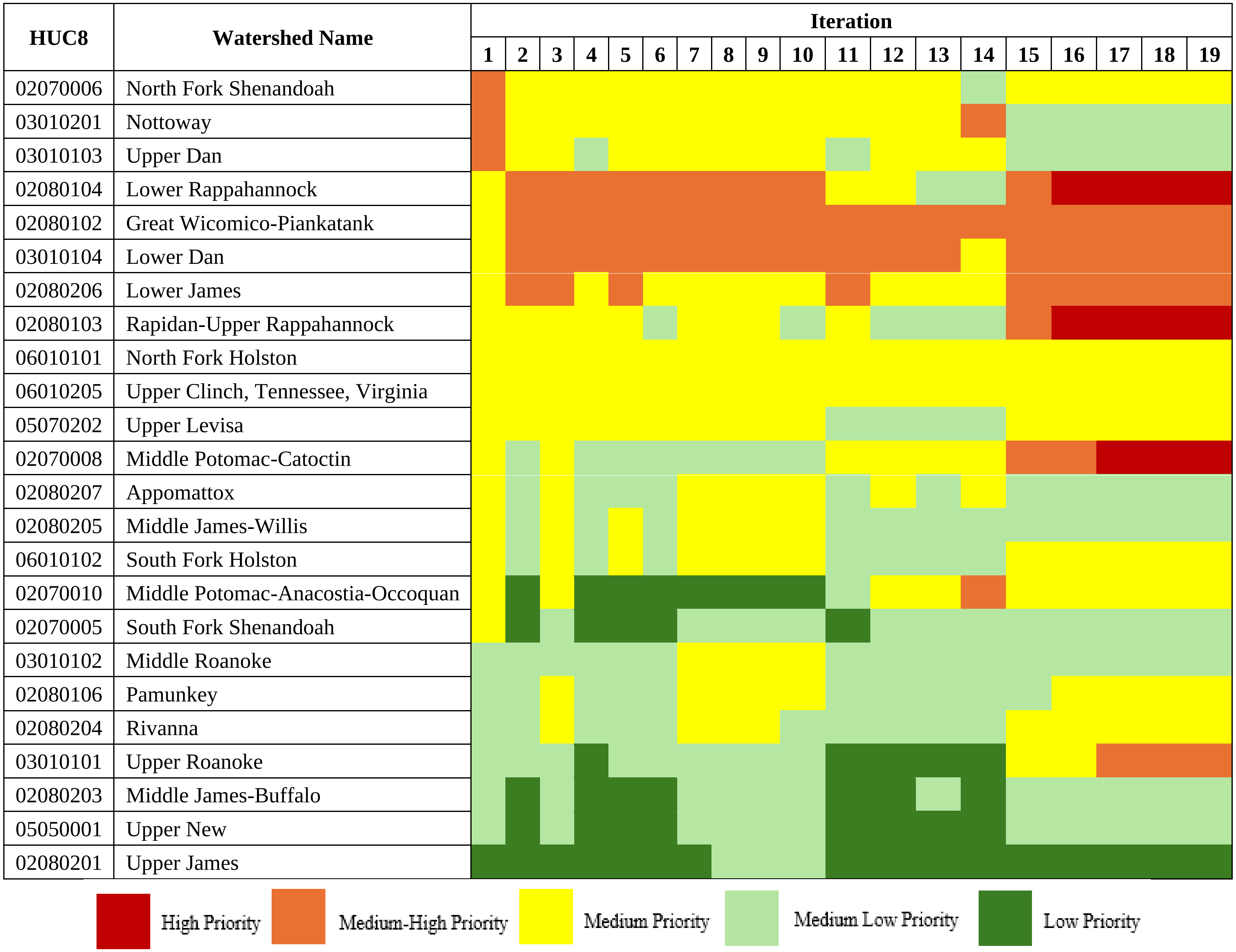

Figure 15. Sensitivity Analysis Results for Watershed Index. HUC8 = Hydrologic Unit Code 8-Digit.

Summary of Watershed Index Results

The watershed index identified watersheds in Virginia's southeastern, southwestern, and northern regions that should be prioritized for further analyses. Further analyses could be an in-depth spatial analysis to identify locations that would benefit from having stream gages or additional streamflow trend analyses.

The watershed index was sensitive to changes in variable weights. Six watersheds changed priority categories, either from low to high or from high to low, when weights associated with either years of data or streamflow trends were adjusted.

