Stressor Identification Analysis
for
Deep Run, Dover Creek, and Upham Brook Watersheds in Goochland and Henrico Counties and the City of Richmond

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Prepared for:
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Acronyms

BCG	Biological Condition Gradient
CADDIS	Causal Analysis/Diagnosis Decision Information System
CCU	Cumulative Criterion Unit
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
EIS	Environmental Impact Statement
EPT	Ephemeroptera, Plecoptera, Trichoptera
JMU	James Madison University
LRBS	Log Relative Bed Stability Index
MFBI	Modified Family Biotic Index
NWBD	National Watershed Boundary Dataset
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyls
PEC	Probable Effect Concentration
SCI	Virginia Stream Condition Index
TDS	Total Dissolved Solids
TEC	Threshold Effect Concentration
TOC	Total Organic Carbon
TRV	Toxicity Reference Value
TSS	Total Suspended Solids
TVS	Total Volatile Solids
USEPA	U.S. Environmental Protection Agency
VDEQ	Virginia Department of Environmental Quality

Executive Summary

This Stressor Identification Analysis Report addresses benthic impairments in Deep Run, Dover Creek, Jordans Branch, North Run, Stony Run, Stony Run UT, and Upham Brook (collectively called the Goochland and Henrico Project). The analysis was conducted in accordance with the U.S. Environmental Protection Agency's (USEPA) Stressor Identification Guidance Document (USEPA, 2000b) using the Causal Analysis/Diagnosis Decision Information System (CADDIS) (USEPA, 2018a). Twenty years of data (2000 – 2020) on over 504 parameters from 50 monitoring stations totaling over 22,000 data points were used in the analysis. These data were evaluated according to 18 lines of evidence to categorize candidate stressors as non-stressors, possible stressors, or probable stressors. Based on the evaluation, sediment was identified as a probable stressor in each of the seven streams, and phosphorus was identified as a probable stressor in Dover Creek, Stony Run, and Upham Brook. As a result, sediment and phosphorus TMDLs should be developed to address these probable stressors and associated impairments. In addition, pH, dissolved oxygen, and organic matter were probable stressors in North Run. These stressors were determined to be due to natural conditions resulting from the decay of organic matter in connected wetlands and the production of natural organic acids. Since these conditions are natural, a TMDL will not be developed to specifically address pH, dissolved oxygen, and organic matter in North Run.

1.0 OVERVIEW

1.1. TMDL Development

Section 303(d) of the Federal Clean Water Act and the U.S. Environmental Protection Agency's (USEPA) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for water bodies that fail to meet designated water quality standards and are placed on the state's Impaired Waters List. A TMDL reflects the total pollutant loading that a water body can receive and still meet water quality standards. A TMDL establishes the maximum allowable pollutant loading from both point and nonpoint sources for a water body, allocates the load among the pollutant contributors, and provides a framework for taking actions to restore water quality.

For impairments that result from the violation of numeric water quality standards, a TMDL can be directly developed for the pollutant that violates the standard. Benthic impairments, however, result from violations of the narrative general standard which states that waters should be free from substances that are harmful to aquatic life. To develop TMDLs that address benthic impairments, the first step is to identify the pollutant(s) causing the impairment. This step is called a Stressor Identification Analysis.

1.2. Benthic Impairments

The Virginia Department of Environmental Quality (VDEQ) contracted Wetland Studies and Solutions, Inc. and James Madison University (JMU) to conduct a stressor identification analysis for benthic impairments in Goochland and Henrico counties (VDEQ, 2020). The seven impaired streams (and ten corresponding assessment units) are listed in Table 1, shown in Figure 1, and collectively referred to as the Goochland and Henrico Project streams. This project addresses benthic impairments in Deep Run, Dover Creek, Jordans Branch, North Run, Stony Run, an unnamed tributary to Stony Run (Stony Run UT), and Upham Brook.

Table 1. Benthic impairments in the Goochland and Henrico Project.

Stream Name	NWBD	Impaired Assessment Units	Cause Group Code	First listed	Length (miles)	Impairment Description
Deep Run	JM84	VAP-H39R_DPR01A00	H39R-27-BEN	2016	4.16	Headwaters to the pond at river mile 1.47
Dover Creek	JM82	VAP-H39R_DOV01A00	H39R-26-BEN	2020	4.76	Headwaters to the upstream limit of Dover Lake
Jordans Branch	JL18	VAP-G05R_JOP01A14	G05R-14-BEN	2016	2.19	Headwaters to the mouth at Upham Brook
North Run	JL18	VAP-G05R_NTR01A00	G05R-09-BEN	2014	4.24	Hungary Creek to the mouth at Upham Brook
	JL18	VAP-G05R_NTR02A06	G05R-09-BEN	2008	3.66	Headwaters to Hungary Creek
Stony Run	JM84	VAP-H39R_SNJ01A04	H39R-13-BEN	2008	1.01	Headwaters to the extent of backwater at the pond
	JM84	VAP-H39R_SNJ02A04	H39R-28-BEN	2016	1.35	From the dam of the pond downstream to the mouth at Deep Run
Stony Run UT	JM84	VAP-H39R_XYT01A08	H39R-15-BEN	2008	1.27	Headwaters to the mouth at Stony Run
Upham Brook	JL18	VAP-G05R_UPM01A02	G05R-16-BEN	2016	10.99	Headwaters to the mouth at the Chickahominy River, excluding Upham Brook from Flippen Creek to the UT above Wilkinson Rd.
	JL18	VAP-G05R_UPM01B08	G05R-16-BEN	2016	1.16	Flippen Creek downstream to UT above Wilkinson Road

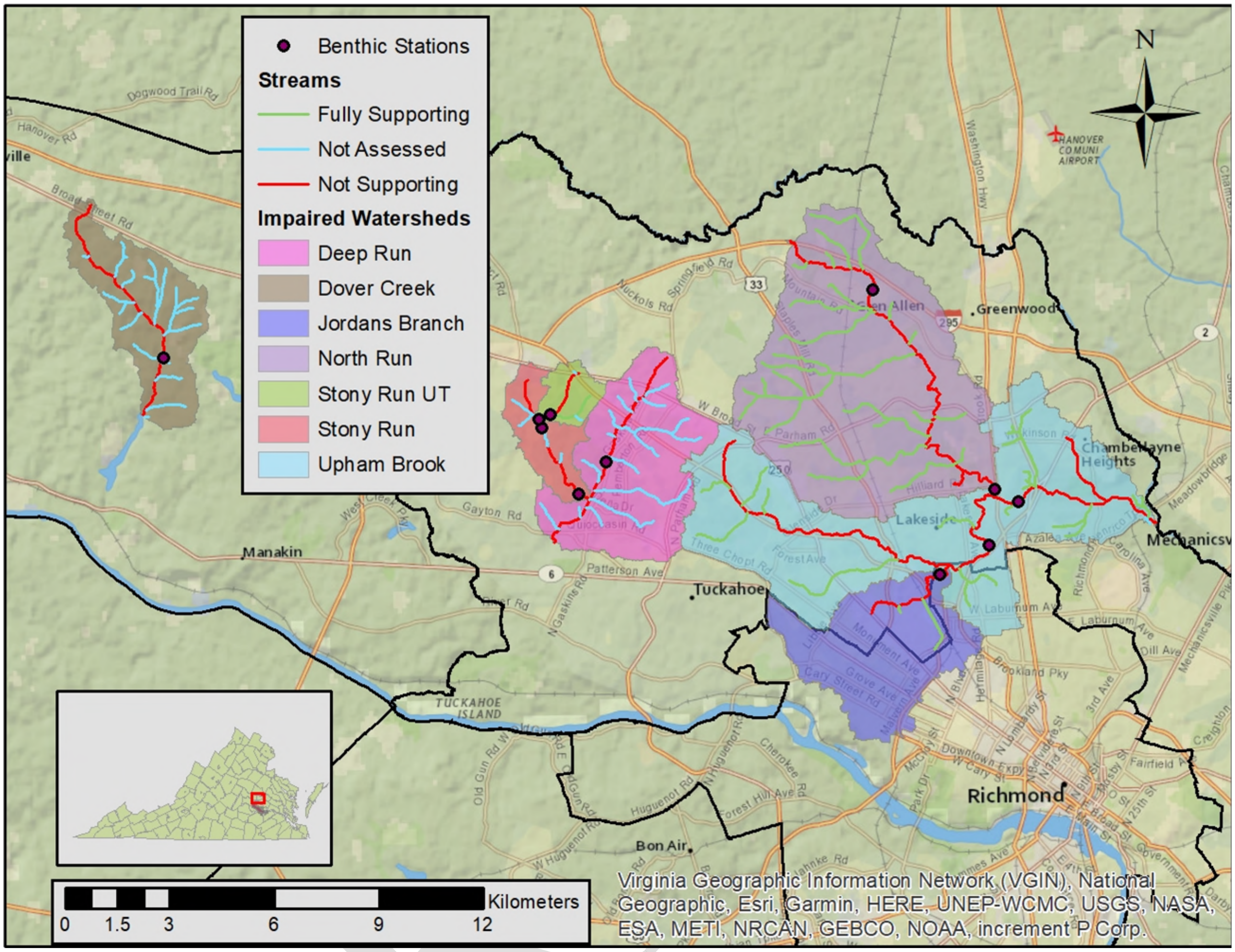

Figure 1. Location of benthic impairments in the Goochland and Henrico Project.

1.3. Stressor Analysis Process

Benthic impairments are based on biological assessments of the benthic community. These biological assessments are effective at determining whether a water body is impaired or not, but they do not provide information on the stressor or source causing the impairment. To determine the cause of the impairment, a stressor identification analysis must be conducted. JMU conducted this analysis according to the U.S. Environmental Protection Agency's (USEPA) Stressor Identification Guidance Document (USEPA, 2000b). In short, the stressor identification analysis identifies the pollutant(s) responsible for the benthic impairment through a weight of evidence approach that evaluates all available information on potential candidate stressors (Figure 2). Once the probable stressor(s) is identified, a TMDL can be developed for that pollutant to reduce sources and restore the aquatic life designated use.

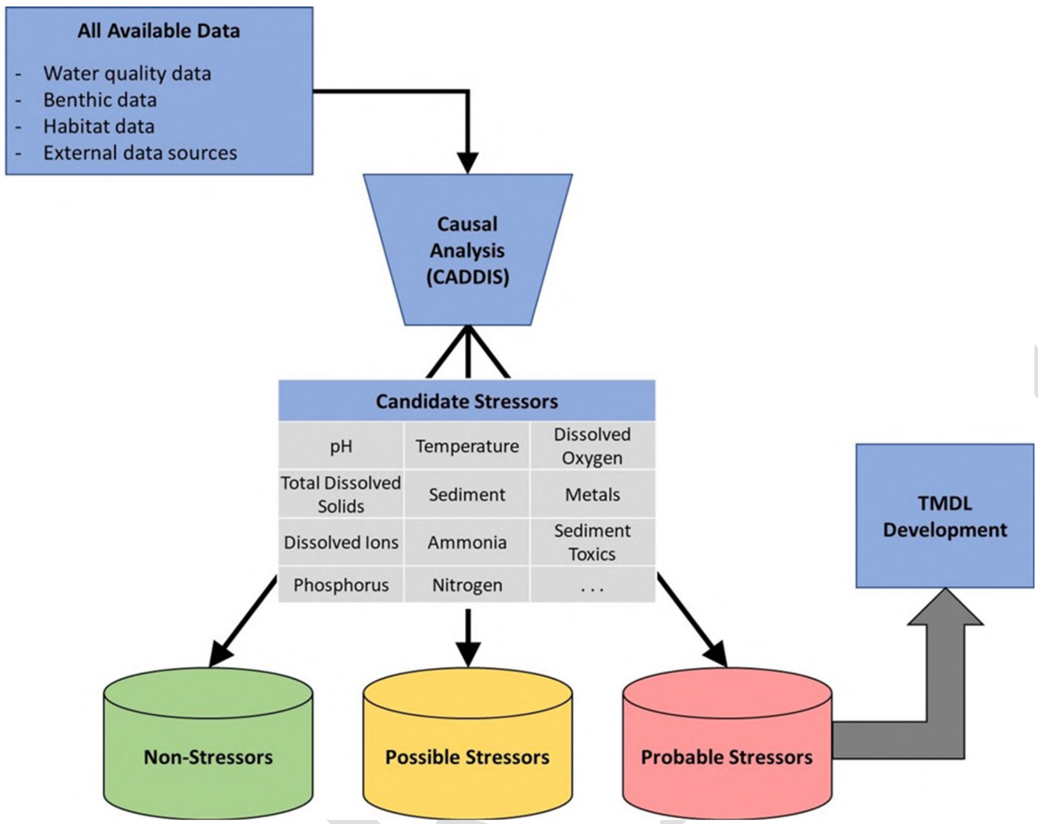

Figure 2. Stressor identification analysis process.

The first step in the stressor identification analysis is to list potential candidate stressors. JMU identified these from the listing information, monitoring data, scientific literature, and historic information. Potential stressors include both pollutants that can be targeted through TMDL development and additional contributing factors that can influence and stress benthic communities but that cannot be effectively targeted through TMDL development (Table 2).

The next step is to analyze all the available evidence to support or eliminate potential candidate stressors. In this step, JMU used the Causal Analysis/Diagnosis Decision Information System (CADDIS) (USEPA, 2018a). The CADDIS approach provides guidance on evaluating various lines of evidence to determine the cause of biological impairments. For this project, JMU used available physical, chemical, and biological data collected throughout the watershed, published water quality standards and threshold values, and available literature from other cases to investigate the potential causes of impairment in each of the impaired streams. Based on the weight of evidence supporting each potential candidate, stressors were then separated into the following categories: non-stressor(s), possible stressor(s), and probable stressor(s).

Table 2. Candidate stressors evaluated in the Goochland and Henrico Project.

Candidate Pollutants		
pH	Dissolved Sulfate	Ammonia
Dissolved Oxygen	Total Dissolved Solids	Dissolved Metals
Temperature	Suspended Solids	Sediment Toxics
Conductivity	Deposited Sediment	Sediment Metals
Dissolved Chloride	Organic Matter	Pesticides
Dissolved Sodium	Nitrogen	Polycyclic Aromatic Hydrocarbons (PAHs)
Dissolved Potassium	Phosphorus	Polychlorinated Biphenyls (PCBs)
Additional Contributing Factors		
Habitat	Hydrologic Alteration	Existing Dams and Impoundments
Underlying Geology and Soils	Current Land Use Practices	Anaerobic Decomposition in Connected Wetlands

Once a probable stressor(s) was identified, a conceptual model was developed to describe the causal pathways linking pollutant sources to the probable stressors and mechanisms of impairment. The pathways in the conceptual model were then evaluated to determine if the existing data support those mechanisms for producing the impairment.

2.0 BIOLOGICAL, PHYSICAL, AND CHEMICAL DATA

For the stressor identification analysis, JMU used biological, physical, and chemical data from 50 VDEQ monitoring stations within the Goochland and Henrico Project area (Table 3). Water quality data was collected from all these stations, and benthic data was collected from 13 of the stations. These VDEQ stations have been monitored for various parameters, lengths of time, and purposes. Table 3 shows the number of samples and the period of time over which individual stations were monitored. All data collected since 2000 was used in the stressor identification analysis.

For benthic monitoring stations, data include the taxonomic identification (family or genus level) and counts of the collected benthic macroinvertebrates, eight calculated benthic metrics, stream condition index scores (SCI), biological condition gradient scores, and visual habitat assessment scores. For water quality monitoring stations, data include results for various physical and chemical parameters. Across all the stations and sampling dates, 504 different water quality parameters were measured. In total, more than 22,000 individual data points were compiled and incorporated into the stressor identification analysis.

For some parameters and analyses, the impaired streams were compared to an unimpaired reference. Jones Creek (2-JOH004.04 and 2-JOH004.23) and Genito Creek (2-GEN001.75) were used as references for the Goochland and Henrico Project streams. Genito Creek was the closest reference, but Jones Creek provided the longest and most robust record of benthic and water quality monitoring. For these reasons, Genito Creek was used for qualitative benthic comparisons such as community composition and functional feeding group analysis, but Jones Creek was used for quantitative and statistical comparisons such as benthic metrics and water quality analysis.

Table 3. Benthic and water quality data used in the stressor analysis.

Watershed	Stream	Station	Benthic Sampling		Water Quality Sampling	
			Monitoring Period	Samples Collected	Monitoring Period	Samples Collected
Deep Run	Deep Run	2-DPR001.00			2001-2019	52
		2-DPR002.46			2000-2019	57
		2-DPR003.75	2014-2020	4	2014-2020	35
		2-DPR004.38			2002-2004	15
	Cabin Branch	2-CBN000.19			2002-2004	13
	Flat Branch	2-FLT001.00			2002-2004	15
	Stony Run	2-SNJ000.19	2014	2	2002-2020	52
		2-SNJ001.77	2006-2020	9	2006-2020	31
		2-SNJ001.88			2002-2020	31
		2-SNJ001.90			2007-2013	22
	Stony Run UT	2BXAM000.19			2012-2013	19
	Stony Run UT	2-XYT000.04	2006	2	2006-2020	19
		2-XYT000.10			2012-2019	31
		2-XYT000.29	2006-2019	3	2006-2020	20
		2-XYT000.83			2007-2019	32
Dover Creek	Dover Creek	2-DOV000.42			2003-2015	20
		2-DOV003.55	2017	2	2017	2
		2-DOV003.96			2017-2021	25
Upham Brook	Upham Brook	2-UPM000.26			2006-2020	39
		2-UPM001.35			2005-2018	47
		2-UPM002.08			2007	3
		2-UPM002.14			2007	3
		2-UPM002.29			2007	5

		2-UPM002.41			2006-2007	28
		2-UPM002.51			2007	10
		2-UPM003.12	2014	2	2014	2
		2-UPM003.53			2000-2018	40
		2-UPM005.26	2020	1	2006-2020	22
		2-UPM007.03			2003-2006	23
		2-UPM008.76			2006-2020	28
	Jordans Branch	2CJOP000.34	2012-2019	3	2012-2020	22
		2-JOP001.27			2006-2019	22
		2-JOP002.23			2013-2015	11
	North Run	2-NTR000.23	2011-2020	5	2005-2020	44
		2-NTR003.42			2003-2006	22
		2-NTR004.77			2006-2020	28
		2-NTR005.53	2002-2004	6	2002-2004	8
	Hungary Creek	2-HUN000.80			2006	12
		2-HUN002.11			2006	12
	Piney Branch	2-PBR000.12			2006	12
	Flippen Creek	2-FLP000.92			2006	12
	Horsepen Creek	2-HOH000.57			2006	12
	Trumpet Branch	2-TPT000.31			2006	12
	Upham Brook UTs	2CXAR000.57			2004-2006	28
		2CXXQ000.69			2015	5
		2-XXP000.23			2006-2014	24
		2-XXQ000.12			2006	12
Reference[1]	Jones Creek	2-JOH004.04			2009-2020	24
		2-JOH004.23	2005-2019	6	2005-2019	7
	Genito Creek	2-GEN000.69			2005-2019	33
		2-GEN001.75	2019	2	2019	2

[1] These streams/stations were used as a benthic and water quality reference.

2.1. Benthic Assessments

From 2002 to 2020, VDEQ conducted benthic assessments at 13 stations within the Goochland and Henrico Project area. Table 4 and Figure 3 show the average SCI scores for each station. SCI scores ranged from 24.5 to 43.0 among impaired streams, while the two reference stations had SCI values above the impairment threshold of 60.

Table 4. Benthic scores in the Goochland and Henrico Project area.

Watershed	Stream	Station	Years Sampled	Samples Collected	SCI Average	Assessment
Deep Run	Deep Run	2-DPR003.75	2014-2020	4	28.5	Impaired
	Stony Run	2-SNJ000.19	2014	2	33.7	Impaired
		2-SNJ001.77	2006-2020	9	31.6	Impaired
	Stony Run UT	2-XYT000.04	2006	2	28.7	Impaired
		2-XYT000.29	2006-2019	3	28.3	Impaired
Dover Creek	Dover Creek	2-DOV003.55	2017	2	43.0	Impaired
Upham Brook	Upham Brook	2-UPM003.12	2014	2	31.9	Impaired
		2-UPM005.26	2020	1	33.4	Impaired
	Jordans Branch	2CJOP000.34	2012-2020	4	24.5	Impaired
	North Run	2-NTR000.23	2011-2020	5	37.7	Impaired
		2-NTR005.53	2002-2004	6	34.8	Impaired
Reference	Jones Creek	2-JOH004.23	2005-2019	6	60.6	Unimpaired
	Genito Creek	2-GEN001.75	2019	2	61.5	Unimpaired

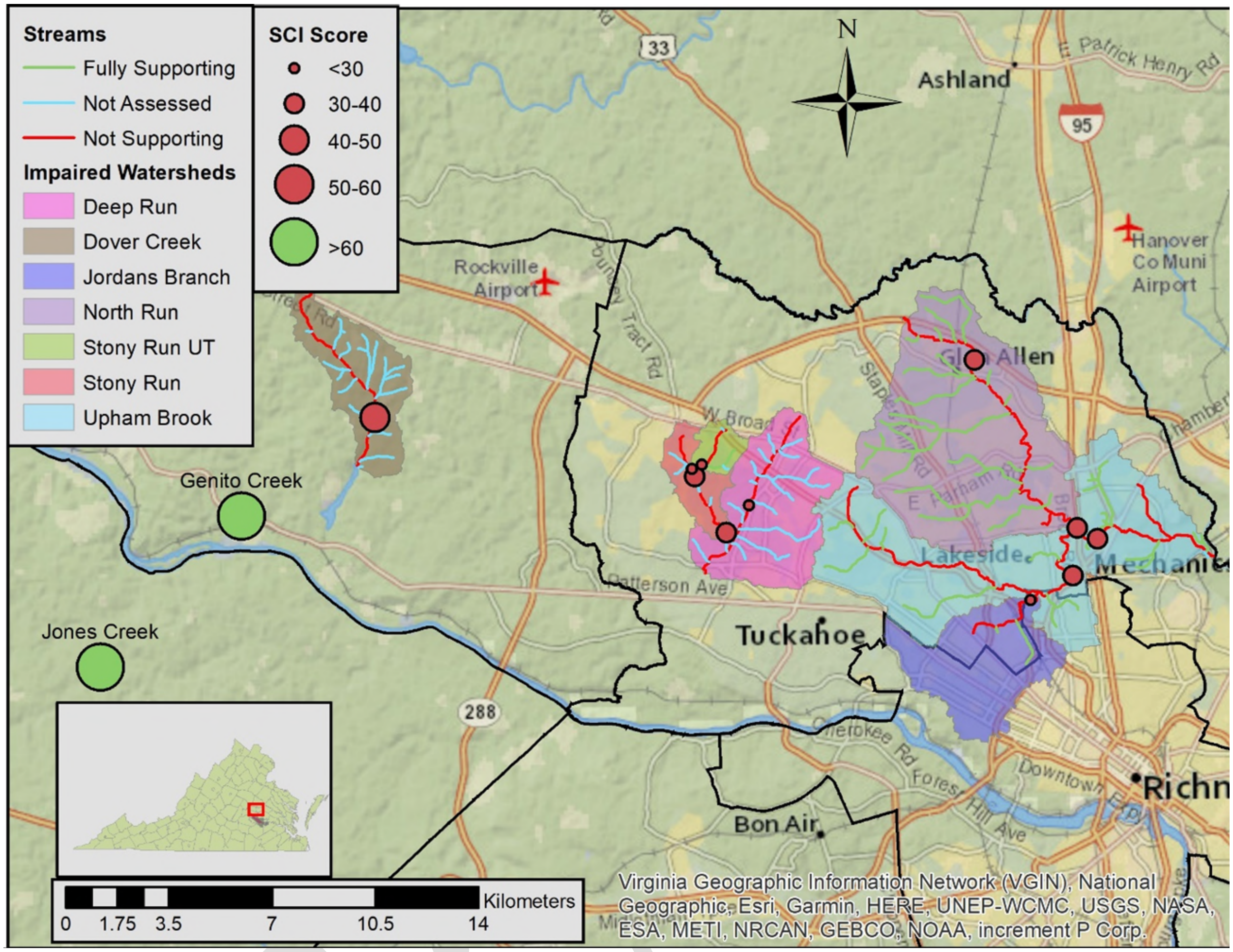

Figure 3. Benthic scores at monitoring stations within the Goochland and Henrico Project area.