CONCLUSIONS

- *DRRM is a valuable tool for incorporating climate change into infrastructure design.* However, using a DRRM has implementation barriers, such as economic feasibility and higher input data requirements.
- *State DOTs use various methods to incorporate climate change into transportation infrastructure design.* The most common method is adjusting the design storm size.
- *Streamflow trends varied across the Commonwealth and by time period. Most trends were non-significantly decreasing from 1966 to 2015, whereas most trends were non-significantly increasing from 1941 to 2015.* The number of stream gages with historical data limited the streamflow trend analysis.
- *Most stream gages classified as minimally altered had a nonsignificant increasing trend for the 1941–2015 period but had a nonsignificant decreasing trend for the 1966–2015 period. Most of these stream gages experienced increased precipitation during these time periods.*
- *Across the three time periods, the researcher observed expected patterns in streamflow trends and watershed size.* Larger watersheds had decreasing trends in streamflow, whereas smaller watersheds had increasing trends.
- *Most regulated stream gages experienced increased precipitation alongside a decreasing trend in streamflow.* This result was observed for all three time periods considered.
- *The urban stream gage had an increasing trend in precipitation and streamflow.*
- *Precipitation increased primarily at the stream gage locations across all three time periods.*
- *An increase in streamflow did not always accompany an increase in precipitation.* Opposing trends in streamflow and precipitation could be because of factors such as normalized dam storage or watershed size.

- *Watersheds in the southeastern, western, and northern regions of the Commonwealth have less stream gage coverage than watersheds in other parts of the Commonwealth.* The watersheds identified in the index had a low number of total gages, stream gages with few years of data, or stream gages with significant or nonsignificant increasing trends. Accordingly, such watersheds are the most productive for further analyses or expanding the stream gage network.

RECOMMENDATIONS

1. *VDOT's Resiliency Research Needs Interest Group, with support from the Virginia Transportation Research Council (VTRC), should identify critical watersheds for which current stream gage coverage is insufficient.*

2. *VDOT's Resiliency Research Needs Interest Group should initiate a study to create a database of historical highwater elevations.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

In regard to Recommendation 1, VDOT's Resiliency Research Needs Interest Group and VTRC will initiate an investment study within a year of this report's publication that recommends optimal locations for additional stream gages. This systematic investment study is required because gage costs are not trivial and were submitted as a research needs statement to VDOT's Resiliency Research Needs Interest Group (Forasté, 2024a). This study will include the following elements:

- *Identification of critical watersheds at either the HUC10 or HUC12 levels for which the current stream gage coverage is insufficient*. This study evaluated the 51 HUC8 watersheds. However, those watersheds are larger than the 502 HUC10 watersheds or the 1251 HUC12 watersheds. An analysis comparable with Kiang et al. (2013) should be conducted for Virginia. This analysis will identify watersheds with spatial or temporal gaps in streamflow data. To determine optimal locations for additional stream gages, researchers will analyze the data regarding spatial and temporal gaps in the existing stream gage network and VDOT's flood frequency data (Dewberry Engineers, Inc. 2024b).

- *Evaluate the suitability of the stream gage network to estimate statistics at ungauged locations.* This analysis should focus on identifying suitable or unsuitable locations for transferring information from gaged to ungauged locations. The outcome of this analysis would help determine high-risk locations because of the absence of stream gage data in order to recommend optimal locations for new stream gages.

Researchers at VTRC will initiate this study. Completing the study will involve coordinating with USGS. The technical review panel should include, but not be limited to, representatives from VDOT Location and Design, VDOT Structure and Bridge, and VDOT Maintenance.

In regard to Recommendation 2, VDOT's Resiliency Research Needs Interest Group will initiate an effort to compile a database of historical highwater elevations within a year of this report's publication. This effort is a synthesis of existing data that support the development of hydrologic models, and it was submitted as a research needs statement to VDOT's Resiliency Research Needs Interest Group (Forasté, 2024b). The need, scope, approach, and form of the study may be considered as follows:

- The study is needed because historical highwater elevations are used to calibrate and validate computer models used for flood predictions. USGS can also use these data to develop regression equations for rural and unregulated streams in Virginia.

- The study's scope is limited to existing datasets. Discussions with VDOT staff suggest that some of these data have been collected but are stored in disparate systems rather than in a central location.