2.1.1. Temporal and Seasonal Trends in Benthic Data

Figure 4 shows the temporal trends in benthic data from the Goochland and Henrico Project streams, and Figure 5 shows the seasonal trends.

- Deep Run – In Deep Run, SCI scores averaged 28.5 and ranged from 19.6 to 36.9, indicating a relatively severe impairment. With only four benthic samples collected from Deep Run, it is difficult to evaluate temporal trends, but the most recent results in 2019 and 2020 were lower than 2014 scores within the same season. This indicates that benthic health trends are not improving. Seasonally, it appears that fall SCI scores are higher than spring scores. Spring scores averaged 22.2, while fall scores averaged 34.8. This represents a 57% increase in SCI scores from spring to fall. This difference was statistically significant (t-test with unequal variance and alpha = 0.05) and may point to stressors that are related to spring high flow (such as nutrients or sediment) or stressors related to winter conditions (such as roadway deicing). Lower springtime scores could also be due to changing habitat or food availability, such as leaf packs that are prevalent in the fall but scarce in the spring.

- Dover Creek – Benthic SCI scores in Dover Creek averaged 43.0 and ranged from 39.6 to 46.3, indicating a moderate impairment. With only two benthic samples, it is difficult to evaluate temporal or seasonal trends, but the two available samples do show consistent impairment.
- Jordans Branch – Benthic SCI scores in Jordans Branch averaged 24.5 and ranged from 22.6 to 29.0, indicating relatively severe impairment. There was no apparent temporal trend in Jordans Branch, with SCI scores remaining consistent from 2012 to 2020. SCI scores were also relatively consistent across seasons with spring scores averaging 22.7 and fall scores averaging 23.4.
- North Run – Benthic SCI scores averaged 34.8 and ranged from 25.2 to 43.5 at the upstream station (2-NTR005.53). At the downstream station (2-NTR000.23), SCI scores averaged 37.7 and ranged from 29.5 to 51.0. This represents relative consistency in benthic health from the upstream to the downstream station. Scores were also relatively consistent over time from 2002 to 2020, with the exception of the most recent score of 51.0 in fall 2020. This could indicate the beginning of an increasing trend in benthic health, but it is too early to tell. Fall SCI scores (averaging 38.1) are slightly higher than spring scores (averaging 34.4), but the difference is modest and not statistically significant.
- Stony Run – Benthic SCI scores averaged 31.6 and ranged from 18.2 to 42.2 at the upstream station (2-SNJ001.77). At the downstream station (2-SNJ000.19), SCI scores averaged 33.7 and ranged from 31.1 to 36.3. This represents relative consistency in benthic health from the upstream to the downstream station. Scores were also relatively consistent over time from 2006 to 2020. The highest SCI score was from the most recent sample in fall 2020 (42.2), but it is too early to tell if this is the beginning of an increasing trend. Fall SCI scores (averaging 35.5) were modestly higher than spring scores (averaging 29.1), representing a 22% increase in SCI scores from spring to fall. While this difference was not statistically significantly different, it might point to stressors that are related to spring

high flow (such as nutrients or sediment) or stressors related to winter conditions (such as roadway deicing).

- Stony Run UT – Benthic SCI scores averaged 28.3 and ranged from 17.0 to 36.9 at the upstream station (2-XYT000.29). At the downstream station (2-XYT000.04), SCI scores averaged 28.7 and ranged from 26.4 to 31.0. This represents relative consistency in benthic health from the upstream to the downstream station. Scores were also relatively consistent over time from 2006 to 2019. Fall SCI scores (averaging 34.0) were modestly higher than spring scores (averaging 24.8), representing a 37% increase in SCI scores from spring to fall. While this difference was not statistically significantly different, it might point to stressors that are related to spring high flow (such as nutrients or sediment) or stressors related to winter conditions (such as roadway deicing).
- Upham Brook – Benthic SCI scores averaged 31.9 and ranged from 31.1 to 32.7 at the downstream station (2-UPM003.12). A single sample with a SCI score of 33.4 was collected from the upstream station (2-UPM005.26). Despite the limited data, benthic scores were relatively consistent from upstream to downstream. Scores were also relatively consistent over time from 2014 to 2020. There were also no apparent seasonal patterns in benthic health, with a spring score of 32.7 and a fall average of 32.2.

In summary, benthic scores in all streams were relatively consistent over time. In Deep Run, the most recent benthic score was the lowest on record, and in North Run and Stony Run the most recent scores were the highest on record, but it is too early to determine whether this represents the beginning of a trend. Three streams (Deep Run, Stony Run, and Stony Run UT) showed apparent seasonal trends with benthic SCI scores lower in the spring and higher in the fall. Differences were not statistically significant due to small datasets, but the apparent seasonal trend could point to stressors that are related to spring high flow (such as nutrients or sediment), stressors related to winter conditions (such as roadway deicing), or changing habitat or food availability.

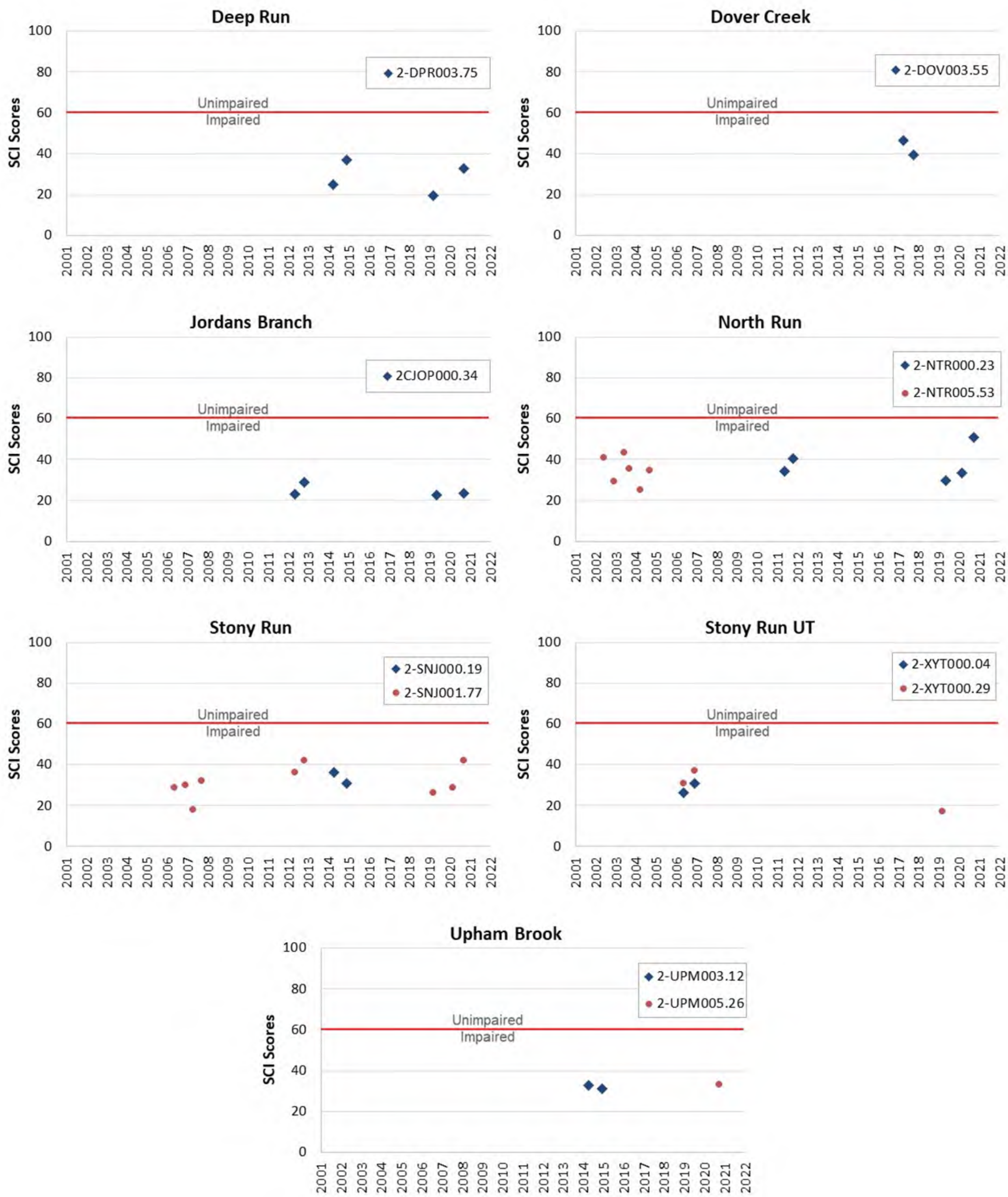

Figure 4. Temporal trends in benthic data for Goochland and Henrico Project streams.

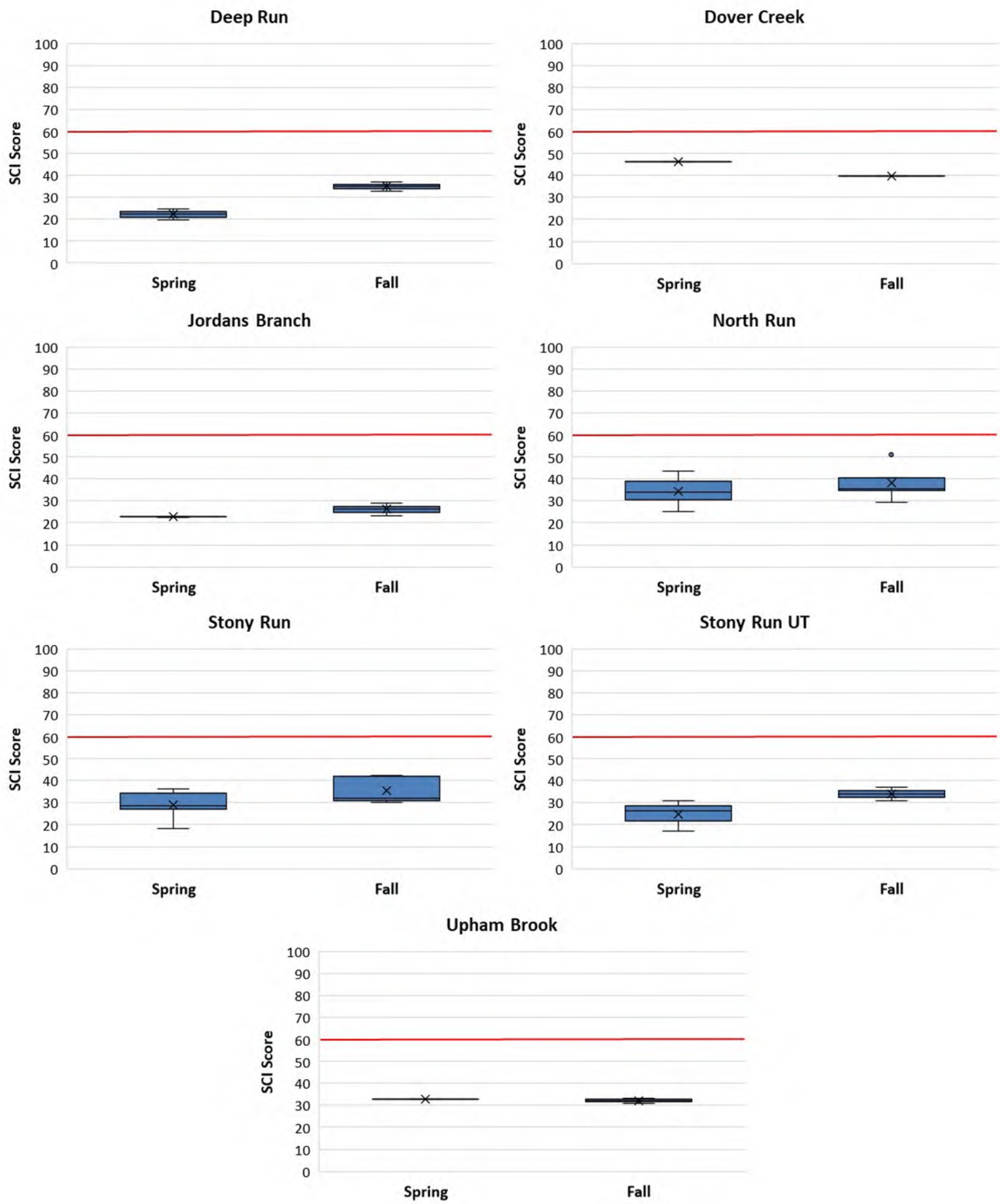

Figure 5. Seasonal trends in benthic data for Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The red line represents the Stream Condition Index threshold for impairment.

2.1.2. Analysis of Benthic Metrics

The Stream Condition Index (SCI) is a multi-metric index composed of eight individual metrics: species richness, Ephemeroptera Plecoptera Trichoptera richness (EPT richness), % Ephemeroptera (% Ephem), % Plecoptera and Trichoptera minus *Hydropsychidae* (% PT-Hydro), % *Chironomidae*, % scraper, % 2 dominant, and the modified family biotic index (MFBI). Assessing these metrics individually can provide clues to potential stressors, since different stressors may impact the benthic community in different ways. To evaluate individual metrics, impaired streams were compared to an unimpaired regional reference, Jones Creek (Figure 6). For each impaired stream, average scores for each metric were compared to the reference using a t-test with unequal variances (alpha = 0.05).

- <u>Deep Run</u> – SCI scores were very low in Deep Run (averaging 28.5), and all the individual metrics were significantly lower ($p<0.05$) than the reference. This is indicative of a severely impaired stream. The lowest scores (those below 25%) were for EPT richness, % Ephem, %PT-Hydro, and % scrapers. These metrics indicate a lack of sensitive species in Deep Run. Only 4 EPT taxa were observed in Deep Run, compared to 12 in the reference. No Plecoptera were found in any of the samples, and on two occasions, no Ephemeroptera taxa were observed. The % scrapers score was also very low, averaging <11% compared to 30% in the reference. This could indicate excess sediment as a stressor, because as sediment covers rocks, the habitat for scrapers is reduced.

- <u>Dover Creek</u> – In Dover Creek, SCI scores were moderately impaired (averaging 43.0) and only two metrics, the % PT-Hydro and % 2 dominant, were significantly lower ($p<0.05$) than the reference. There were only three Plecoptera taxa and zero non-*Hydropsychidae* Trichoptera taxa in Dover Creek, while there were 12 Plecoptera and 15 non-*Hydropsychidae* Trichoptera taxa in the reference. This indicates a general lack of sensitive taxa. The % 2 dominant score in Dover Creek was 51%, compared to 68% in the reference. On the two sampling dates in Dover Creek, the two most dominant taxa were *Chironomidae* and either the mayfly *Plauditus* or the black fly *Simulium*.

- <u>Jordans Branch</u> – Like Deep Run, SCI scores were very low in Jordans Branch (averaging 24.5), and all the individual metrics were significantly lower ($p<0.05$) than the reference. This is indicative of a severely impaired stream. The lowest scores (those below 25%) were for EPT richness, % Ephem, % PT-Hydro, and % scrapers. These metrics indicate a lack of sensitive species in Jordans Branch. Only three EPT taxa were observed in Jordans Branch, compared to 12 in the reference. No Plecoptera were found in any of the samples, and on two occasions, no Ephemeroptera taxa were observed. The % scrapers score was also very low, averaging 4% compared to 30% in the reference. This could indicate excess sediment as a stressor, because as sediment covers rocks, the habitat for scrapers is reduced.

- North Run – In North Run, all benthic metrics were significantly lower ($p<0.05$) than the reference except for % *Chironomidae* and % scraper scores. The lowest scores (those below 25%) were for EPT richness, % Ephem, and % PT-Hydro. These metrics indicate a lack of sensitive species in North Run, but conditions were not as severe as in Deep Run and Jordans Branch. Up to six EPT taxa were observed in North Run, compared to 12 in the reference. No Plecoptera were found in any of the samples, but Ephemeroptera were found in all but one sample.
- Stony Run – Like North Run, all benthic metrics were significantly lower ($p<0.05$) in Stony Run than in the reference except for % *Chironomidae* and % scraper scores. The lowest scores (those below 25%) were for EPT richness, % Ephem, and % PT-Hydro. These metrics indicate a lack of sensitive species in Stony Run. Only three EPT taxa were observed in Stony Run, compared to 12 in the reference. No Plecoptera were found in any of the samples, and no Ephemeroptera were found in more than 50% of samples.
- Stony Run UT – Like North Run and Stony Run, all benthic metrics were significantly lower ($p<0.05$) in Stony Run UT than the reference except for % *Chironomidae* and % scraper scores. The lowest scores (those below 25%) were for EPT richness, % Ephem, and % PT-Hydro. These metrics indicate a lack of sensitive species in Stony Run UT. Only two EPT taxa were observed in Stony Run UT, compared to 12 in the reference. No Plecoptera were found in any of the samples, and only one Ephemeroptera taxa was found in one sample from the upstream station.
- Upham Brook – Like North Run, Stony Run, and Stony Run UT, all benthic metrics were significantly lower ($p<0.05$) in Upham Brook than the reference except for % *Chironomidae* and % scraper scores. The lowest scores (those below 25%) were for EPT richness, % Ephem, % PT-Hydro, and % scrapers, although the % scrapers score was not

statistically different from the reference. These metrics indicate a lack of sensitive species in Upham Brook. Only three EPT taxa were observed in Upham Brook, compared to 12 in the reference. No Plecoptera were found in any of the samples, and only a single Ephemeroptera taxa was found in each sample.

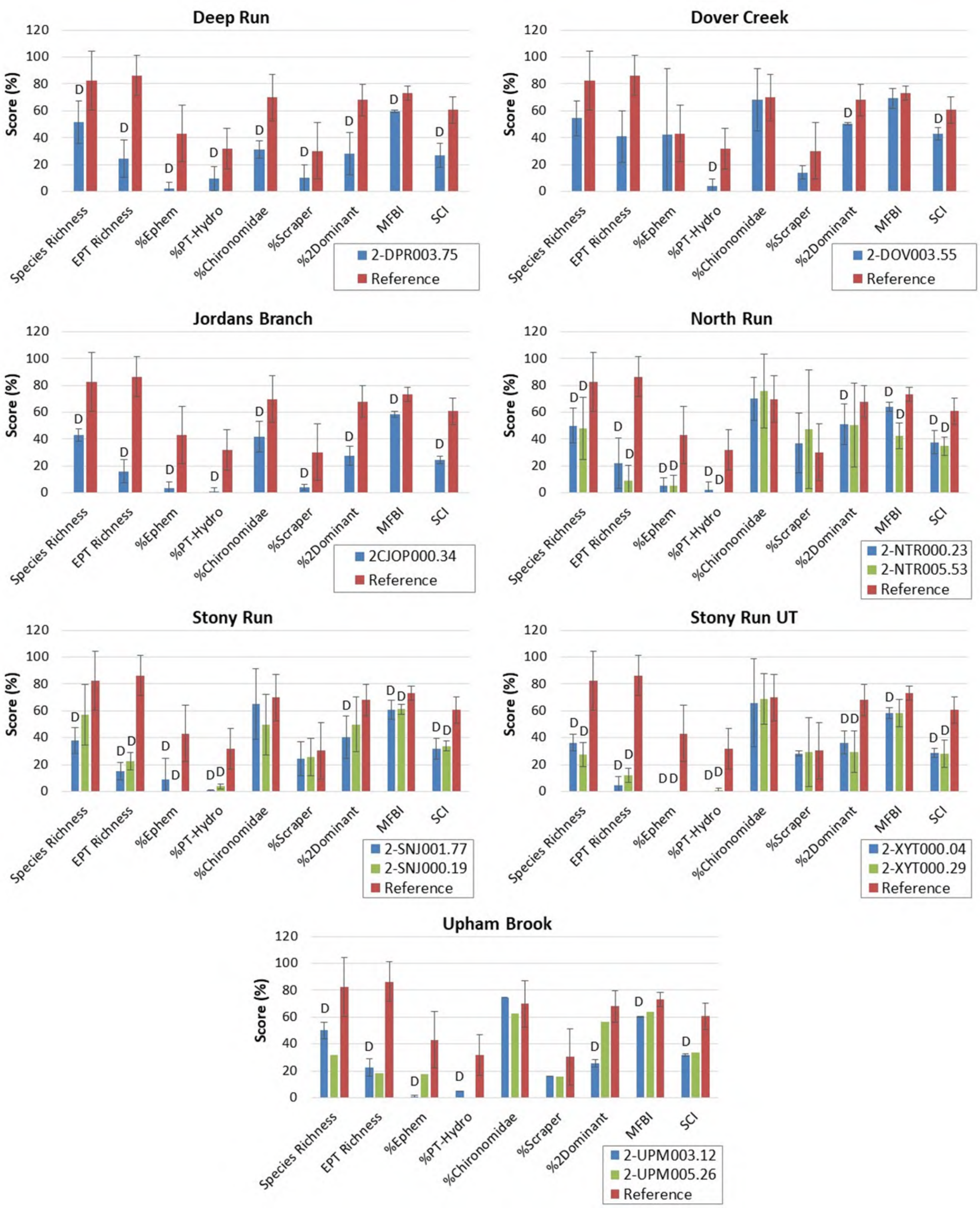

Figure 6. Individual metric scores comprising the stream condition index (SCI) in Goochland and Henrico Project streams. Metrics with a "D" are statistically lower than the Jones Creek reference site.