- This central database should be compiled by consulting each district's Location and Design section regarding where such data are stored. The database should ideally contain the following fields: date, water surface elevation (relative to a vertical datum), latitude and longitude of location, stream name, and any available explanatory factors.

- This study may take the form of a technical assistance effort if a full report is not needed.

Benefits

Both initiatives respond to a limitation uncovered in this study: limited stream gage data. Stream gage data are essential for making flood predictions, creating hydrologic models, designing transportation infrastructure, water supply planning, and drought monitoring. Expanding stream gage data collection decreases uncertainty in estimates of streamflow statistics (Kiang et al., 2013; Thomas, 2004), leading to two types of cost reductions: lifecycle costs (associated with construction) and damage costs.

Reduction in Uncertainty

Uncertainty or standard error of flood discharges at stream gaging stations depends on the record of length and standard deviation (Kiang et al., 2013). These variables are related by Equation 3:

$$SE = \frac{s}{\sqrt{n}} \qquad \text{(Equation 3)}$$

Where:
SE = standard error.
s = standard deviation of the annual mean flow time series.
n = number of years of record.

Figure 16 illustrates that the standard error decreases as the number of years of record increases. USGS also evaluated the relationship between years of record and uncertainty in streamflow statistics at the national level. This analysis showed that, when only 10 years of streamflow record is available, the mean annual flow has greater variability and that uncertainty decreases significantly when 100 years of record are available. When 50 or 100 years of data were available, most stand errors decreased to the 0.0–0.1 range (Kiang et al., 2013).

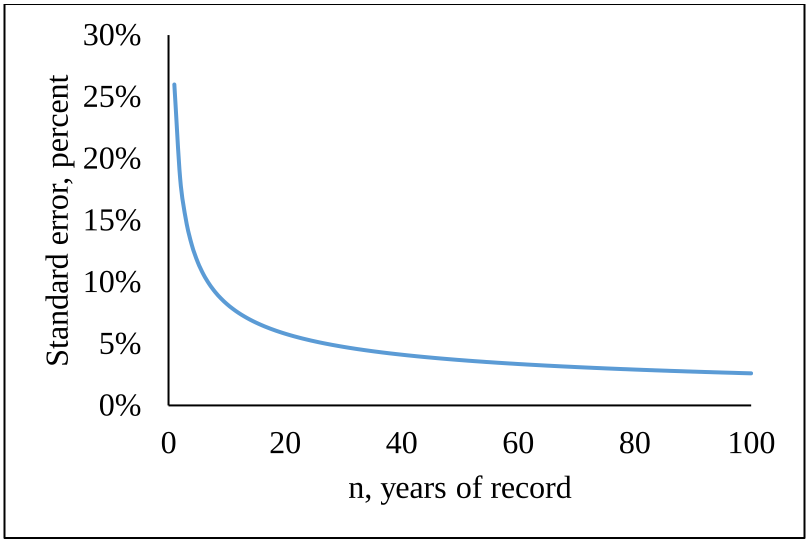

Figure 16. Relationship between Standard Error (%) and Years of Record (n). This calculation assumed a standard deviation of 0.26 for the Eastern United States and presumes a mean of 1 (Thomas, 2004). For instance, with 20 years of record, the standard error from Equation 3 is 0.26/200.5 = 0.058, and as a percentage of the mean, it is 0.058/1 = 0.058, or 5.8%.

Reduction in Lifecycle Costs

Transportation infrastructure is designed using streamflow data. If a project is under-designed, damages can occur. However, overdesigned infrastructure leads to excess construction costs (David Ford Consulting Engineers, 2006). A Minnesota study showed how better streamflow data can lead to more cost-effective culvert designs, considering three different climate scenarios. The authors assessed the performance of the existing or proposed facility, identified adaptations, assessed the performance of the adaptation, and conducted an economic analysis. The authors considered costs with and without social costs, for two different case study culverts, and across three climate scenarios. Social costs included costs due to detours and injuries. Table 13 shows the results of the case studies (Parsons Brinckerhoff, 2014a, 2014b).