2.1.3. Analysis of Community Composition

The taxonomic composition of the benthic communities was analyzed to identify shifts in composition at impaired stations that might provide clues to sources or mechanisms of impairment. Figure 7 compares the taxonomic composition in Goochland and Henrico Project streams to an unimpaired local reference stream (Genito Creek). In the reference stream, taxonomic composition is relatively balanced, with no more than 30% of the community represented by a single taxonomic group. The community was also represented by a high percentage of sensitive Ephemeroptera (30%) and Plecoptera (27%) taxa. In impaired streams, the community composition is often less balanced and shifted towards less sensitive taxa.

- Deep Run – Taxonomic composition in Deep Run was heavily skewed towards Diptera, which represented 71% of the community. Sensitive EPT taxa represented less than 5% of the community combined. The Diptera present in Deep Run were predominantly midges (*Chironomidae*), which could be indicative of nutrient enrichment or excess sediment. Lawrence and Gressens (2011) showed that Chironomid abundance correlated with increased nutrient enrichment in urban and rural streams. Bjornn *et al.* (1977) demonstrated in artificial mesocosm experiments that increases in fine sediment significantly reduced EPT taxa but were tolerated by Chironomid taxa. This shift in community composition indicates that fine sediment and deposited organic matter may be stressors in Deep Run.
- Dover Creek – The taxonomic composition of Dover Creek was also dominated by Diptera, but the more sensitive Ephemeroptera were relatively well-represented at 24% of the population. Like Deep Run, the Diptera in Dover Creek were mostly *Chironomidae* (63%), but the black fly, *Simulium*, was also dominant (31%). As described above, the dominance of *Chironomidae* could be indicative of excess sediment or organic matter enrichment. The black fly larvae, *Simulium*, can be common in fast flowing water, and due to their filter feeding nature, their presence in high numbers can be an indicator of moderate organic or nutrient enrichment (Voshell, 2002).
- Jordans Branch – The taxonomic composition of Jordans Branch was dominated by Diptera (55%), but the "Other" category also contributed 31%. Sensitive EPT taxa represented only 2.4% of the population. The predominant Diptera taxon was *Chironomidae*, and as explained above, this could be an indicator of excess sediment or organic matter

enrichment. The predominant taxon in the “Other” category were amphipods in the *Gammaridae* family or more specifically the genus *Gammarus*. MacNeil et al. (1997) described Gammarus as quickly colonizing and thriving in disturbance prone environments. Jordans Branch has very high imperviousness in the watershed (54%), so frequent flushing and scouring from high flow storm events could produce disturbance conditions within which *Gammarus* could quickly recolonize and thrive.

- North Run – Benthic community composition in North Run was assessed at two locations (2-NTR000.23 and 2-NTR005.53). At the downstream location (2-NTR000.23), the community was dominated by Diptera (34%) and “Other” (23%). Sensitive EPT taxa represented 4.7% of the community. The predominant Diptera taxon was *Chironomidae*, and as explained above, this could be an indicator of excess sediment or organic matter enrichment. The predominant taxon in the “Other” category was the amphipod *Gammarus*, which is common in disturbance prone environments. Imperviousness in the lower North Run watershed was relatively high (31%), and frequent flushing and scouring from high flow storm events could produce disturbance conditions within which *Gammarus* could quickly recolonize and thrive. The community composition at the upstream North Run station (2-NTR005.53) was relatively similar, with 33% of the community represented by Diptera (primarily *Chironomidae*) and 4.7% represented by EPT taxa, however, “Other” organisms represented a larger percentage of the community (56%). At the upstream station, very few *Gammarus* were found, and the “Other” category was primarily represented by snails and damselflies in the family *Coenagrionidae*. There is significantly less impervious area in the upper watershed (18% compared to 31% in the lower watershed), so the disturbance regime suggested as the cause of high *Gammarus* populations in the lower watershed might not be present in the upper watershed. The snail and damselfly populations present at the upstream location prefer slower moving water with ample vegetation. There is a significant wetland presence near this site, which explains the dominance of these species. In an analysis of land cover within the watershed draining to this site, 14% of land was classified as “Other.” Overlaying the land cover analysis with the National Wetland Inventory, all of this 14% is accounted for by wetlands, and the most predominant wetland type was freshwater forested/shrub wetlands. This wetland environment explains the predominance of snail and damselflies at the upper North Run station.

- Stony Run – Benthic community composition in Stony Run was assessed at two locations (2-SNJ000.19 and 2-SNJ001.77). At the downstream location (2-SNJ000.19), the community was dominated by Diptera (65%) of the family *Chironomidae,* indicating possible excess sediment or organic matter enrichment. EPT taxa represented less than 1% of the community at this location. At the upstream location (2-SNJ001.77), Diptera of the family *Chironomidae* were still the predominate taxon, but EPT representation was higher (6.3%) and *Hydropsychidae* (27%) and Oligochaeta/Tubificida worms (15%) represented high proportions. *Hydropsychidae* are net-spinning caddisflies that filter organic matter from the water with their nets. The dominance of *Hydropsychidae* can be an indicator of excess sediment, nutrient, or organic matter enrichment in the water column. Similarly, the Oligochaeta/Tubificida taxa thrive in fine sediment rich in organic matter (Voshell, 2002). These shifts in community composition indicate that fine sediment, deposited organic matter, and nutrients may be stressors in Stony Run.

- Stony Run UT – Benthic community composition in Stony Run UT was assessed at two locations (2-XYT000.04 and 2-XYT000.29). Both locations were dominated by Diptera of the family *Chironomidae* (32-36%) and *Hydropsychidae* (33%). Oligochaeta/Tubificida worms also represented a significant proportion of the population (14-20%). EPT taxa were less than 1% of both populations. As described above, the predominance of *Chironomidae*, *Hydropsychidae*, and Oligochaeta/Tubificida all indicate the presence of fine sediment, deposited organic matter, and potentially excess nutrients.

- Upham Brook – Benthic community composition in Upham Brook was assessed at two locations (2-UPM003.12 and 2-UPM005.26). At the downstream location, the community was dominated by *Gammarus* (59%) in the "Other" category and Diptera of the family *Chironomidae* (25%). EPT taxa represented only 2.4% of the community. At the upstream location, the community was dominated by Diptera of the family *Chironomidae* (39%), *Gammarus* (24%) in the "Other" category, and *Hydropsychidae* (17%). EPT taxa represented 8.7% of the community at the upstream station. As described above, the predominance of Gammarus may indicate a disturbance-prone environment from periodic flushing and scouring. Imperviousness in the Upham Brook watershed ranged from 38-45%. The predominance of *Chironomidae* and *Hydropsychidae* suggest conditions of suspended and deposited organic rich sediment and excess nutrients.

In summary, all of the impaired streams were dominated to some extent by Diptera of the family *Chironomidae*. The Genito Creek reference consisted of 28% Diptera, while impaired streams ranged from 32-71% Diptera. The only exception was station 2-UPM003.12, which contained only 25% Diptera. Stony Run and Stony Run UT were also dominated by *Hydropsychidae* and Oligochaeta/Tubificida worms. The predominance of the net-spinning caddisfly, *Hydropsychidae*, which catches food in its web, indicates excess suspended sediment, organic matter, and potentially nutrients in the water column. The predominance of *Chironomidae* and Oligochaeta/Tubificida indicates excess deposited sediment, since these organisms feed on deposited sediments. In addition, streams in the Upham Brook watershed, including Jordans Branch, North Run, and Upham Brook were dominated by the amphipod *Gammarus*, which thrives in disturbance-prone environments. Their presence may indicate hydrologic modification in this watershed from impervious runoff that produces flushing and scouring effects.

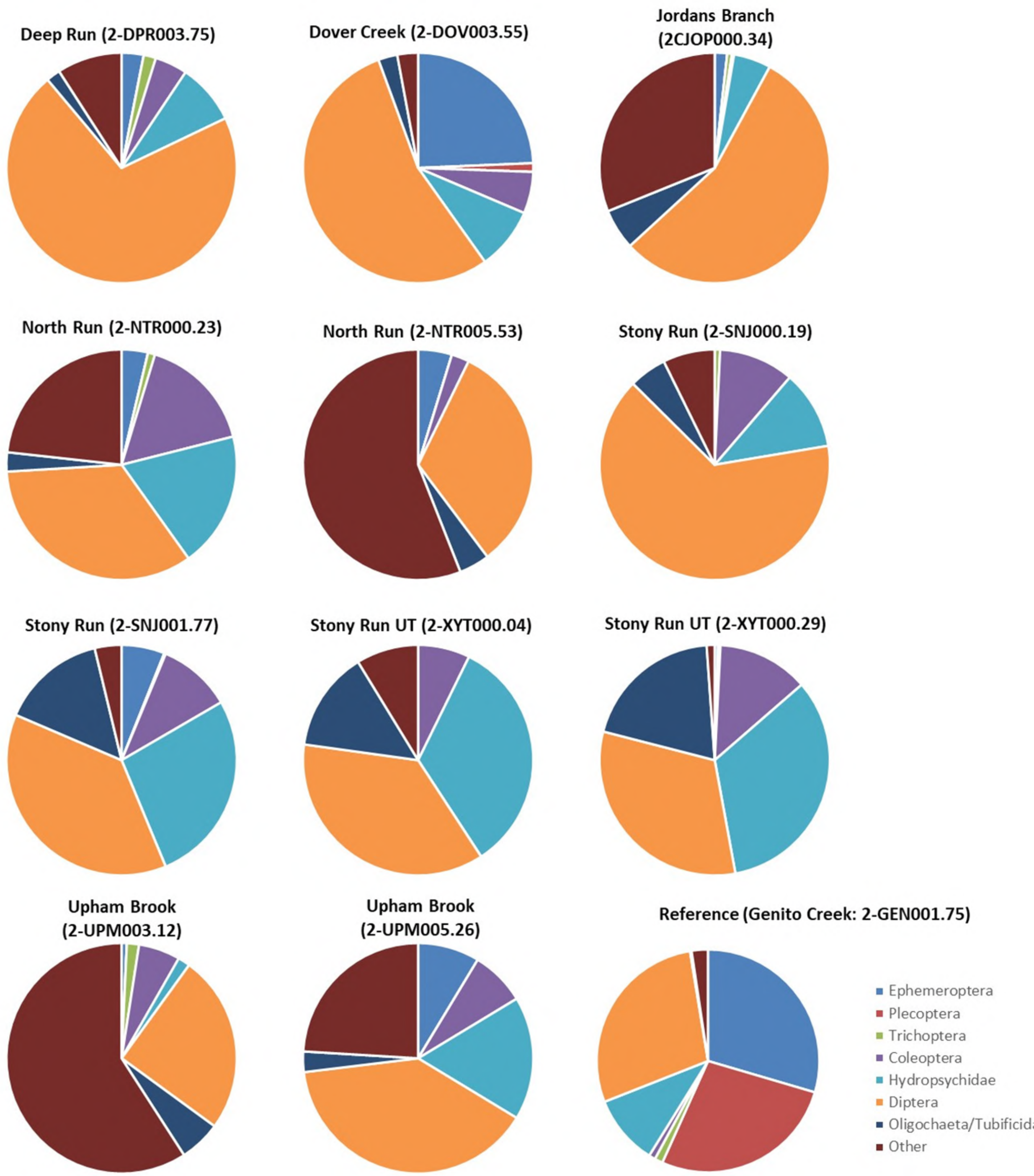

Figure 7. Taxonomic composition of Goochland and Henrico Project streams compared to the Genito Creek reference.

2.1.4. Biological Condition Gradient Analysis

In 2019, Tetra Tech worked with mid-Atlantic region states (including Virginia) to develop a conceptual model of environmental condition called the Biological Condition Gradient (BCG). The BCG model describes environmental conditions by analyzing patterns of pollution tolerance among fish and macroinvertebrates present (Tetra Tech, 2019). The model defined six attributes related to pollution tolerance and scored these attributes across 560 macroinvertebrate taxa for 10 specific stressors (Table 5). Attributes were scored for each taxa and stressor combination based on statistical analysis of regional data and expert consensus. The result is a database that can be useful for stressor analysis.

Using attribute data from the BCG model, taxa present at each of the impaired Goochland and Henrico Project streams were assigned attribute scores for each stressor. The average scores and the scores for predominant species were evaluated for each stressor to identify potential stressors that might be indicative of the pattern of organism tolerance observed. Table 6 shows the BCG scores for the three most prevalent taxa at each of the impaired monitoring stations. Attribute scores of 5 indicate tolerant taxa that would be expected to increase in number when the respective stressor is present. Some taxa, like *Gammaridae*, are relatively tolerant to a wide range of stressors and don't show much differentiation with respect to stressor identification. Others, however, show better differentiation and can be indicators of specific stressors.

Table 5. Biological condition gradient attributes and stressors evaluated.

Attribute	Explanation	Stressors Evaluated
I	Historically documented, sensitive, long-lived or regionally endemic taxa	Dissolved oxygen Acidity
II	Highly sensitive taxa	Alkalinity
III	Intermediate sensitive taxa	Specific Conductivity
IV	Intermediate tolerant taxa	Chloride
V	Tolerant taxa	Sulfate
VI	Non-native taxa	Total Nitrogen and Phosphorus
		Total Habitat Relative Bed Stability %Imperviousness

Across Goochland and Henrico Project streams, BCG analysis of predominant taxa indicated a wide variety of potential stressors. In Deep Run, predominant taxa indicated conductivity, sulfate, nutrients, or imperviousness as potential stressors. In Dover Creek, predominant taxa indicated sulfate and nutrients as potential stressors. In Jordans Branch, predominant taxa indicated dissolved oxygen (DO), conductivity, and habitat as potential stressors. All of the BCG stressor categories except for acidity, chloride, and sulfate were identified by predominant taxa in North Run. In Stony Run, conductivity, sulfate, nutrients, habitat, and imperviousness were all identified as potential stressors by predominant taxa. The same stressors, in addition to relative bed stability, were identified in Stony Run UT. In Upham Brook, predominant taxa indicated DO, conductivity, nutrients, habitat, and imperviousness as potential stressors.

In addition to analyzing the BCG attribute scores for the top three dominant taxa in each impaired stream, BCG attribute scores of all present taxa were averaged to calculate mean scores for each stressor in each stream. Those scores were then ranked to identify the stressors with the highest scores (Table 7). These represent the stressors that have the greatest likelihood of impact on each stream based on the taxa present and BCG attribute scores for those taxa. For all impaired streams except for Dover Creek and the upstream station on North Run, % imperviousness was ranked as the top stressor. In Dover Creek, nutrients were ranked as the top stressor, and at the upstream North Run station, DO was ranked as the top stressor. These results are remarkably consistent with other lines of evidence for stressors in these streams. Those streams that had % imperviousness ranked as the top stressor all had more than 31% imperviousness in the watershed. Brabec *et al.* (2002), who reviewed the biological impacts of watershed imperviousness, found that fish and macroinvertebrate diversity decreased when watersheds exceeded 3.6 to 15% imperviousness, and all of the Goochland and Henrico Project streams except for Dover Creek exceed this range by more than double. In Dover Creek, where BCG analysis ranked nutrients as the top stressor, phosphorus levels were higher than in any of the other streams. In the upstream North Run station, where BCG analysis ranked DO as the top stressor, diurnal DO measurements were the lowest of any Goochland and Henrico Project stream.

Table 6. Biological condition gradient scores for three most prevalent taxa at each impaired station.

Stream	Station	Predominant Taxa	Diss. Oxy.	Acidity	Alkalinity	Spec. Cond.	Chloride	Sulfate	TN/TP	Total Habitat	RBS	% Imp.
Deep Run	2-DPR003.75	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Simulium	4	4	4	4	3	5	5	4	4	4
		Cheumatopsyche	4	3	4	5	4	4	5	4	4	5
Dover Creek	2-DOV003.55	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Plauditus	3	3	3	4	3	4	4	3	4	3
		Simulium	4	4	4	4	3	5	5	4	4	4
Jordans Branch	2CJOP000.34	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Gammaridae	4	4	4	4	4	4	4	4	4	4
		Gammarus	5	4	4	5	4	4	4	5		4
North Run	2-NTR000.23	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Gammarus	5	4	4	5	4	4	4	5		4
		Cheumatopsyche	4	3	4	5	4	4	5	4	4	5
	2-NTR005.53	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Physidae	5	4	5	5	4	3	5	5	5	5
		Coenagrionidae	5	4	3	4	4	3	4	4	4	5
Stony Run	2-SNJ000.19	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Simulium	4	4	4	4	3	5	5	4	4	4
		Stenelmis	4	4	4	5	4	4	4	5	4	5
	2-SNJ001.77	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Hydropsychidae	3	3	4	4	3	4	4	4	4	4
		Hydropsyche	3	3		5	4	5	5	4	4	5
Stony Run UT	2-XYT000.04	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Hydropsychidae	3	3	4	4	3	4	4	4	4	4
		Oligochaeta	4	4	3	5	4	4	5	5	5	5
	2-XYT000.29	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Hydropsychidae	3	3	4	4	3	4	4	4	4	4
		Naididae										
Upham Brook	2-UPM003.12	Gammaridae	4	4	4	4	4	4	4	4	4	4
		Gammarus	5	4	4	5	4	4	4	5		4
		Chironomidae	4	4	4	4	4	4	4	4	4	4
	2-UPM005.26	Chironomidae	4	4	4	4	4	4	4	4	4	4
		Gammarus	5	4	4	5	4	4	4	5		4
		Cheumatopsyche	4	3	4	5	4	4	5	4	4	5

Table 7. Rank of average biological condition gradient scores for each stressor in each impaired stream.

Stream	Station	Diss. Oxy.	Acidity	Alkalinity	Spec. Cond.	Chloride	Sulfate	TN/TP	Total Habitat	RBS	% Imp.
Deep Run	2-DPR003.75	7	9	10	4	8	6	2	3	5	1
Dover Creek	2-DOV003.55	10	7	9	4	8	3	1	6	2	4
Jordans Branch	2CJOP000.34	6	9	10	4	8	7	2	3	5	1
North Run	2-NTR000.23	6	10	9	3	8	7	2	4	5	1
	2-NTR005.53	1	7	9	6	8	10	4	3	5	2
Stony Run	2-SNJ000.19	7	9	10	3	8	6	2	4	5	1
	2-SNJ001.77	8	10	9	3	7	6	2	4	5	1
Stony Run UT	2-XYT000.04	6	7	10	5	9	8	4	3	1	1
	2-XYT000.29	8	10	9	3	7	6	2	4	5	1
Upham Brook	2-UPM003.12	6	9	10	4	8	7	2	3	5	1
	2-UPM005.26	9	10	8	1	7	4	3	4	6	1

2.1.5. Analysis of Functional Feeding Groups

The composition of functional feeding groups comprising the benthic community was also analyzed to identify shifts in composition at impaired stations that might provide clues to sources or mechanisms of impairment. Figure 8 shows the composition of functional feeding groups within the Goochland and Henrico Project streams in comparison to a local reference stream (Genito Creek). Two distinct patterns emerged from this analysis. In each of the impaired streams, communities shifted to a higher percentage of collectors, while shredders and predators decreased. Collectors increased by 25% in Deep Run, 17% in Dover Creek, 42% in Jordans Branch, 14% in North Run, 14% in Stony Run, 10% in Stony Run UT, and 44% in Upham Brook. This shift in functional feeding group is indicative of increased deposited sediment and deposited organic material. As the amount of deposited organic matter increases, the niche of macroinvertebrates that collect their food from bottom deposits (collectors) expands. To a lesser extent, filterers also increased in most of these streams. Filterers increased by 2% in Deep Run, 13% in Dover Creek, 9% in North Run, 11% in Stony Run, and 21% in Stony Run UT. An increase in filterers can also indicate an increase in suspended sediment and organic matter. As particulate matter in the water column increases, more food is available for filtering organisms and that feeding niche expands.

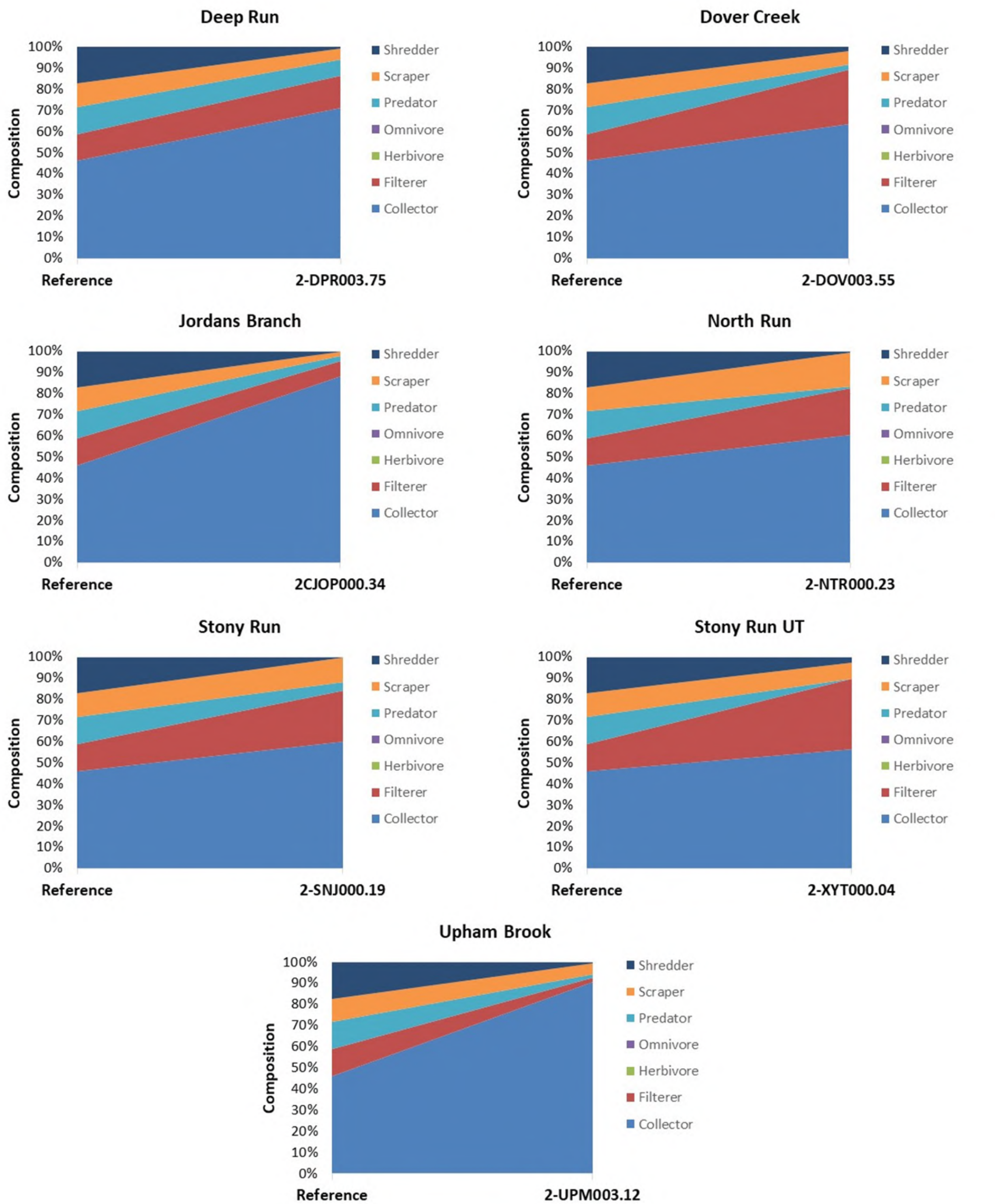

Figure 8. Functional feeding group composition in Goochland and Henrico Project streams compared to the Genito Creek reference.