Table 13. Total Lifecycle Costs by 2100 and Costs Saved for Two Culverts (Parsons Brinckerhoff, 2014a, 2014b)

Case [a]	Social Costs	Climate Scenario	Design	Total Lifecycle Costs by 2100	Costs Saved
1	Without Social Costs	Low (RCP 4.5)	Base case: replace in kind	$719,863 [b]	$6,132
			Increase size of two-cell culvert	$725,995	
		Medium (RCP 6.0)	Base case: replace in kind	$730,951	$1,369
			Increase size of two-cell culvert	$729,582 [b]	
		High (RCP 8.5)	Base case: replace in kind	$799,108	$46,534
			Increase size of two-cell culvert	$752,574 [b]	
	With Social Costs	Low (RCP 4.5)	Base case: replace in kind	$832,727	$106,750
			Increase size of two-cell culvert	$725,977 [b]	
		Medium (RCP 6.0)	Base case: replace in kind	$832,727	$106,750
			Increase size of two-cell culvert	$725,977 [b]	
		High (RCP 8.5)	Base case: replace in kind	$1,106,086	$239,359
			Increase size of two-cell culvert	$866,727 [b]	
2	Without Social Costs	Low (RCP 4.5)	Base case: replace in kind	$1,555,380	
			Increase number of culvert cells	$1,470,187 [b]	$85,193
		Medium (RCP 6.0)	Base case: replace in kind	$1,594,662	$157,631
			Increase number of culvert cells	$1,437,031 [b]	
		High (RCP 8.5)	Base case: replace in kind	$1,704,028	$153,277
			Increase number of culvert cells	$1,550,751 [b]	
	With Social Costs	Low (RCP 4.5)	Base case: replace in kind	$2,072,336	$377,362
			Increase number of culvert cells	$1,694,974 [b]	
		Medium (RCP 6.0)	Base case: replace in kind	$2,111,618	$398,747
			Increase number of culvert cells	$1,712,871 [b]	
		High (RCP 8.5)	Base case: replace in kind	$2,290,276	$499,429
			Increase number of culvert cells	$1,790,847 [b]	

RCP = recycled concrete pavement. [a] Case 1 is increasing the size of culvert cells (Silver Creek). Case 2 is adding additional culvert cells. [b] Indicates the most cost-effective option.

Usually, increasing the number or the size of the cells instead of replacing the culvert in-kind was the most cost-effective option. However, for the low-climate scenario without social costs, replacing a culvert in-kind instead of increasing the size of the cells was the most cost-effective option. Actions based on this analysis could save Minnesota DOT $1,369 to $239,359 for one culvert and $85,193 to $499,429 for the other culvert, depending on the climate change scenario and whether social costs were included. If one excludes social costs, the range of savings based on climate change scenario was roughly $6,000 to $47,000 for the first culvert and $85,000 to $153,000 for the latter culvert.

Adapting designs for climate change can have cost implications. Oversizing infrastructure to account for climate change could lead to high construction costs. However, in case study 2, the authors found that increasing the size of the drainage structure led to cost savings during the structure's lifetime. Lifetime costs were compared between the original structure design, which did not account for climate change, and the adaptive designs. Note that the original structure would cost $460,000 to remove, and the authors estimate that the worst-case damage costs are $250,000.

Reduction in Damage Costs

The value of stream gage data could also be quantified based on losses avoided. The Federal Emergency Management Agency (FEMA) conducts loss-avoidance studies to understand the cost-effectiveness of mitigation measures. The authors conducted a loss-avoidance study on six flood mitigation projects in Northern California (FEMA, 2021). This study compared losses from before the flood mitigation measures were in place with losses after project completion. FEMA uses physical losses (damage to structures and content), loss of function (i.e., lost business income, wages, or public services), and the cost of emergency services required to deal with flooding to calculate costs. This study was only based on one post-project flood event, but the authors anticipate that losses avoided will likely increase if additional flooding events occur during the lifespan of the projects. The values were calculated in 2008 dollars. Two culvert projects were included in this study. In one project, a culvert was enlarged, an inlet and outlet projection was installed, and the canal was dredged. In the other project, the culvert was also enlarged, and additional work was performed on the creek. The authors found that these mitigation measures saved thousands of dollars in losses. **Error! Reference source not found.**14 shows the losses avoided and costs for the culvert projects. In this case, stream gage data were used to design the structures and make calculations related to flood damage. Because stream gage data were available and analyzed, these communities were able to avoid $67,924 to $1,603,849 in losses (FEMA, 2021).