2.2. Habitat Assessment

As part of the Rapid Bioassessment Protocol, a visual habitat assessment is performed at the time of each benthic sample collection. This assessment entails scoring each of a series of habitat components from 0 to 20. These habitat components include epifaunal substrate, embeddedness (or pool substrate for low gradient streams), velocity (or pool variability for low gradient streams), sediment, flow, channel alteration, riffles (or sinuosity for low gradient streams), bank stability, bank vegetation, and riparian vegetation. The individual scores for each of these measures are then added for a total habitat score. Figure 9 compares the total habitat scores in the Goochland and Henrico Project streams with those from an unimpaired regional reference stream (Jones Creek). While total habitat scores averaged 137 in the reference, scores at impaired stations ranged from 105 in Upham Brook (2-UPM005.26) to 138 in North Run (2-NTR005.53). Total habitat scores were statistically lower ($p<0.05$ in a one-tailed t-test with unequal variance) than the reference in Jordans Branch (2CJOP000.34), North Run (2-NTR000.23), Stony Run (2-SNJ000.19), and Upham Brook (2-UPM003.12).

Based on VDEQ's analysis of probabilistic monitoring data (VDEQ, 2017), the colors shown in Figure 9 represent the probability of habitat being a stressor on the aquatic community. Stations in each of the impaired streams except for Deep Run fell in the medium probability range for stressor effects. This indicates that habitat could be a stressor in these streams. Average total habitat scores in Deep Run fell in the low probability category, but scores were relatively variable over time at this station. Older scores from 2014 averaged 145, but more recent scores from 2019 and 2020 averaged much lower at 118. This may indicate degrading habitat conditions in Deep Run as well as the other Goochland and Henrico Project streams.

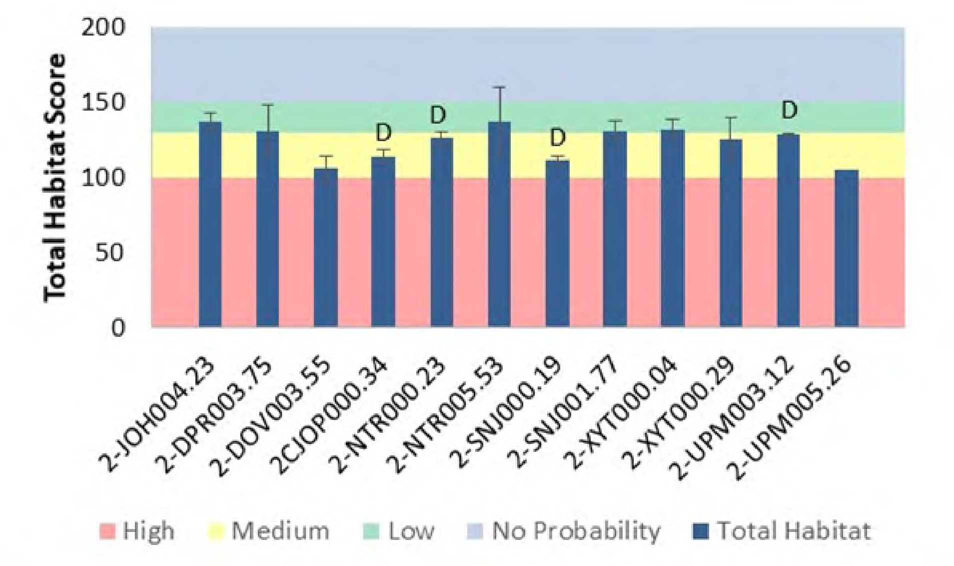

Figure 9. Total habitat scores for Goochland and Henrico Project streams. Streams with a "D" have statistically lower habitat scores than the Jones Creek reference site. Colors represent the probability that data within that range would be responsible for causing stress.

Figure 10 compares the individual habitat metrics in each impaired stream with metric scores from a regional reference station (Jones Creek). Statistical differences were determined using a one-tailed t-test with unequal variances and alpha = 0.05. All streams had one or more habitat metrics that were significantly lower than the reference. Metrics that indicate degraded instream habitat conditions (substrate, embeddedness, or sediment) were consistently decreased in impaired streams. All streams were significantly lower in substrate and embeddedness scores than the reference, and all but three (Deep Run, North Run, and Upham Brook) were significantly lower in sediment scores. These observations of degraded instream habitat conditions could indicate excess sediment as a stressor.

Some streams had lower scores for metrics that indicate degraded bank conditions (bank stability, channel alteration, bank vegetation, or riparian vegetation). All streams except for Jordans Branch had channel alteration scores significantly lower than the reference, but only Dover Creek had bank or bank vegetation scores that were statistically lower. This indicates that banks were relatively stable and vegetated in most of the impaired streams. The width of the riparian vegetation in North Run, Stony Run, and Stony Run UT was significantly lower than in the reference.

Most streams also had lower scores for metrics that indicate degraded hydrologic conditions (flow, riffles, or velocity/depth). All streams except for Dover Creek and North Run had lower velocity/pool variability scores than the reference. Dover Creek had lower flow scores, and North Run had lower riffle/sinuosity scores. This indicates that instream hydrologic conditions do not provide a diversity of habitats for aquatic life. This can be exacerbated by channel alterations, sediment deposition, and watershed changes such as imperviousness that reduce baseline flow.

In summary, while a different combination of metrics was reduced across the different stations, all impaired stations had reductions in several habitat metrics that included those related to instream sediment conditions, bank or channel condition, and hydrologic condition.

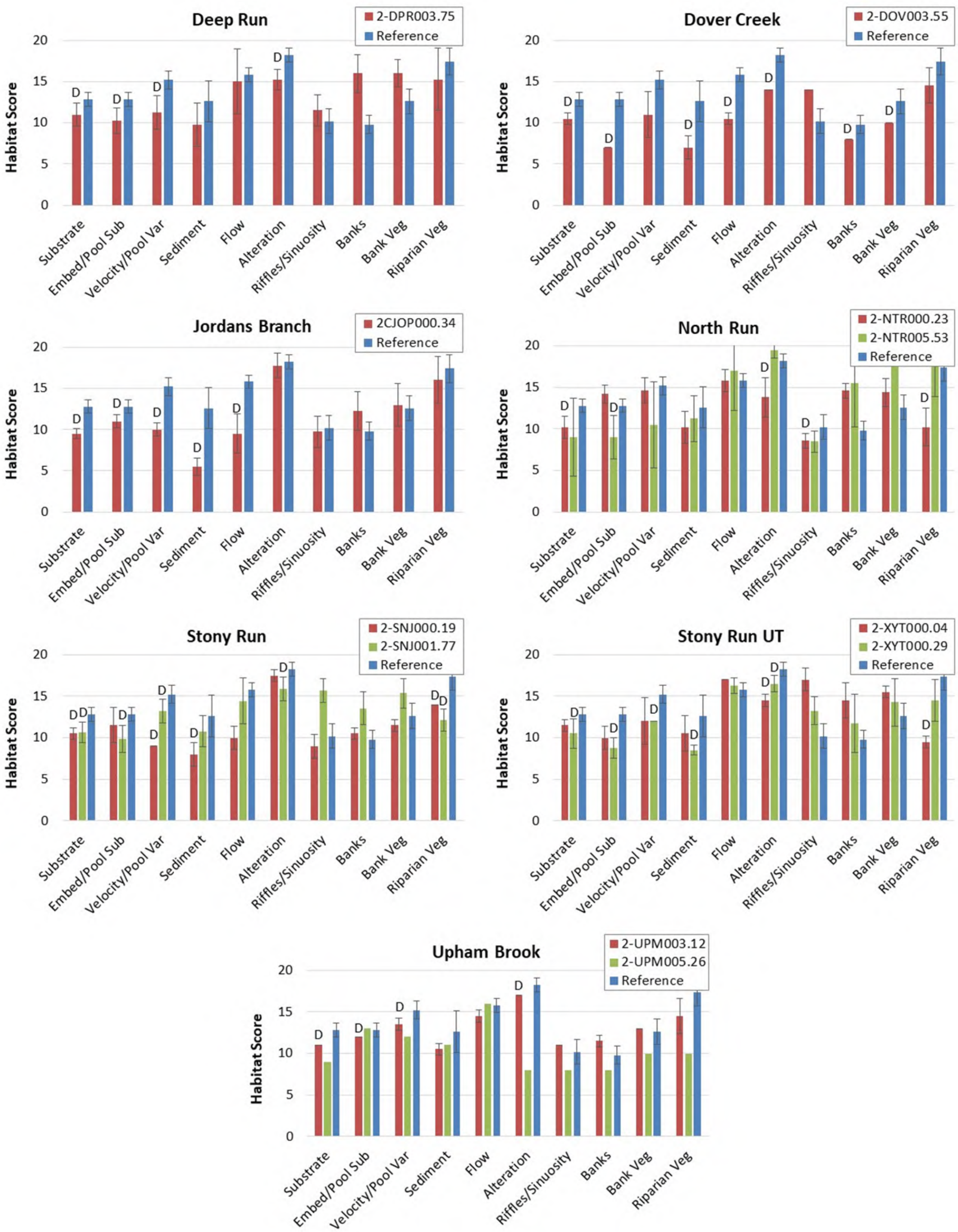

Figure 10. Habitat metric scores for the Goochland and Henrico Project streams. Metrics with a "D" are statistically lower than the Jones Creek reference site.

As a part of TMDL monitoring, VDEQ conducted a detailed physical habitat assessment of the impaired streams according to EPA methods for *Quantifying Physical Habitat in Wadeable Streams* (Kaufmann *et al*., 1999). This analysis involved the measurement of channel dimensions and substrate composition at numerous transects within a 150 to 800-m stream reach surrounding the benthic monitoring station. The outcome of this analysis is the calculation of a log relative bed stability index (LRBS). The LRBS is the ratio between the observed size distribution of in-stream sediments and the predicted sediment size distribution based on bankfull depth. LRBS values near zero indicate that the stream is stable. Large negative values indicate that the stream is unstable and depositing excess sediment. Large positive numbers, while less common, indicate that the stream is unstable and sediment starved. In an analysis of streams across the commonwealth, VDEQ has determined that LRBS scores between -1.0 and -1.5 have a medium probability of stressing aquatic life, and LRBS scores <-1.5 have a high probability of stressing aquatic life (VDEQ, 2017). LRBS scores that are too high can also stress benthic macroinvertebrates, and scores >0.5 are also in the medium probability range for stress effects.

Table 8 shows the results of relative bed stability analysis in Goochland and Henrico Project streams. Relative bed stability analysis was conducted in each of impaired streams except for Dover Creek. Bottom substrate ranged from 12% sand and fines in Upham Brook to 95% in Deep Run. Embeddedness ranged from 43% in Stony Run to 96% in Deep Run. LRBS indices were in the high probability range for stressor effects in Deep Run, indicating that substrate instability from sediment deposition could be a stressor in this stream. North Run, Upham Brook, and the reference (Jones Creek) had LRBS index values in the medium probability range for stressor effects. Interestingly, Upham Brook had a positive LRBS value above 1.0, indicating that instability from scouring conditions could be a stressor. This watershed has high % imperviousness (45%), so scouring events may be common. All other streams had LRBS values in the low to no probability range for stressor effects. For streams that were analyzed for relative bed stability on multiple occasions, there was often high variability. For instance, Deep Run received an LRBS score of -1.55 on 12/4/2014 and a score of -0.21 on 9/24/2020. For these urban streams with high imperviousness, there is a possibility that stream substrate conditions vary through scour and deposition cycles, making infrequent measurements such as LRBS difficult to interpret.

Table 8. Log relative bed stability index for Goochland and Henrico Project streams.

Stream	Station	Date	Slope	% Sand and Fines	Embeddedness (%)	Log Relative Bed Stability Index (LRBS)[1]
Deep Run	2-DPR003.75	12/4/2014	0.095	95	96	-1.55
	2-DPR003.75	9/24/2020	0.175	68	74	-0.21
Jordans Branch	2CJOP000.34	10/23/2012	0.215	57	84	-0.92
	2CJOP000.34	9/29/2020	0.188	39	78	-0.34
North Run	2-NTR000.23	10/13/2011	0.163	58	76	-1.04
	2-NTR000.23	10/5/2020	0.200	44	79	-0.24
Stony Run	2-SNJ001.77	9/10/2007	0.735	31	43	-0.50
	2-SNJ001.77	10/1/2020	0.653	32	66	-0.46
Stony Run UT	2-XYT000.29	10/1/2020	0.480	46	76	-0.09
Upham Brook	2-UPM005.26	11/9/2020	0.100	12	57	1.10
Reference	2-JOH004.23	10/19/2005	0.313	66	79	-1.39

[1] Values in blue are in the no probability range for stressor effects, values in green are in the low probability range, values in yellow are in the medium probability range, and values in red are in the high probability range for stressor effects.

2.3. Land Cover Assessment

While a more detailed land cover assessment will be part of the Goochland and Henrico Project TMDL Report, the stressor analysis evaluated the potential connections between land cover patterns within the watershed and impaired benthic stations. Table 9 shows the land cover contributing to each of the benthic monitoring stations in the Goochland and Henrico Project area. Most of the impaired watersheds (except for Dover Creek and the upper North Run station) were urban/suburban with a mixture of impervious area and residential trees and grasses. Impervious area ranged from 31% to 54%, urban and residential trees ranged from 17% to 27%, and urban and residential grasses ranged from 26% to 33% of the watersheds. No other land use comprised more than 10% of the land area in these watersheds. The Dover Creek watershed was unique from the other impaired watersheds in that it contained substantially more forest (52%), pasture (26%), and cropland (4.8%) and considerably less imperviousness (2.8%). The upper North Run station watershed also differed from the other stations in that it contained a sizable proportion of wetlands (14%), which were classified as “Other.”

Regression analyses were used to compare these land use trends to benthic SCI scores at the respective stations. Statistically significant regressions were observed between SCI scores and three land use categories: forest, impervious, and urban/residential grasses. No other land use categories were significantly correlated with benthic health. SCI scores were positively correlated with forest cover (0.92 correlation coefficient) and negatively correlated with imperviousness (-0.89 correlation coefficient) and urban/residential grasses (-0.81 correlation coefficient). For those land cover categories with significant regressions, the r^2 values ranged from 0.65 to 0.85, indicating that these land cover categories can account for two thirds or more of the variability in benthic health scores. Figure 11 shows the relationship between SCI scores and forest and impervious cover within the watersheds. As forest land decreases in these watersheds and imperviousness (along with residential areas) increases, benthic health begins to decline.

The finding that stream health is correlated with imperviousness in the watershed is consistent with Brabec *et al.* (2002), who reviewed the biological impacts of watershed imperviousness and found that fish- and macroinvertebrate diversity decreased when watersheds exceeded 3.6 to 15% imperviousness. The watersheds of each of the impaired streams (except for Dover Creek) exceed 15% imperviousness. As a watershed develops and the percentage of impervious surfaces increases, runoff during precipitation events increases. As the amount of runoff increases, peak flows in local streams increase causing streambank erosion and stream bed scouring. This scenario causes unstable habitat conditions for benthic macroinvertebrates and increased sediment loads, which could result in impairment.

Urban/residential grasses were also significantly correlated with stream health scores, although this relationship is likely a result of cross-correlation with imperviousness rather than any causal relationship. The presence of urban/residential grasses were more strongly correlated with imperviousness (0.82 correlation coefficient) than stream health. As urban and residential areas develop, both land uses increase, but the increase in imperviousness is likely the causal factor in reducing stream health.

Table 9. Land use upstream from each benthic monitoring station.

Stream	Station	Water	Impervious	Barren	Forest	Urban/ Res. Trees	Scrub/ Shrub	Harvested/ Disturbed	Urban/ Res. Grass	Pasture	Cropland	Other
Deep Run	2-DPR003.75	0.30%	41.10%	0.11%	6.04%	20.38%	0.00%	0.00%	29.01%	0.00%	0.00%	3.06%
Stony Run	2-SNJ000.19	1.37%	35.86%	0.00%	5.30%	26.55%	0.00%	0.00%	27.53%	0.00%	0.00%	3.38%
	2-SNJ001.77	1.08%	40.08%	0.34%	4.94%	19.49%	0.00%	0.00%	29.73%	0.00%	0.00%	4.35%
Stony Run UT	2-XYT000.04	0.27%	44.21%	0.00%	4.24%	20.42%	0.00%	0.00%	26.76%	0.00%	0.00%	4.09%
	2-XYT000.29	0.31%	46.58%	0.00%	3.33%	19.35%	0.00%	0.00%	26.09%	0.00%	0.00%	4.34%
Dover Creek	2-DOV003.55	1.19%	2.79%	0.00%	52.39%	7.13%	0.00%	0.00%	4.72%	25.89%	4.80%	1.10%
Upham Brook	2-UPM003.12	0.32%	37.74%	0.19%	5.18%	19.85%	0.46%	0.00%	31.66%	0.23%	0.14%	4.23%
	2-UPM005.26	0.14%	45.40%	0.16%	2.87%	20.33%	0.08%	0.00%	29.61%	0.03%	0.00%	1.39%
Jordans Branch	2CJOP000.34	0.00%	54.22%	0.26%	2.27%	16.75%	0.09%	0.00%	25.88%	0.00%	0.00%	0.52%
North Run	2-NTR000.23	0.48%	31.08%	0.25%	7.23%	19.77%	0.66%	0.00%	33.18%	0.45%	0.29%	6.61%
	2-NTR005.53	0.19%	17.66%	0.15%	15.91%	18.73%	1.23%	0.00%	28.59%	3.11%	0.68%	13.75%
Jones Creek	2-JOH004.23	0.81%	4.05%	0.00%	62.10%	16.96%	0.33%	1.72%	7.59%	0.54%	0.84%	5.05%
Genito Creek	2-GEN000.69	0.91%	2.44%	0.00%	55.67%	10.45%	1.06%	0.13%	5.26%	16.11%	4.82%	3.13%

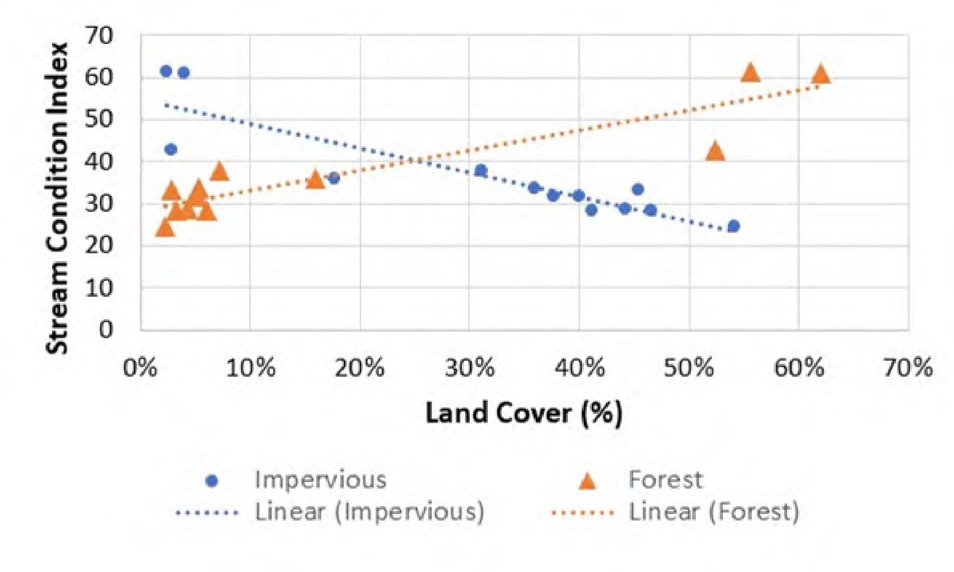

Figure 11. Regression between impervious land cover and forest in the watershed and benthic health.

Table 10. Regression relationship between land cover and stream condition index (SCI) scores.

Parameter	Correlation Coefficient	Regression Significant (Y/N)	r^2	p-value
Forest	0.92	Y	0.85	0.0000084
Impervious	-0.89	Y	0.79	0.000048
Urban/Res. Grass	-0.81	Y	0.65	0.00082
Cropland	0.67	N	0.45	0.012
Harvested/Disturbed	0.66	N	0.44	0.013
Urban/Res. Trees	-0.54	N	0.29	0.059
Pasture	0.5	N	0.25	0.084
Scrub/Shrub	0.49	N	0.24	0.088
Water	0.47	N	0.22	0.11
Barren	-0.43	N	0.19	0.14
Other	0.08	N	0.0058	0.81

2.4. Water Quality Data Assessment

Water quality data for all the candidate stressors were evaluated to assess trends and compare to relevant water quality standards and stressor thresholds.