Table 14. Losses Avoided and Project Costs for Two Studied Culverts (FEMA, 2021)

Project	Losses Avoided	Project Cost
Humboldt Road Culvert at Mallory Creek	$67,924	$257,106
Broadway Culvert Replacement	$1,603,849	$138,961

Choosing the Number of Additional Gages

The number of additional gages that should be considered depends on the number of assets throughout Virginia, by which better information could reduce costs, as was the case in Tables 13 and 14. One way to consider this number is to presume that, on a per-asset basis, an agency is willing to budget $150,000 toward investing in streamflow data, which is within the range of the cost savings or loss avoided in the case study examples of Tables 13 and 14.

This budget could be spent on either installing stream gages or operating stream gages, or both. It is assumed that the capital costs for a USGS stream gage are $25,000 to $40,000, the yearly operational costs are $16,500 to $32,000, and the agency has entered the USGS cooperative matching funds program, which provides a 50% federal match with tribal, regional, state, and local partners (Normand, 2021). Tables 15 and 16 show the number of stream gages that could be bought with $150,000 and the number of years of operation that $150,000 would pay for, respectively. For instance, with minimal capital costs ($25,000 and a 50% match), an agency could purchase 12 stream gages, as the top of Table 15 shows. Alternatively, that same budget could fund one gage for 19 years, provided that the agency has the lowest operational cost of one-half of $16,500 annually.

Table 15. Number of Stream Gages that Could Be Bought with $150,000

Cost Scenario	Number of Stream gages
Minimum Capital Costs	12
Average Capital Costs	9
Maximum Capital Costs	8

Table 16. Number of Years One Stream Gage Could Be Operated with $150,000

Cost Scenario	Years Operational
Minimum Operating Costs	19
Average Operating Costs	13
Maximum Operating Costs	10

In practice, an agency must buy and maintain these gages. Table 17 shows these tradeoffs, again considering the number of stream gages and how long they could be operated with $150,000. For instance, with average capital costs and average operating costs, an agency could buy three gages and operate them for 4 years, or purchase six gages and operate them for 2 years.

Table 17. Number of Stream Gages and Years Operational with a $150,000 Budget

	Number of Stream Gages	Cost of Stream Gages ($)	Budget for Operating Costs ($)	Minimum Operating Costs	Average Operating Cost	Maximum Operating Cost
				Operating Years	Operating Years	Operating Years
Minimum Capital Costs	1	12,500	137,500	8	6	4
	2	25,000	125,000	8	5	4
	3	37,500	112,500	7	5	4
	4	50,000	100,000	6	4	3
	5	62,500	87,500	5	4	3
	6	75,000	75,000	5	3	2
	7	87,500	62,500	4	3	2
	8	100,000	50,000	3	2	2
	9	112,500	37,500	2	2	1
	10	125,000	25,000	2	1	1
Average Capital Costs	1	16,250	133,750	8	6	4
	2	32,500	117,500	7	5	4
	3	48,750	101,250	6	4	3
	4	65,000	85,000	5	4	3
	5	81,250	68,750	4	3	2
	6	97,500	52,500	3	2	2
	7	113,750	36,250	2	1	1
	8	130,000	20,000	1	1	1
Maximum Capital Costs	1	20,000	130,000	8	5	4
	2	40,000	110,000	7	5	3
	3	60,000	90,000	5	4	3
	4	80,000	70,000	4	3	2
	5	100,000	50,000	3	2	2
	6	120,000	30,000	2	1	1
	7	140,000	10,000	1	0	0

Summary of Benefits

The decreases in uncertainty that would accompany the installation of additional stream gages (Figure 16) translate into dollars saved in terms of better design decisions (Table 13) and losses avoided (Table 14). If one excludes the costs of detours and injuries and chooses the low scenario—the most conservative estimate from Table 13—then better design decisions alone could save between $6,000 and $85,000 based solely on culvert characteristics, based on the Minnesota DOT effort. If one considers losses avoided based on Table 14, the most conservative estimate is $68,000 based on culvert characteristics. Conservatively, therefore, stream gages could result in potential savings of between $6,000 and $68,000 to $6,000 and $85,000 when considering better design and losses avoided—that is, a range of $74,000 to $91,000 per culvert during the lifetime of the asset. If these figures apply to 10 culverts, then Virginia could see conservative savings of approximately $0.75 to $0.91 million over the lifetimes of those assets.

A detailed study that can identify where these additional gages should be placed, as shown in the first implementation bullet, can enable VDOT to choose the optimal number of gages based on an analysis comparable with that shown in Table 17.

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