2.4.1. Temperature

VDEQ measures temperature when collecting benthic or water quality samples, so periodic temperature data are available from 2000 to present from each of the impaired streams (Figure 12). Temperatures obviously vary by season, so ranges are wide when year-round measurements are considered. Two of the impaired streams (Jordans Branch and Stony Run) had statistically higher temperatures than the Jones Creek reference station ($p<0.05$ in t-test with unequal variances), however none of the benthic stations had temperature measurements above the water quality standard of 32°C. Maximum temperatures ranged from 20.7°C in Dover Creek to 29.7°C in Upham Brook (2-UPM005.26) (Figure 13). In addition to the impaired benthic stations, temperature data from 36 other stations within the impaired watersheds were analyzed. Of these 1035 measurements, none exceeded the Virginia water quality standard for temperature (32°C).

VDEQ also collected diurnal temperature at each of the primary benthic stations during the summer of 2021. Diurnal data were collected at 15-minute intervals for 1 week at each location. Temperature data during diurnal deployments are shown in Figure 14. Diurnal temperatures exhibited the natural cycle of increases during the day from solar heating and decreases at night. No stations exceeded the Virginia water quality standard of 32ºC. At all stations, the daytime maximum temperature was below 30ºC. This is an indication that temperature is not a primary stressor in these streams.

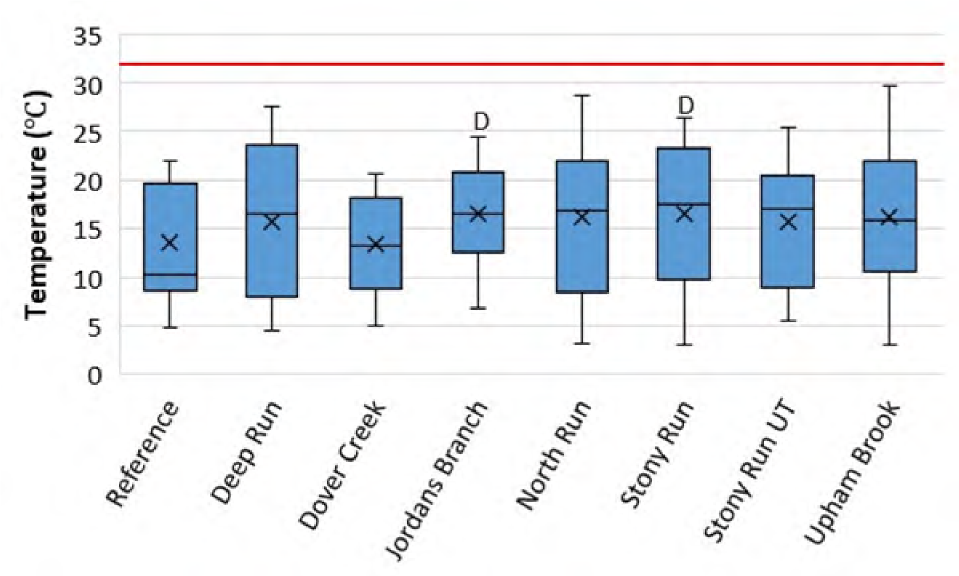

Figure 12. Periodic temperature measurements in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. The red line represents the Virginia water quality standard.

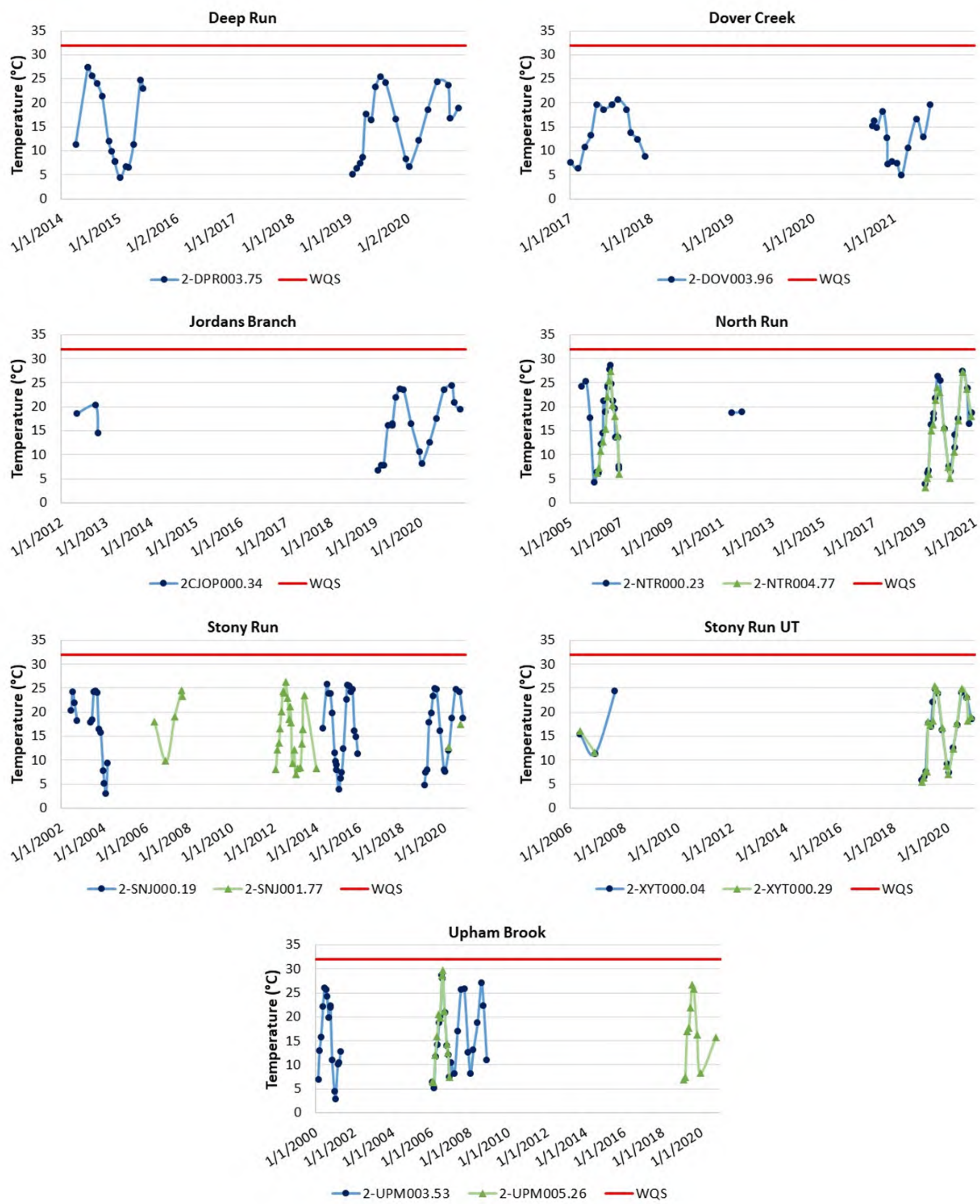

Figure 13. Temperature time series in Goochland and Henrico Project streams. The red line represents the Virginia water quality standard.

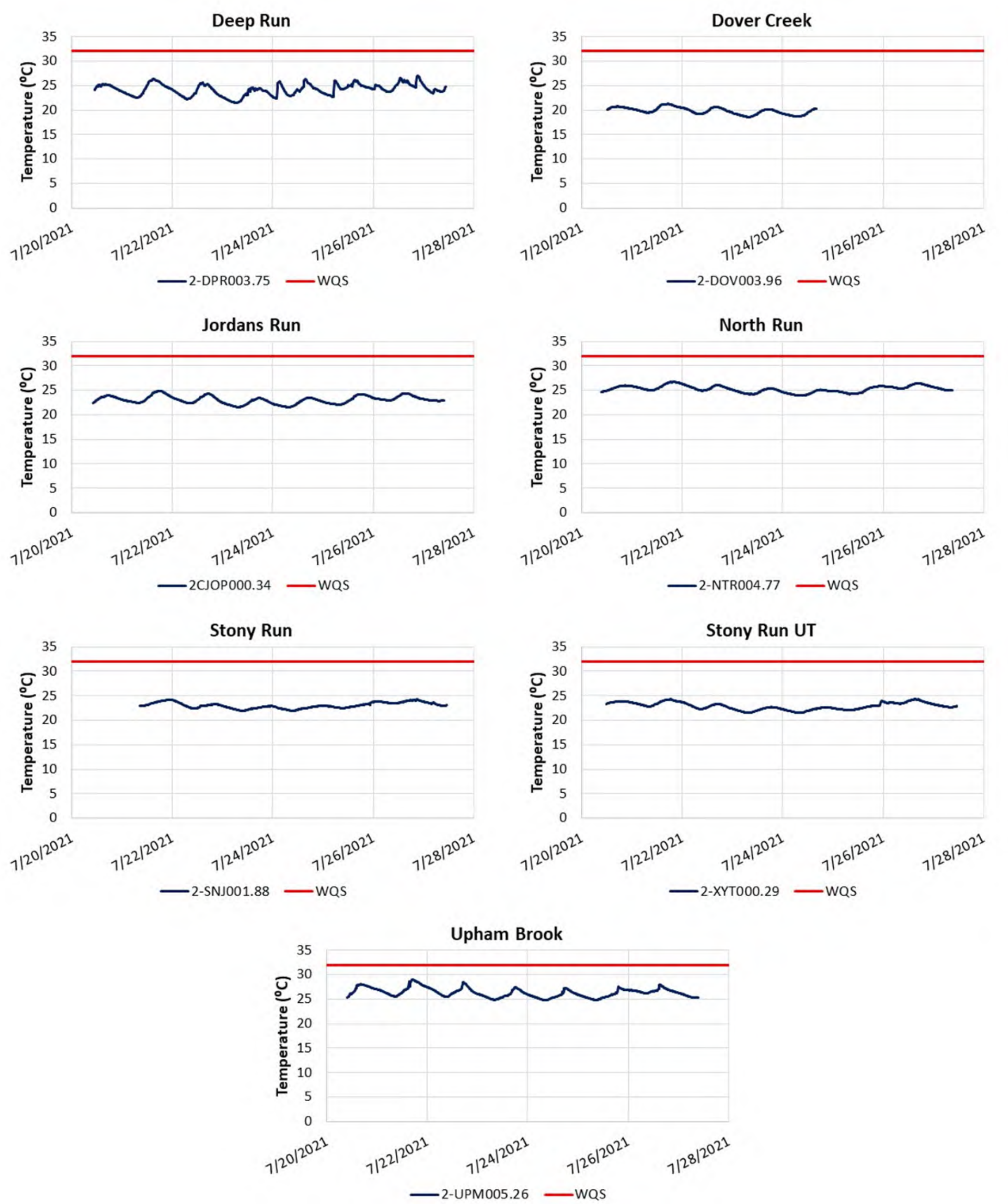

Figure 14. Diurnal temperature conditions in Goochland and Henrico Project streams. The red line represents the Virginia water quality standard.

2.4.2. pH

VDEQ measures pH when collecting benthic or water quality samples, so periodic pH data are available from each of the impaired streams (Figure 15). Measured pH values were neutral to slightly acidic in each of the impaired streams and averaged from 6.68 in North Run to 6.95 in Deep Run. Several of the streams (Deep Run, Dover Creek, Jordans Branch, Stony Run, and Upham Brook) were statistically higher in pH than the Jones Creek reference site ($p<0.05$ in t-test with unequal variance), but median pH values at all sites were within the low probability range for stressor effects. Figure 16 show the time series of pH values in Goochland and Henrico Project streams. While pH varied over time, most samples were between 6 and 9 and were within the water quality standards. One sample in Upham Brook (1/7/2008 at 2-UPM003.53) and four samples in North Run (between 2002 and 2004 at 2-NTR005.53) were below the water quality standard of 6.0. The minimum pH at Upham Brook benthic stations was 5.5 and the minimum pH at North Run benthic stations was 5.9. North Run, from its headwaters to Hungary Creek, is listed for a pH impairment, based on 3/6 pH violations in the 2006 assessment cycle.

In addition to the impaired benthic stations, pH data from 36 other stations within the impaired watersheds were analyzed. Of these 1023 measurements, three additional samples were below the water quality standard of 6.0. Two samples at station 2-DPR001.00 and one sample in an unnamed tributary to Upham Brook (2CXXQ000.69) exhibited pH values of 5.5, 5.6, and 5.58, respectively.

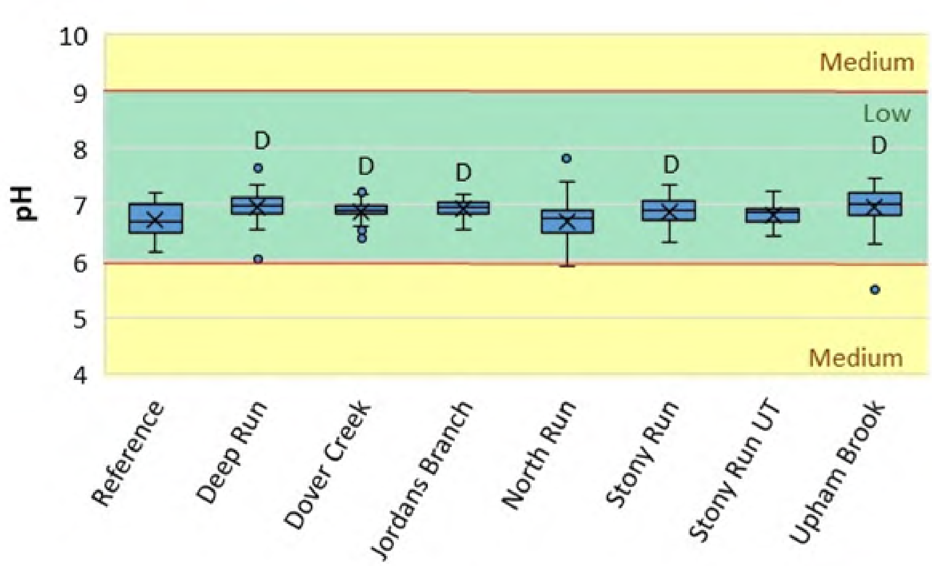

Figure 15. pH in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. The red line represents the Virginia water quality standard. Colors represent the low and medium probability ranges for stressor effects.

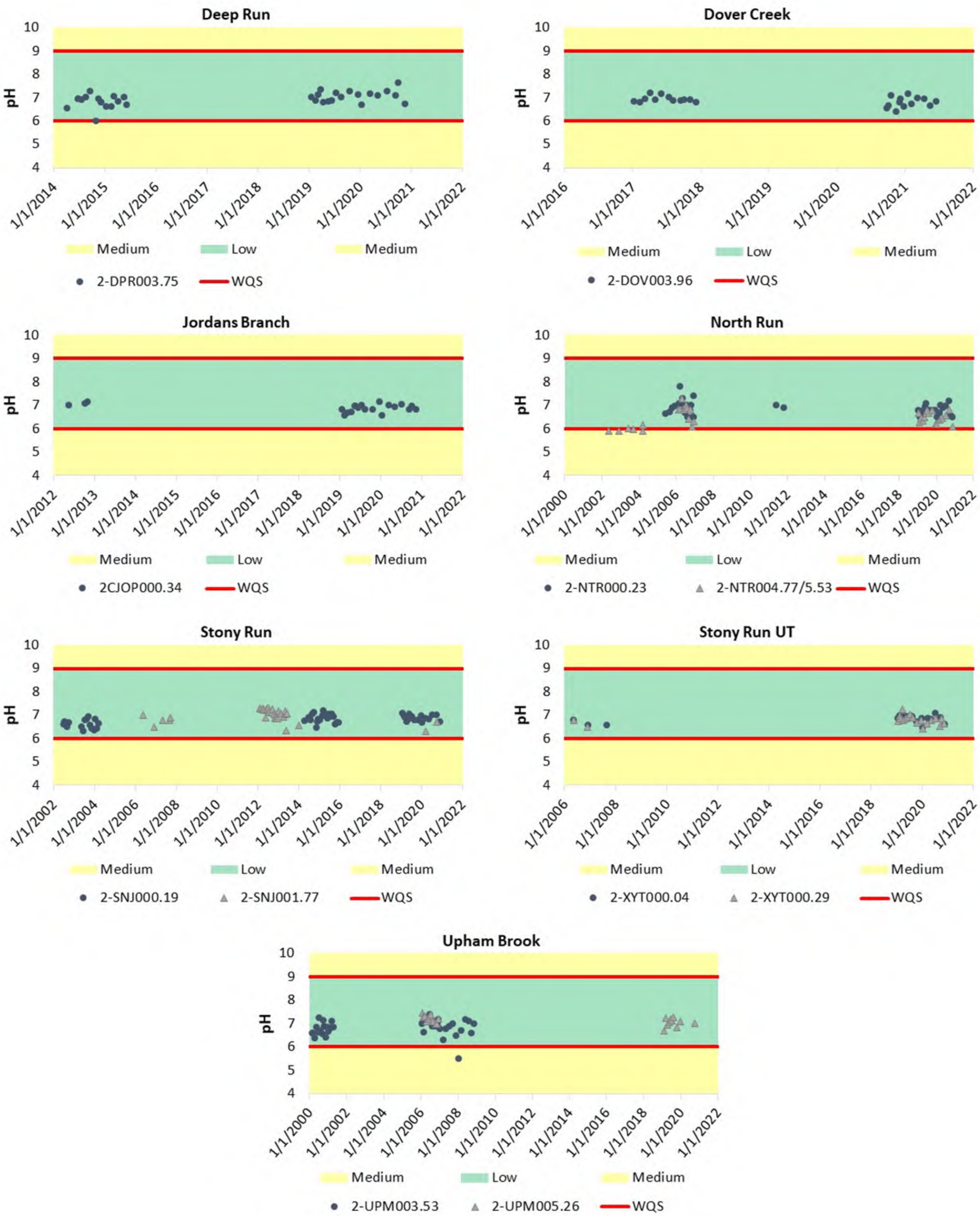

Figure 16. pH in Goochland and Henrico Project streams. The red line represents the Virginia water quality standard. Colors represent the low and medium probability ranges for stressor effects.

2.4.3. Dissolved Oxygen

VDEQ measures dissolved oxygen (DO) when collecting benthic or water quality samples, so periodic DO data are available from 2000 to present in each of the impaired streams (Figure 17). Average dissolved oxygen levels at impaired benthic stations ranged from 7.89 mg/L in Jordans Branch to 9.66 mg/L in Dover Creek. Median DO values were in the low probability range for stressor effects in all streams except for Jordans Branch, where the median was in the medium probability range. Deep Run, Jordans Branch, North Run, and Stony Run had statistically lower DO than the Jones Creek reference station ($p<0.05$ in t-test with unequal variance).

Figure 18 shows the time series of DO concentrations in each impaired stream. Each of the impaired streams had DO excursions into the high probability range for stressor effects, and Deep Run, North Run, Stony Run, and Upham Brook had DO excursions below the average daily water quality standard of 5.0 mg/L. At Deep Run station 2-DPR003.75, 1 out of 34 samples (3%) was below the average daily water quality standard of 5.0 mg/L. In North Run, (2-NTR005.53 and nearby 2-NTR004.77) 6 out of 35 samples (17%) were below the standard. In Stony Run (2-SNJ000.19), 8 out of 52 samples (15%) were below the standard. In Upham Brook, 5% of samples (2/40) at 2-UPM003.53 and 9% of samples (2/22) at 2-UPM005.26 were below the standard. DO minimums were 4.88 mg/L in Deep Run, 1.92 mg/L in North Run, 1.63 mg/L in Stony Run, and 3.1 mg/L in Upham Brook.

In addition to the impaired benthic stations, DO data from 36 other stations within the impaired watersheds were analyzed. DO measurements were below 5.0 mg/L at additional stations in Deep Run (2-DPR001.00, 2.46, and 4.38), Dover Creek (2-DOV000.42), Jordans Branch (2CJOP001.27), North Run (2-NTR003.42), Stony Run (2-SNJ001.90), and Upham Brook (multiple stations from mile 000.26 to 008.76), as well as tributaries to Deep Run and Upham Brook. The following stations were listed for DO impairment on the 2022 305(b)/303(d) Water Quality Assessment Integrated Report (VDEQ, 2022): 2-DPR001.00, 2-DOV000.42, 2-NTR004.77, and 2-UPM002.41.

In addition to periodic dissolved oxygen measurements, VDEQ collected diurnal dissolved oxygen data at each of the primary benthic stations during the summer of 2021. Diurnal data were collected at 15-minute intervals for 1 week at each station. Diurnal monitoring of dissolved oxygen is important, because critical dissolved oxygen levels are typically encountered just before sunrise.

This is due to the combination of oxygen consumption from respiration and the absence of oxygen production from photosynthesis during the night. Diurnal monitoring was conducted in late July, because critical dissolved oxygen levels are also more common during the hot and dry summer months.

Dissolved oxygen data during diurnal deployments are shown in Figure 19. Diurnal dissolved oxygen values at all stations exhibited the natural cycle of increases during the day while plants are photosynthesizing and decreases at night while respiration dominates. This daily cycle was modest in some streams, like Dover Creek and Stony Run UT, but was very dramatic in others, like Upham Brook. Dissolved oxygen fluctuated from above 12 mg/L during the day to below 5.0 mg/L at night in Upham Brook. This represents DO percent saturation swings from over 160% saturation during the day to near 50% saturation at night. Large diurnal swings in dissolved oxygen are an indicator of nutrient effects, because as prolific algae growth is spurred by nutrient enrichment, those algae increase daytime oxygen concentrations through photosynthesis and decrease nighttime oxygen concentrations through respiration.

Diurnal dissolved oxygen levels in Dover Creek were consistently in the low probability range for stressor effects, while all other streams exhibited DO conditions in the medium and high probability range. Dover Creek DO was near 100% saturation throughout the day and night. Deep Run and Jordans Branch had nighttime DO levels in the high probability range, but levels in these streams did not violate the average or minimum DO standards. These two streams maintained approximately 90% DO saturation during the day and 70% saturation at night. In Stony Run, Stony Run UT, and Upham Brook, nighttime DO levels dropped below 5.0 mg/L but did not violate the 4.0 mg/L minimum DO standard. DO saturation in Stony Run was maintained between 60 and 80%, and Stony Run UT was primarily between 50 and 70%. Upham Brook exhibited extreme diurnal swings from over 160% saturation during the day to near 50% saturation at night. In North Run, DO levels were consistently below the 4.0 mg/L minimum DO standard for the entire week of diurnal monitoring. Minimum DO in North Run was 1.74 mg/L, and DO saturation was consistently below 50%. Low DO in the upper North Run watershed is partially explained by the influence of forested/shrub wetlands that contribute 14% of the land area. In these permanently or periodically flooded wetlands, oxygen is quickly depleted as dense organic matter decays.

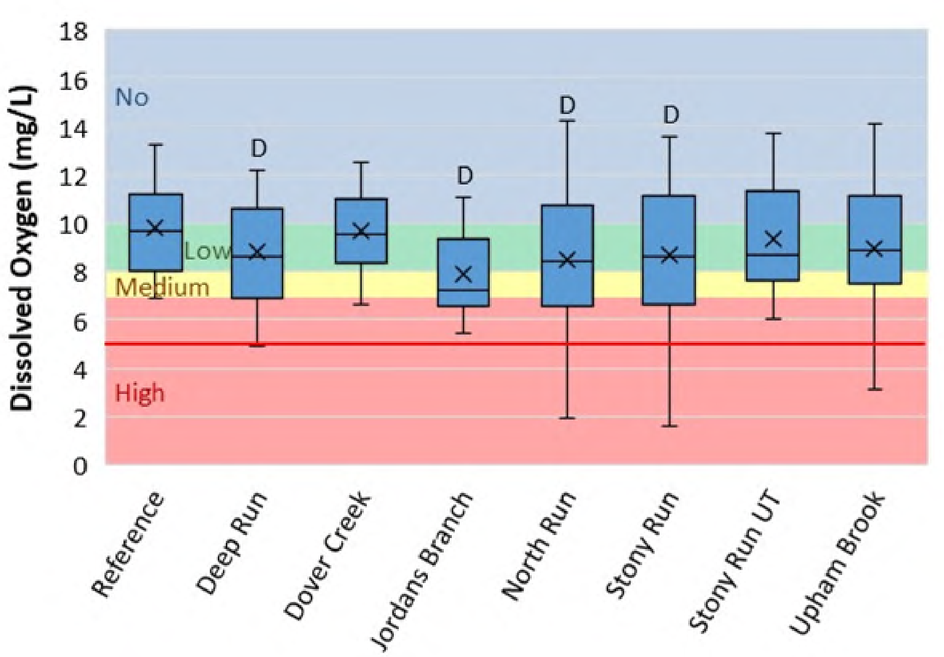

Figure 17. Dissolved oxygen in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

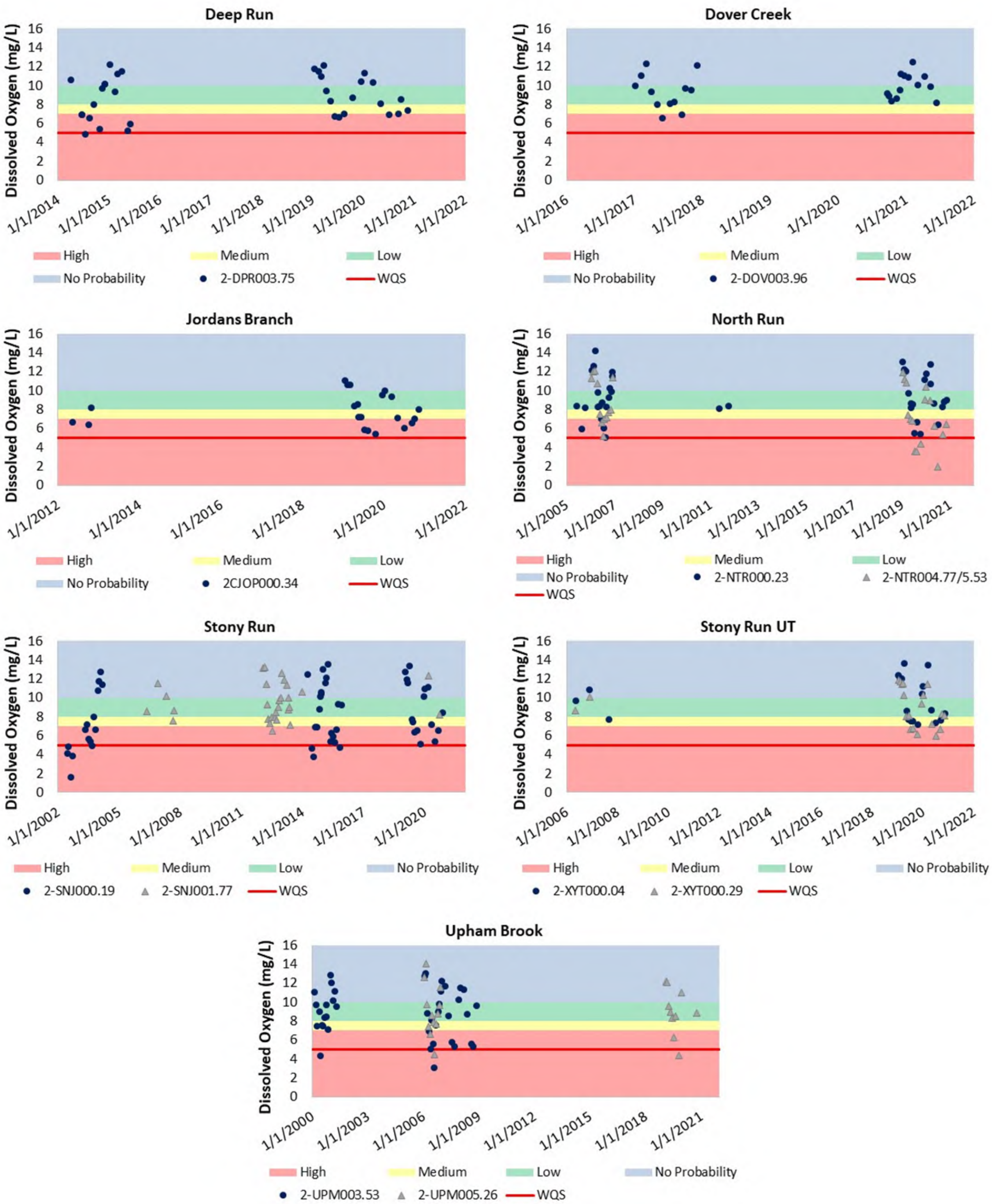

Figure 18. Dissolved oxygen over time in Goochland and Henrico Project streams. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

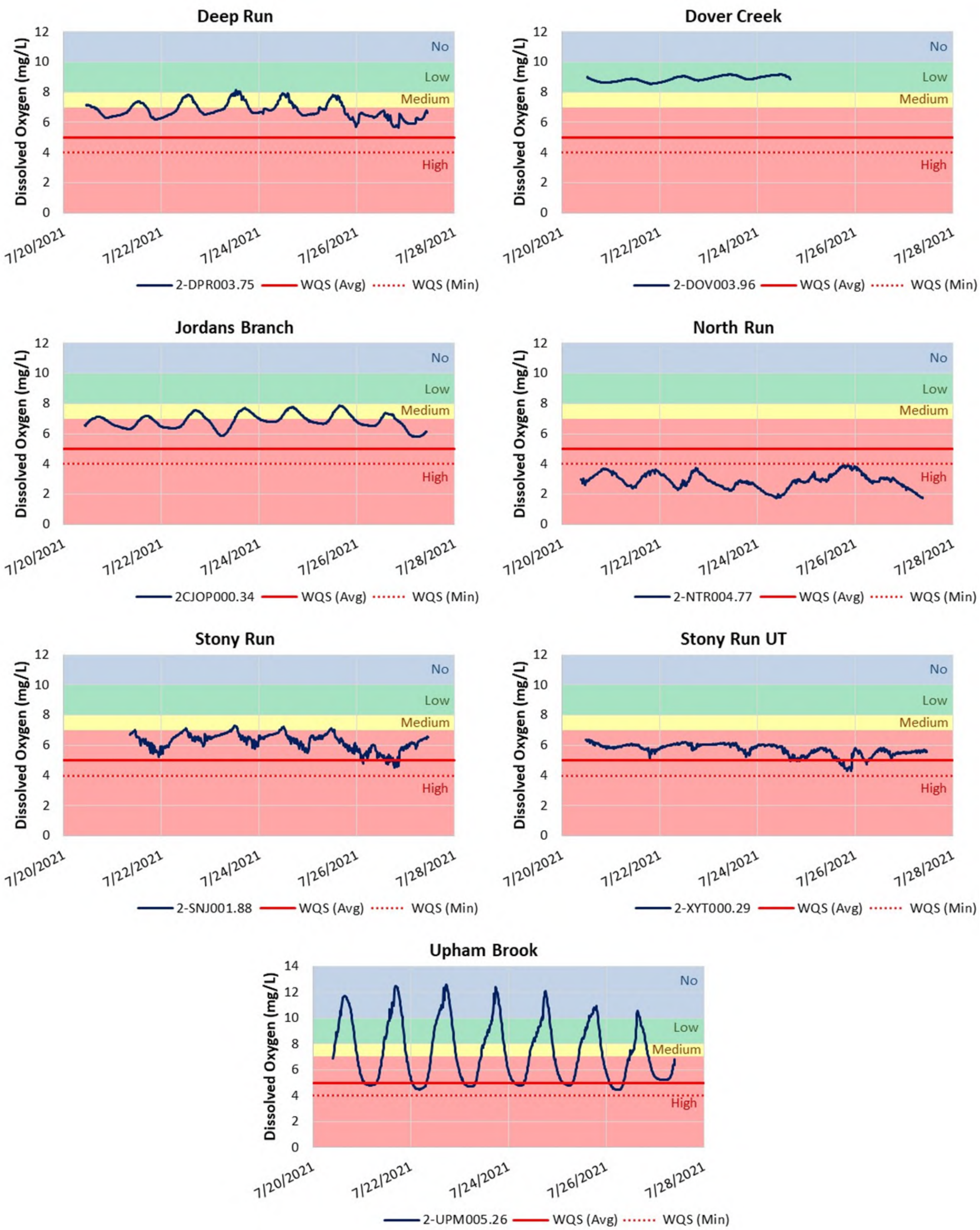

Figure 19. Diurnal dissolved oxygen conditions in Goochland and Henrico Project streams. The red line represents the Virginia water quality standard. Colors represent the probability that data within that range would be responsible for causing stress.

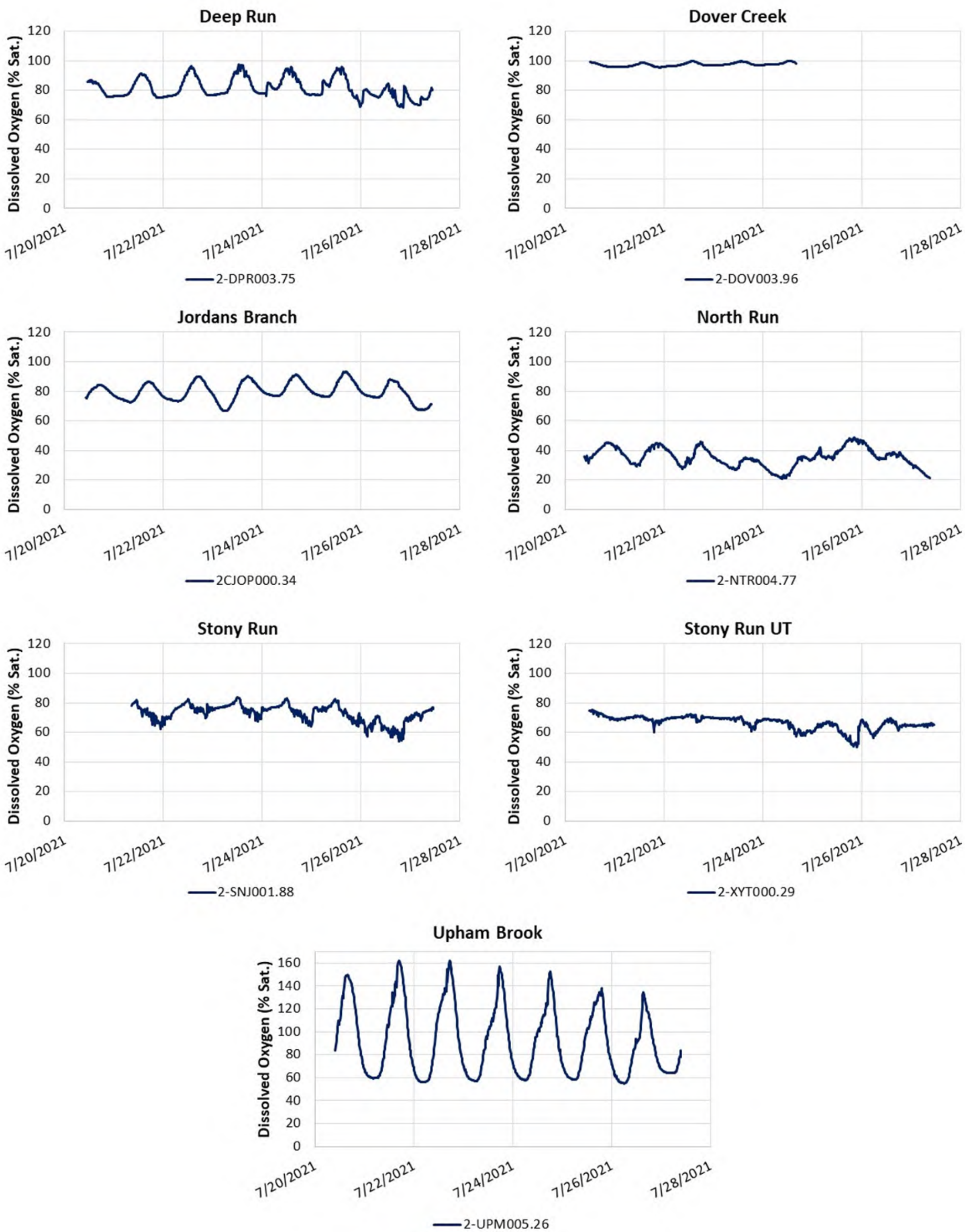

Figure 20. Percent saturation of diurnal dissolved oxygen in Goochland and Henrico Project streams.

2.4.4. Conductivity and Total Dissolved Solids

Conductivity is a measure of the electrical potential of water based on the ionic charges of dissolved compounds. For this reason, the conductivity of water is closely related to the total dissolved solids present. VDEQ measures conductivity when collecting benthic or water quality samples, so periodic conductivity data are available from 2000 to present (Figure 21). Average conductivity in Goochland and Henrico Project streams ranged from 109 µS/cm in Dover Creek to 338 µS/cm in Stony Run UT. All impaired streams had statistically higher conductivity ($p<0.05$ in t-test with unequal variance) than the Jones Creek reference site, although median conductivity levels were still in the no- to low probability range for stressor effects.

Figure 22 shows conductivity levels over time in each of the Goochland and Henrico Project streams. Conductivity varied over time, likely due to rainfall and flow conditions. In all streams except for Dover Creek, one or more samples were in the high probability range for stressor effects. In all cases, these conductivity excursions were during the winter (December through March) and were likely due to runoff of roadway deicing salts from impervious surfaces.

Total dissolved solids (TDS) are closely tied to conductivity, since it is the dissolved ions that transmit electrical current. Figure 23 shows TDS levels in Goochland and Henrico Project streams. TDS averaged from 80.7 mg/L in Dover Creek to 180 mg/L in Upham Brook. Each of the impaired streams was statistically higher in TDS (t-test with unequal variance and alpha = 0.05) than the reference, which averaged only 65 mg/L. Like conductivity, all median TDS values were in the no- to low probability range for stressor effects. Only a single sample from Stony Run UT was in the high probability range.

In summary, conductivity and TDS are not likely continuous stressors in Goochland and Henrico Project streams. Values were generally in the no- to low probability range for stressor effects. However, those streams with high imperviousness exhibited occasional conductivity excursions into the high probability range during winter roadway deicing events. The application of roadway deicing salts and subsequent runoff could be a possible episodic stressor to freshwater aquatic life in these streams.

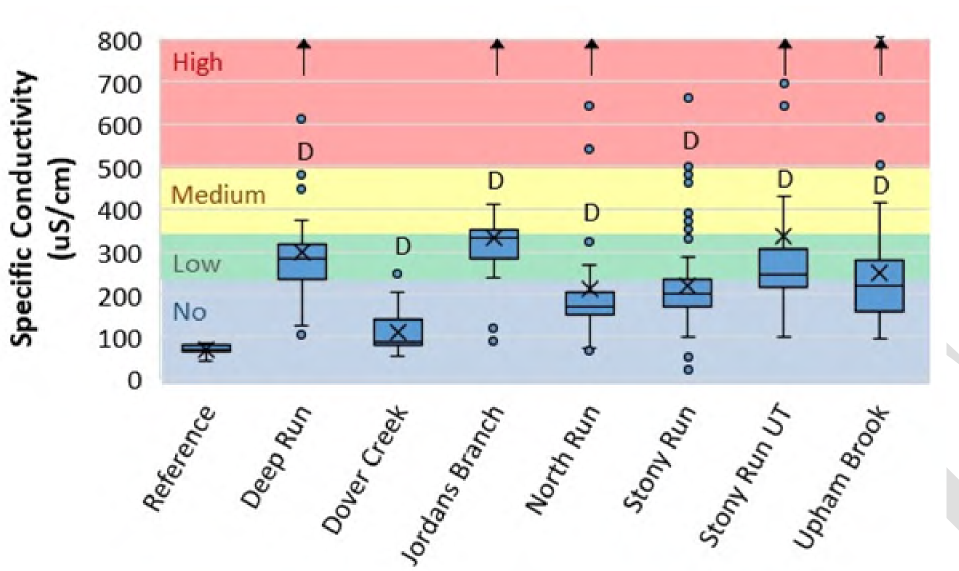

Figure 21. Conductivity in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. Colors represent the probability that data within that range would be responsible for causing stress. Arrows indicate that one or more results exceeds the graph scale.

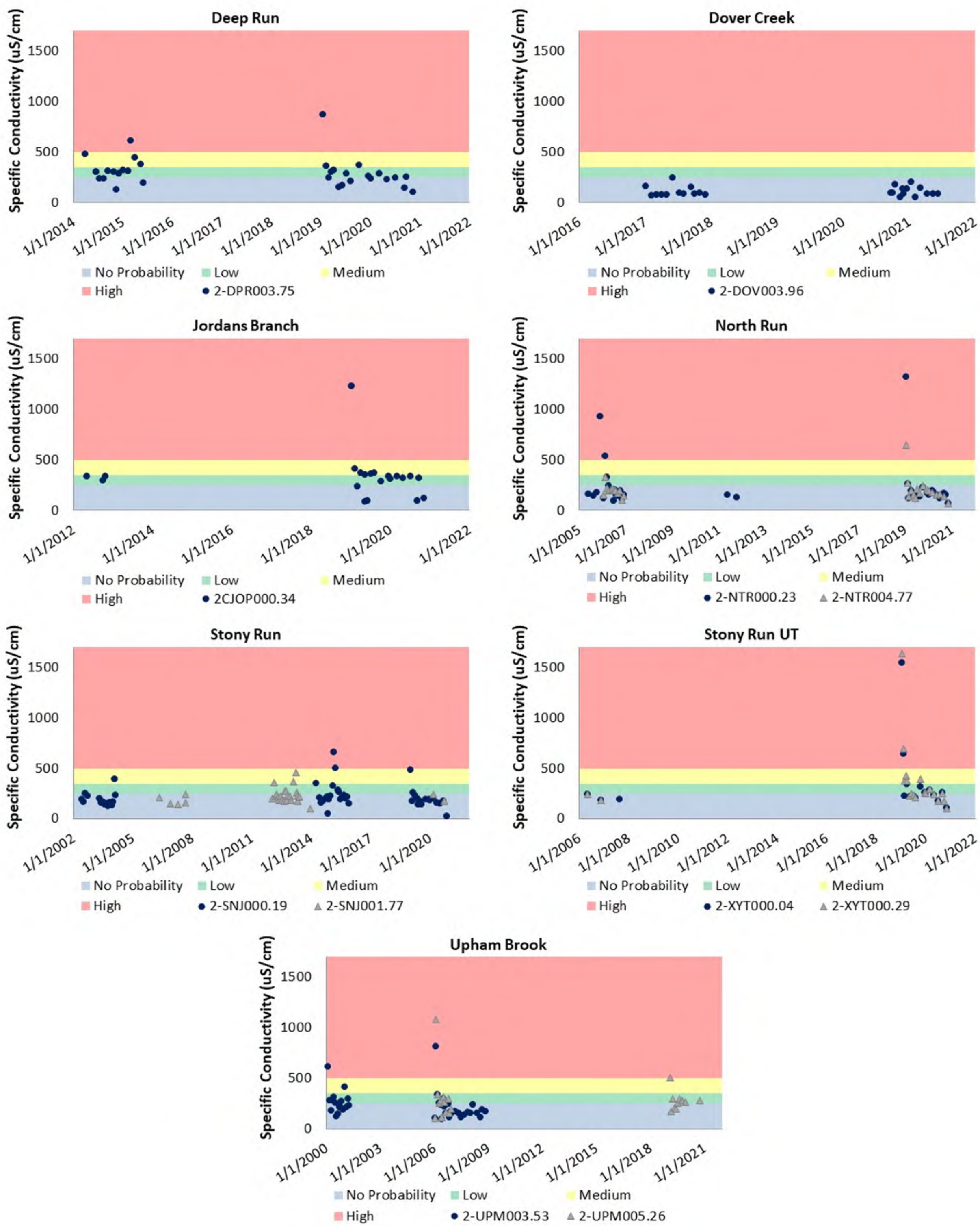

Figure 22. Conductivity over time in Goochland and Henrico Project streams. Colors represent the probability that data within that range would be responsible for causing stress.

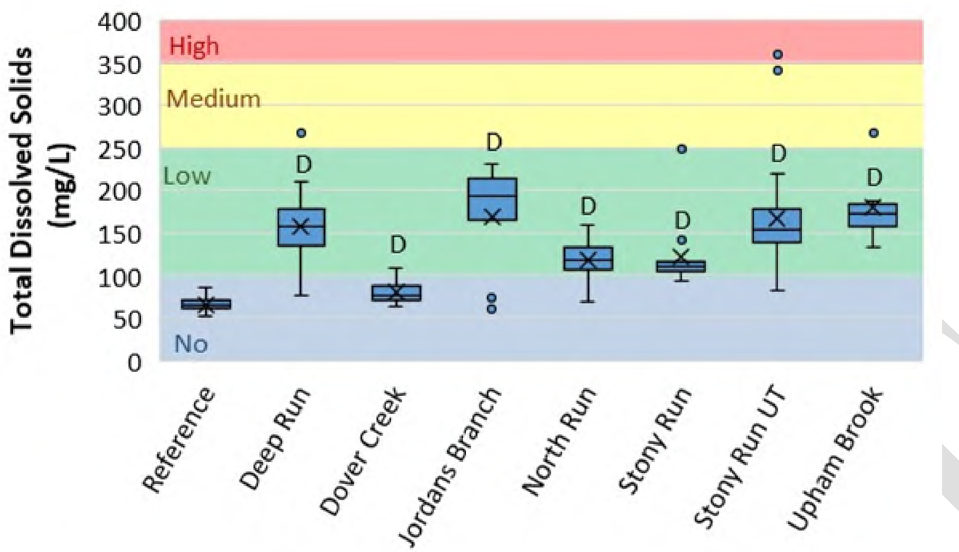

Figure 23. Total dissolved solids in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. Colors represent the probability that data within that range would be responsible for causing stress.

2.4.5. Dissolved Ions

Dissolved sodium, potassium, chloride, and sulfate were measured in Goochland and Henrico Project streams (Figure 24). Dissolved sodium concentrations averaged from 5.66 mg/L in Dover Creek to 31.3 mg/L in Stony Run UT. Sodium concentrations in all streams except for Dover Creek were statistically higher than the Jones Creek reference ($p<0.05$ in t-test with unequal variances). The median dissolved sodium value in Dover Creek was in the no probability range for stressor effects. Median sodium levels in North Run and Stony Run were in the medium probability range for stressor effects, and medians were in the high probability range in Deep Run, Jordans Branch, Stony Run UT, and Upham Brook. Sodium levels in these four streams were in the high probability range 64%, 80%, 72%, and 86% of the time, respectively. The maximum dissolved sodium concentration of 102 mg/L was observed in Stony Run UT (2-XYT000.29) on 2/11/2019.

Dissolved potassium concentrations in Goochland and Henrico Project streams averaged from 2.53 mg/L in North Run to 7.12 mg/L in Dover Creek. Potassium concentrations in all streams were statistically higher than in the Jones Creek reference ($p<0.05$ in t-test with unequal variances), where dissolved potassium averaged 2.02 mg/L. The median dissolved potassium value in all streams was in the medium probability range for stressor effects. In Dover Creek, 27% of values were in the high probability range for stressor effects, and the maximum potassium concentration was 16.2 mg/L. No other stream exhibited potassium concentrations in the high probability range for stressor effects.

Dissolved chloride concentrations in Goochland and Henrico Project streams averaged from 7.02 mg/L in Dover Creek to 51.0 mg/L in Stony Run UT. Chloride concentrations in all streams were statistically higher than in the Jones Creek reference ($p<0.05$ in t-test with unequal variances), where dissolved chloride averaged 5.55 mg/L. The median dissolved chloride value in Dover Creek was in the no probability range for stressor effects. Median chloride levels in North Run and Stony Run were in the low probability range for stressor effects, and medians were in the medium probability range in Deep Run, Jordans Branch, Stony Run UT, and Upham Brook. Each of the streams except for Dover Creek had excursions into the high probability range. Chloride levels were in the high probability range less than 10% of the time in North Run and Stony Run. In Deep Run, Jordans Branch, Stony Run UT, and Upham Brook, chloride levels were in the high probability range 31%, 22%, 29%, and 33% of the time, respectively. The maximum dissolved chloride concentration of 190 mg/L was observed in Stony Run UT (2-XYT000.29) on 2/11/2019, the same day as the maximum sodium concentration. Even this maximum concentration was well below the chloride water quality criteria of 230 mg/L.

Dissolved sulfate concentrations in Goochland and Henrico Project streams averaged from 2.18 mg/L in Dover Creek to 21.9 mg/L in Upham Brook. Sulfate concentrations in all streams except for Dover Creek were statistically higher than in the Jones Creek reference ($p<0.05$ in t-test with unequal variances), where dissolved sulfate averaged 1.84 mg/L. The median dissolved sulfate values in all streams were in the no- to low probability range for stressor effects, and no individual values were in the high probability range.

In summary, median dissolved sodium levels were in the high probability range for stressor effects in Deep Run, Jordans Branch, Stony Run UT, and Upham Brook. Median chloride levels were in the medium probability range for these same streams, and median potassium levels were in the medium range for all streams. The observed ranges of these ions, however, do not appear to be within toxic ranges reported by Mount *et al.* (2016). Sodium is considered to be the least toxic of the major ions and Mount *et al.* (2016) found that sodium was typically only toxic to freshwater invertebrates at concentrations of 20-40 mM (or 460-920 mg/L Na). This is approximately an order of magnitude above the sodium concentrations found in Goochland and Henrico Project streams. Similarly, chloride levels were well below Virginia's water quality standard of 230 mg/L chloride. All samples were also well below toxic levels of potassium (78-390 mg/L) and sulfate (96-2400 mg/L) reported by Mount *et al.* (2016).

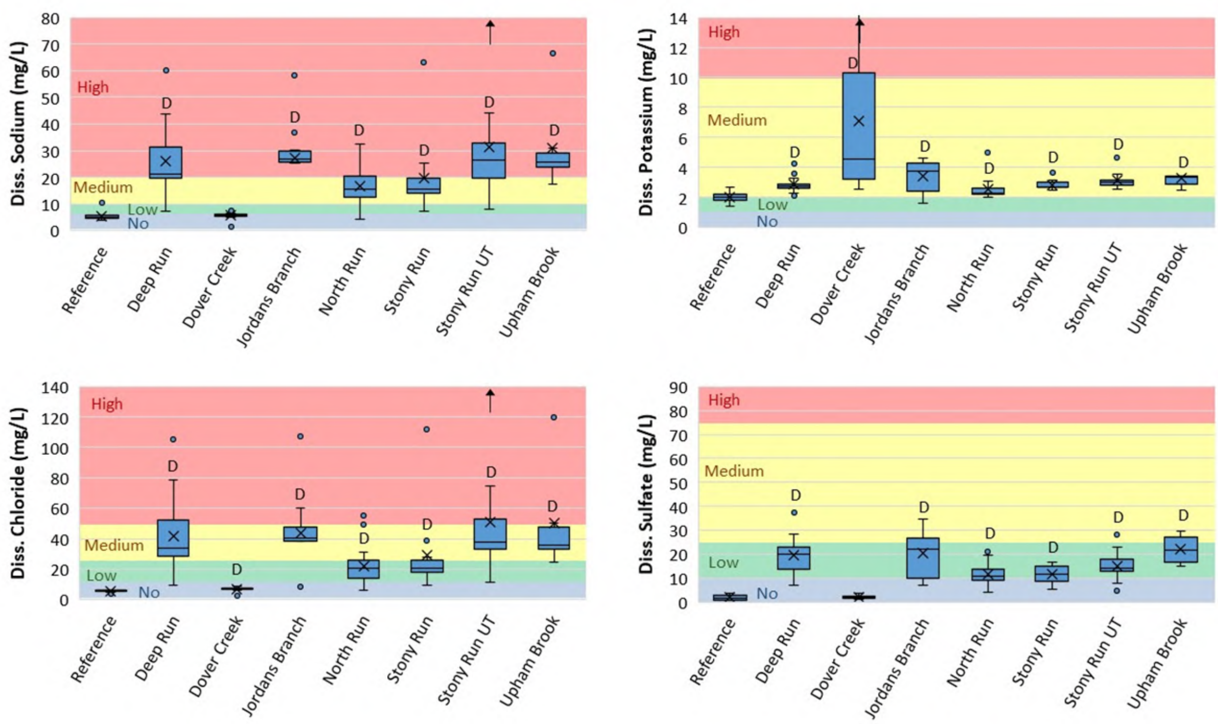

Figure 24. Dissolved ions in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. Colors represent the probability that data within that range would be responsible for causing stress. Arrows indicate that one or more results exceeds the graph scale.

2.4.6. Solids

Figure 25 shows total suspended solids (TSS) measured in Goochland and Henrico Project streams. Average TSS values ranged from 5.8 mg/L in the reference to 24.6 mg/L in Stony Run UT. Because TSS was not regularly measured in the Jones Creek reference, Genito Creek was used as the reference for comparison of TSS and turbidity levels. TSS in North Run, Stony Run, and Stony Run UT was statistically higher (p-value <0.05 in t-test with unequal variances) than the Genito Creek reference.

Figure 26 shows the cumulative frequency of TSS concentrations at the impaired stations compared to the Genito Creek reference station. For the majority of the time in all impaired streams, TSS concentrations were relatively low. However, the upper 20% of TSS levels began to diverge considerably from the reference condition. For instance, 90% of samples at the reference station were less than 10.2 mg/L, but the 90th percentile of TSS concentrations in the impaired streams was 19.1 mg/L in Deep Run, 15.3 mg/L in Dover Creek, 29.2 mg/L in North Run, 24 mg/L in Stony Run, 78.4 mg/L in Stony Run UT, and 18 mg/L in Upham Brook. This means that while all streams have low TSS levels during non-storm conditions, impaired streams have higher sediment concentrations during storm events.

In addition to TSS concentrations, turbidity levels were measured in Goochland and Henrico Project streams (Figure 27). Turbidity levels averaged from 6.47 NTU in the Genito Creek reference to 16.1 NTU in North Run. Turbidity in Deep Run, North Run, and Upham Brook was statistically higher (p-value <0.05 in t-test with unequal variances) than in the reference. Only a single turbidity measurement was taken in Jordans Branch and Stony Run, and no turbidity data were available for Stony Run UT.

Figure 28 shows the cumulative frequency of turbidity at the impaired stations compared to the Genito Creek reference station. Like TSS distributions, the impaired stations diverged from the reference station at the upper end of the cumulative frequency curve. This divergence was even more pronounced for turbidity than for TSS. While 90% of samples at the reference station were less than 8.88 NTU, the 90th percentile of turbidity in the impaired streams was 22.0, 22.3, 35.3, and 14 NTU in Deep Run, Dover Creek, North Run, and Upham Brook, respectively.

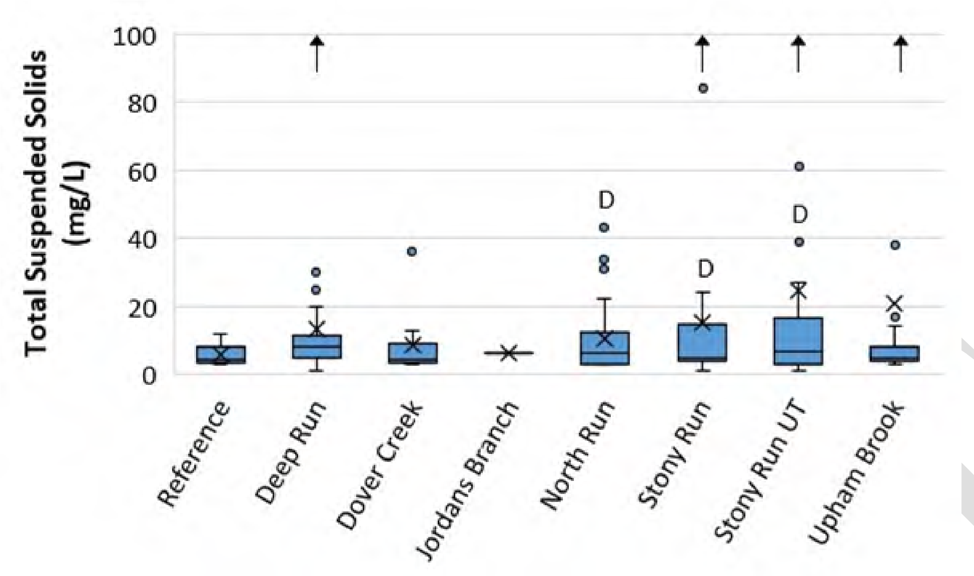

Figure 25. Total suspended solids in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Genito Creek reference station. Arrows indicate that one or more results exceeds the graph scale.

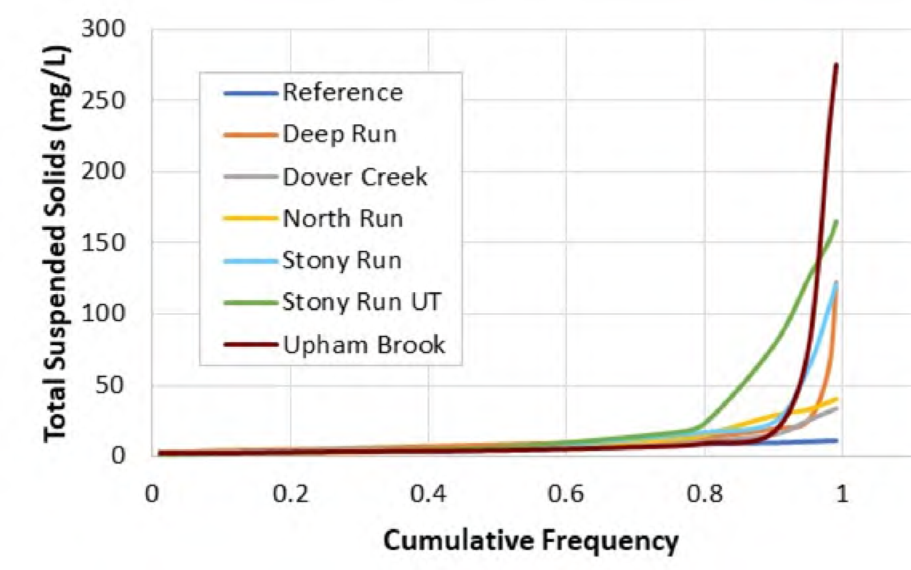

Figure 26. Cumulative frequency of TSS concentrations in Goochland and Henrico Project streams compared to the Genito Creek reference.

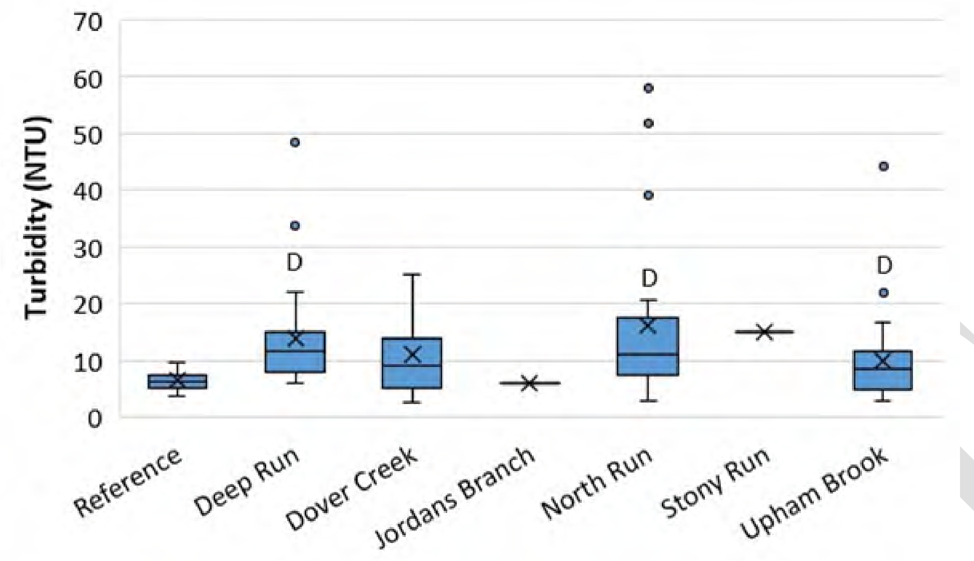

Figure 27. Turbidity in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Genito Creek reference station.

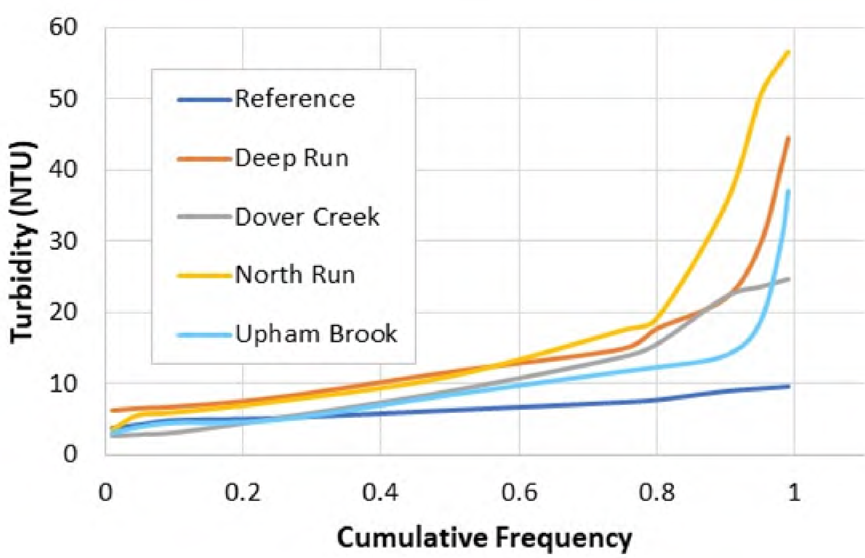

Figure 28. Cumulative frequency of turbidity in Goochland and Henrico Project streams compared to the Genito Creek reference.

2.4.7. *Organic Matter*

Various forms of organic matter were measured in Goochland and Henrico Project streams. The measurement of total volatile solids (TVS) captures the mass of suspended or dissolved solids in the stream that volatilizes when heated to 550°C. At this temperature, only inorganic material remains, so TVS represents the organic fraction. TVS concentrations in Goochland and Henrico Project streams are shown in Figure 29. TVS averaged 41 mg/L in Deep Run, 50 mg/L in North Run, and 43 mg/L in Upham Brook. No TVS data were available for Dover Creek and Stony Run UT, and only a single TVS measurement was made in the Jones Creek reference stream (15 mg/L), Jordans Branch (40 mg/L), and Stony Run (28 mg/L), so no statistical comparisons could be made.

Total organic carbon (TOC) was also measured in some Goochland and Henrico Project streams (Figure 30). TOC is the mass of carbon in organic form dissolved or suspended in the water column. TOC averaged 5.3 mg/L in Deep Run and 15 mg/L in North Run. TOC was lower in the Jones Creek reference (2.2 mg/L), Jordans Branch (2.98 mg/L), and Stony Run (5.1 mg/L), but only a single measurement was available in these streams. No TOC data were available for Dover Creek, Stony Run UT, and Upham Brook.

In general, total volatile solids and total organic carbon were the highest in North Run. Fractions of total organic carbon in the dissolved form were also relatively high. For stations that had total and dissolved organic carbon (DOC) measurements, the average percentage of TOC in the dissolved form was 88%. This means that high TOC concentrations of 15 mg/L in North Run would translate to 13 mg/L of dissolved organic carbon. In a survey of eastern streams, Kaufmann *et al.* (1991) found that only two regions (Florida and the Mid-Atlantic coastal plain) exceeded a median DOC of 2 mg/L. The Goochland and Henrico Project streams are located in this Mid-Atlantic coastal plain region, where DOC is naturally higher, but levels observed in North Run are above the upper 80^{th} percentile of streams within this Mid-Atlantic coastal plain region. Other streams with TOC or DOC data (Deep Run, Jordans Branch, and Stony Run) were closer to median DOC values for the Mid-Atlantic coastal plain region.

In the Mid-Atlantic coastal plain region, stream slopes are very shallow and hydrologically connected wetlands are common. In these low-lying areas, organic matter from growing- or dead vegetation accumulates in rich wetland soils. When flooded and hydrologically connected to larger drainage networks, these wetland areas feed high levels of organic matter to downstream creeks.

These streams exhibit high levels of organic carbon (measured as either TVS or TOC), particularly in the dissolved phase (DOC). This labile organic matter represents a readily available food source for heterotrophic microbes, and when degraded, oxygen is consumed, potentially causing decreases in in-stream dissolved oxygen. Streams in this region that exhibit these conditions are characterized by shallow slopes, sandy substrate, dark discolored water (blackwater), and low dissolved oxygen. This condition is naturally occurring in blackwater swamps and blackwater creeks but may also be exacerbated by anthropogenic inputs of nutrients, which fuel algal growth and further decrease oxygen levels. North Run appears to at least in part exhibit these blackwater conditions.

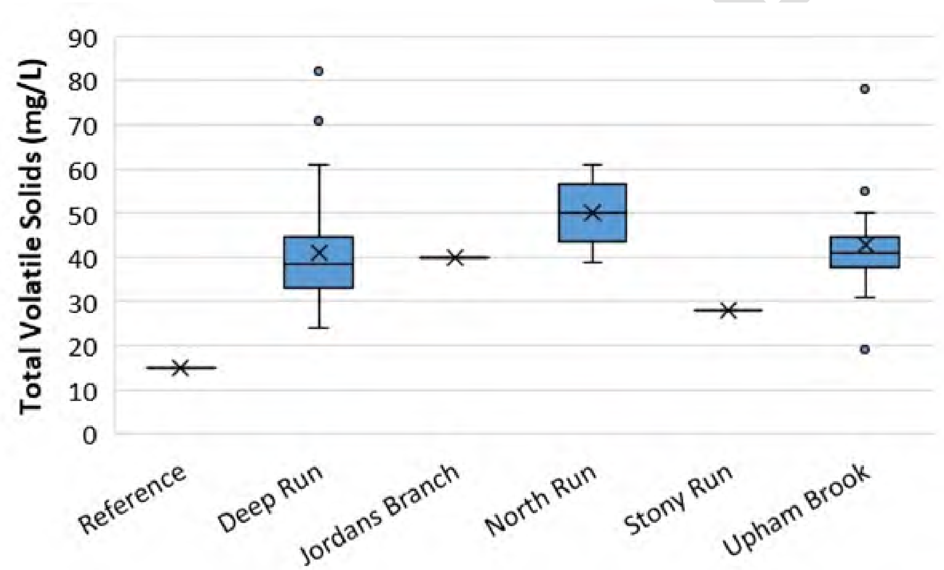

Figure 29. Total volatile solids in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station.

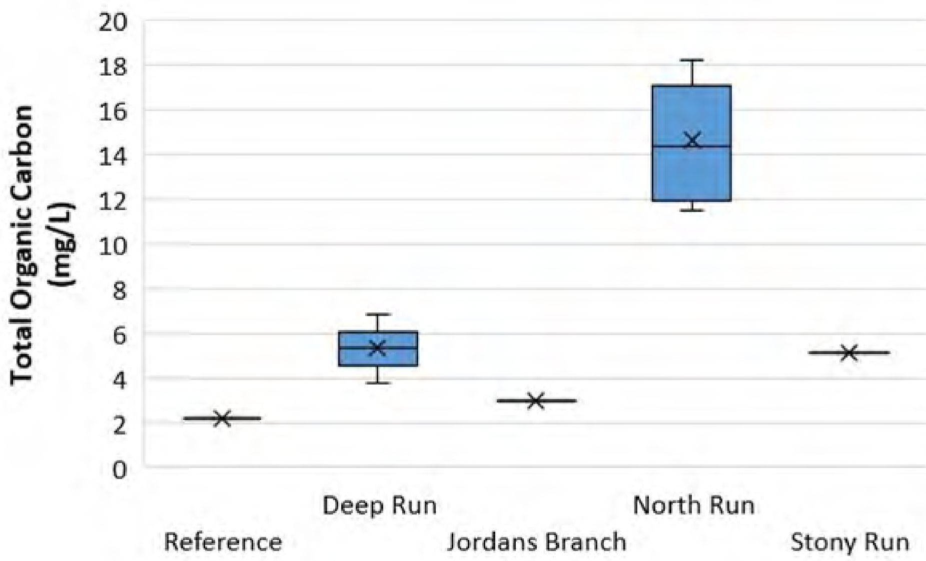

Figure 30. Total organic carbon in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station.

2.4.8. Nutrients - Phosphorus

Nitrogen and phosphorus are the primary nutrients of concern in freshwater. These nutrients are necessary to support healthy ecosystems, but excess nutrients can lead to eutrophication. Excess nutrients spur algae growth and can change the benthic community composition. An overabundance of algae can reduce oxygen levels, leading to further changes in community composition and eventually hypoxic conditions. The initiation of this eutrophication process is not reliant upon the total nutrient availability, but upon the availability of the limiting nutrient. The typical ratio of nitrogen to phosphorus in algae is 16:1 (Redfield, 1958) on a molar basis, or 7.2:1 on a N to P mass basis. So, ratios of nitrogen to phosphorus concentrations above 7.2 indicate that phosphorus is the limiting nutrient and ratios below 7.2 indicate that nitrogen is the limiting nutrient. In Goochland and Henrico Project streams, average nitrogen to phosphorus ratios range from 10 to 40, indicating that phosphorus is the limiting nutrient.

Over time, VDEQ has measured various forms of phosphorus (total and dissolved orthophosphate, and total and dissolved phosphorus). While these various forms signal the availability of nutrients for biological uptake, total phosphorus is used in the stressor analysis to identify the potential for nutrient enrichment. Figure 31 shows the total phosphorus levels in Goochland and Henrico Project streams. Total phosphorus averaged from 0.04 mg/L in Stony Run UT to 0.37 mg/L in Dover Creek. Only Dover Creek had statistically higher total phosphorus levels than the Jones Creek reference site (t-test with unequal variance and alpha = 0.05), which averaged 0.06 mg/L. Median total phosphorus values were in the low probability range for stressor effects in Deep Run and Stony Run UT, medium probability range in Jordans Branch, North Run, Stony Run, and Upham Brook, and high probability range for stressor effects in Dover Creek.

Figure 32 shows the time series of total phosphorus levels in Goochland and Henrico Project streams. Total phosphorus concentrations varied widely over time and by season in some streams. All streams except for Stony Run UT had individual samples above 0.1 mg/L total phosphorus and in the high probability range for stressor effects. In Dover Creek, 70% of samples were above 0.1 mg/L total phosphorus, and the maximum was as high as 2.27 mg/L. In other streams, excursions above 0.1 mg/L were much less prevalent and represented only 5% to 17% of samples.

While VDEQ does not have nutrient criteria for freshwater streams, USEPA has published recommended criteria by ecoregion (USEPA, 2000a). Deep Run, Dover Creek, Stony Run, and Stony Run UT are in the Piedmont Level 3 Ecoregion, and the Upham Brook watershed including North Run and Jordans Branch are primarily in the Southeastern Plains Level 3 Ecoregion (Figure 33). Based on these ecoregion designations, the recommended total phosphorus criterion based on the 25th percentile of streams is 0.03 mg/L for the Piedmont and 0.0225 mg/L for the Southeastern Plains. All of the impaired streams exceeded these recommended criteria, while the reference station did not.

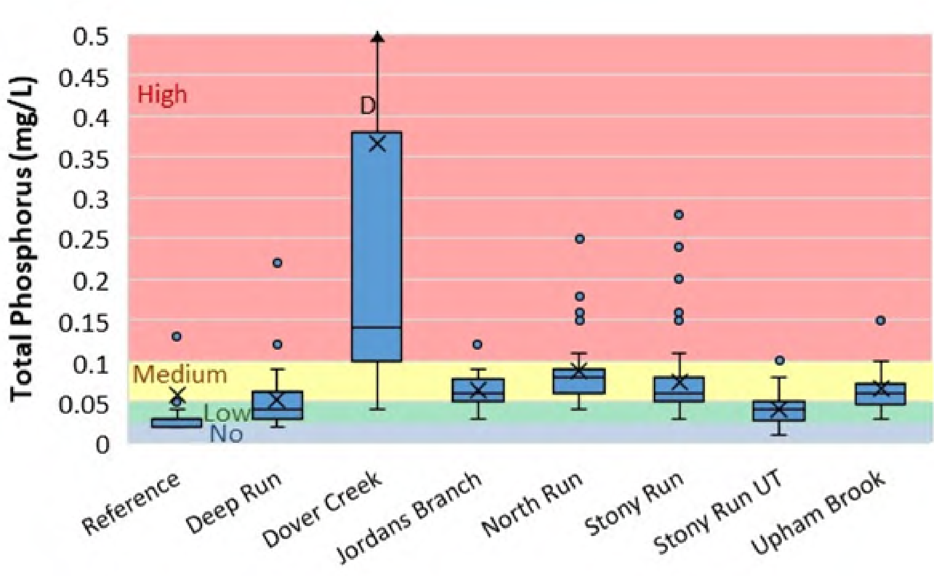

Figure 31. Total phosphorus in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. Colors represent the probability that data within that range would be responsible for causing stress. Arrows indicate that one or more results exceeds the graph scale.

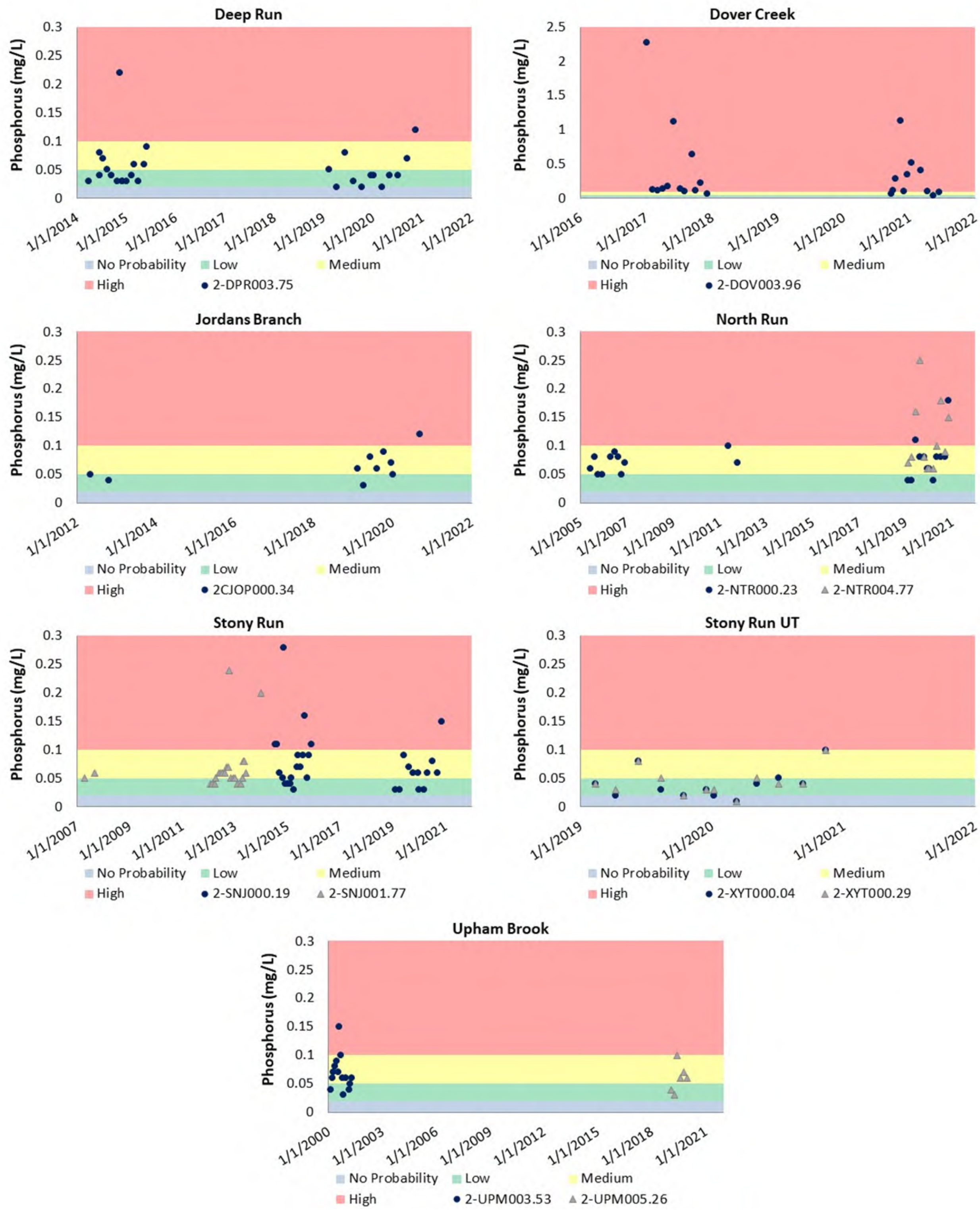

Figure 32. Total phosphorus over time in Goochland and Henrico Project streams. Colors represent the probability that data within that range would be responsible for causing stress. Due to higher phosphorus levels, the scale for Dover Creek is higher than for other streams.

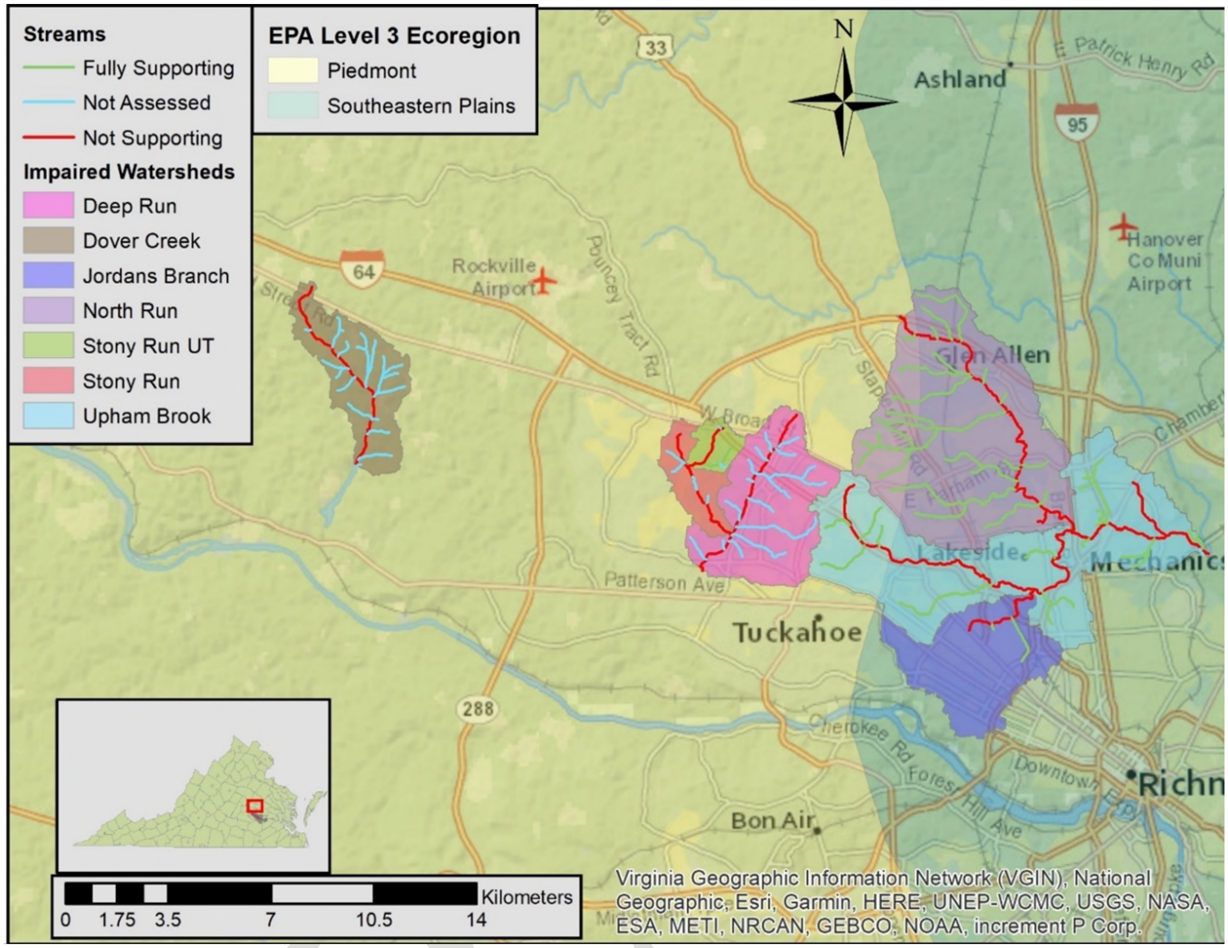

Figure 33. Location of impaired watersheds within EPA Level 3 Ecoregions.

2.4.9. Nutrients - Nitrogen

Over time, VDEQ has measured various forms of nitrogen (total and dissolved nitrite, total and dissolved nitrate, total and dissolved ammonia, total Kjeldahl nitrogen, and total nitrogen). While these various forms signal the availability of nutrients for biological uptake, total nitrogen is used in the stressor analysis to identify the potential for nutrient enrichment. Figure 34 shows the total nitrogen levels in Goochland and Henrico Project streams. Total nitrogen averaged from 0.67 mg/L in Deep Run to 3.7 mg/L in Dover Creek. Dover Creek, Jordans Branch, and Upham Brook were statistically higher in total nitrogen than the Jones Creek reference (t-test with unequal variance and alpha = 0.05). Median total nitrogen concentrations were in the low probability range for stressor effects in Deep Run, North Run, Stony Run, and Stony Run UT. Median values were in the medium probability range in Dover Creek and Upham Brook and in the high probability range in Jordans Branch.

Figure 35 shows total nitrogen concentrations over time in each of the Goochland and Henrico Project streams. Total nitrogen concentrations varied widely over time and by season in some streams. Concentrations were generally in the low to medium probability range for stressor effects in most streams. Only Dover Creek, Jordans Branch, and Upham Brook had excursions into the high probability range. In these streams, 43%, 60%, and 17% of samples were in the high probability range, respectively.

While VDEQ does not have nutrient criteria for freshwater streams, USEPA has published recommended criteria by ecoregion (USEPA, 2000a). Deep Run, Dover Creek, Stony Run, and Stony Run UT are in the Piedmont Level 3 Ecoregion, and the Upham Brook watershed including North Run and Jordans Branch are in the Southeastern Plains Level 3 Ecoregion (Figure 33). The recommended total nitrogen criterion based on the 25th percentile of streams is 0.615 mg/L for the Piedmont and 0.618 mg/L for the Southeastern Plains. All Goochland and Henrico Project streams, including the Jones Creek reference, exceeded these criteria.

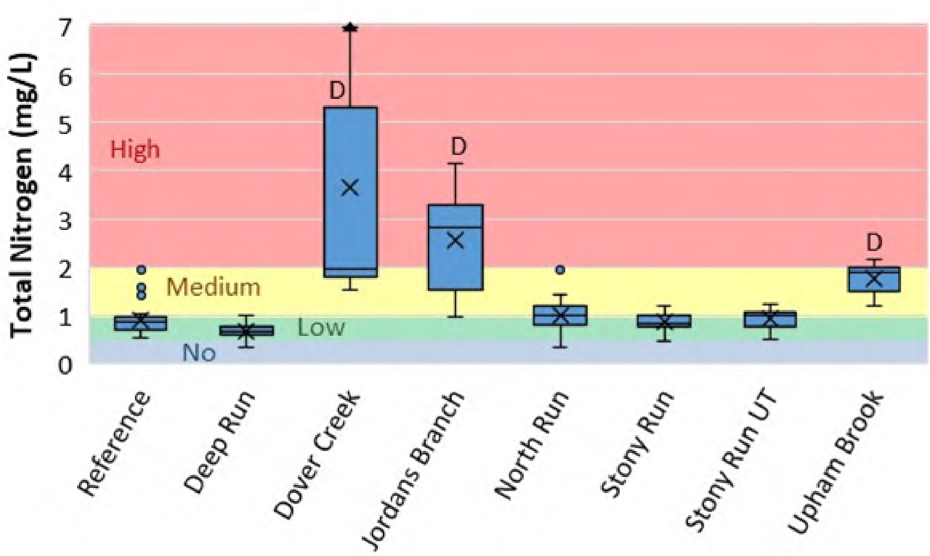

Figure 34. Total nitrogen in Goochland and Henrico Project streams. Boxes represent the inter-quartile range, whiskers represent minimum and maximum values excluding outliers, lines represent the median, and the X represents the mean. Dots represent outliers that are greater than 1.5 times the inter-quartile range away from the mean. The "D" indicates a statistically significant difference from the Jones Creek reference station. Colors represent the probability that data within that range would be responsible for causing stress. Arrows indicate that one or more results exceeds the graph scale.

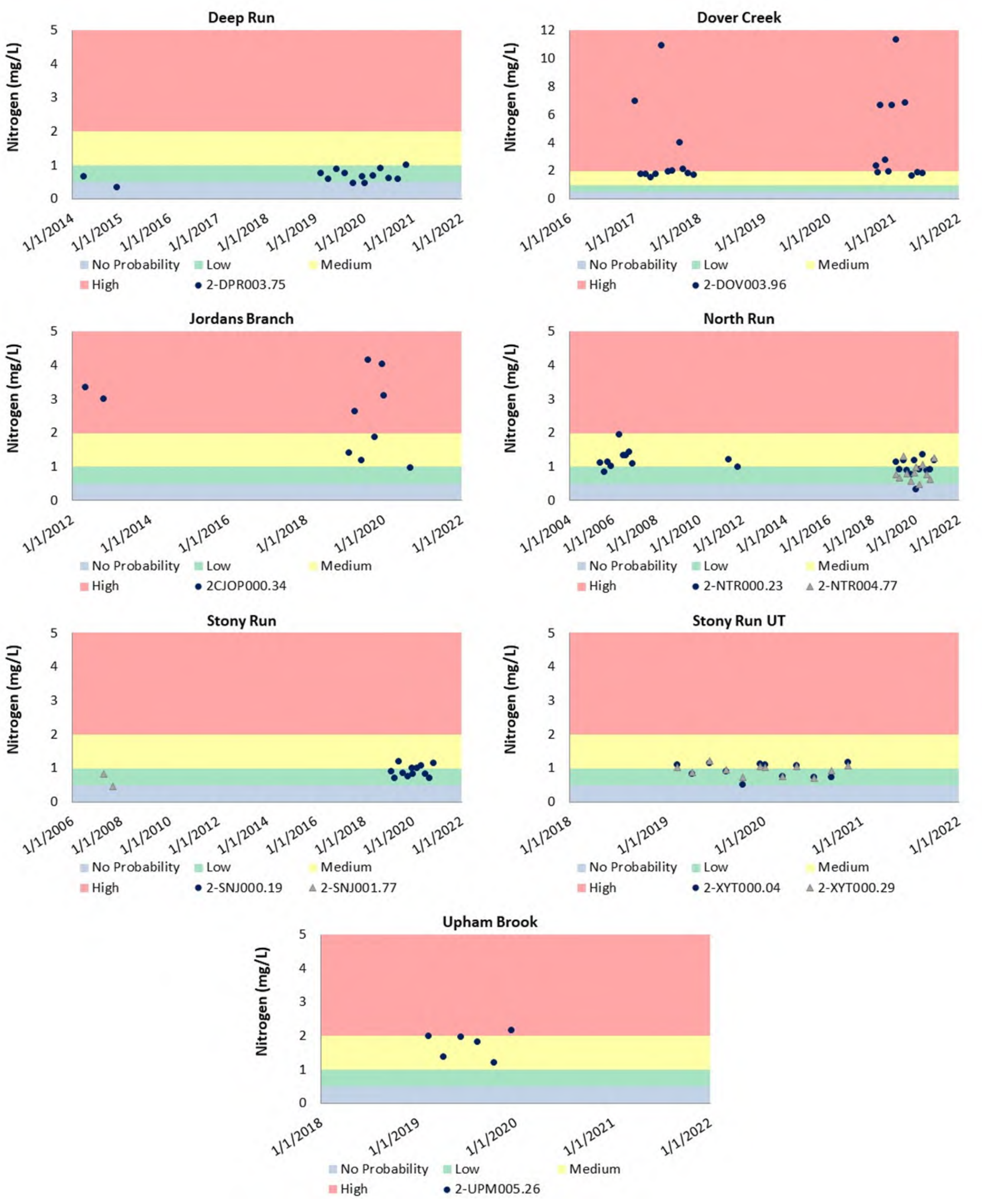

Figure 35. Total nitrogen concentration over time in Goochland and Henrico Project streams. Colors represent the probability that data within that range would be responsible for causing stress. Due to higher nitrogen levels, the scale for Dover Creek is higher than for other streams.

2.4.10. Ammonia

Ammonia is a reduced form of nitrogen that can be toxic at certain temperatures and pHs. Figure 36 shows the ammonia levels in Goochland and Henrico Project streams along with the relevant water quality standards. The water quality standard for ammonia is dependent upon pH and temperature, so it varies with each sample. None of the samples at any of the impaired stations had ammonia levels above, or even close to, the water quality standard. Ammonia levels averaged from the detection limit of 0.04 mg/L in Stony Run and Stony Run UT to 0.20 mg/L in Dover Creek. In addition to the impaired benthic stations, ammonia data from 11 other stations within the impaired watersheds were analyzed. Among 137 ammonia measurements from these stations, none were above the respective water quality standard based on the temperature and pH at the time of sampling. The maximum observed ammonia level at any of the stations was 0.52 mg/L at station 2-NTR003.42. Even at this maximum level, it was well below the calculated chronic water quality criterion of 4.9 mg/L.

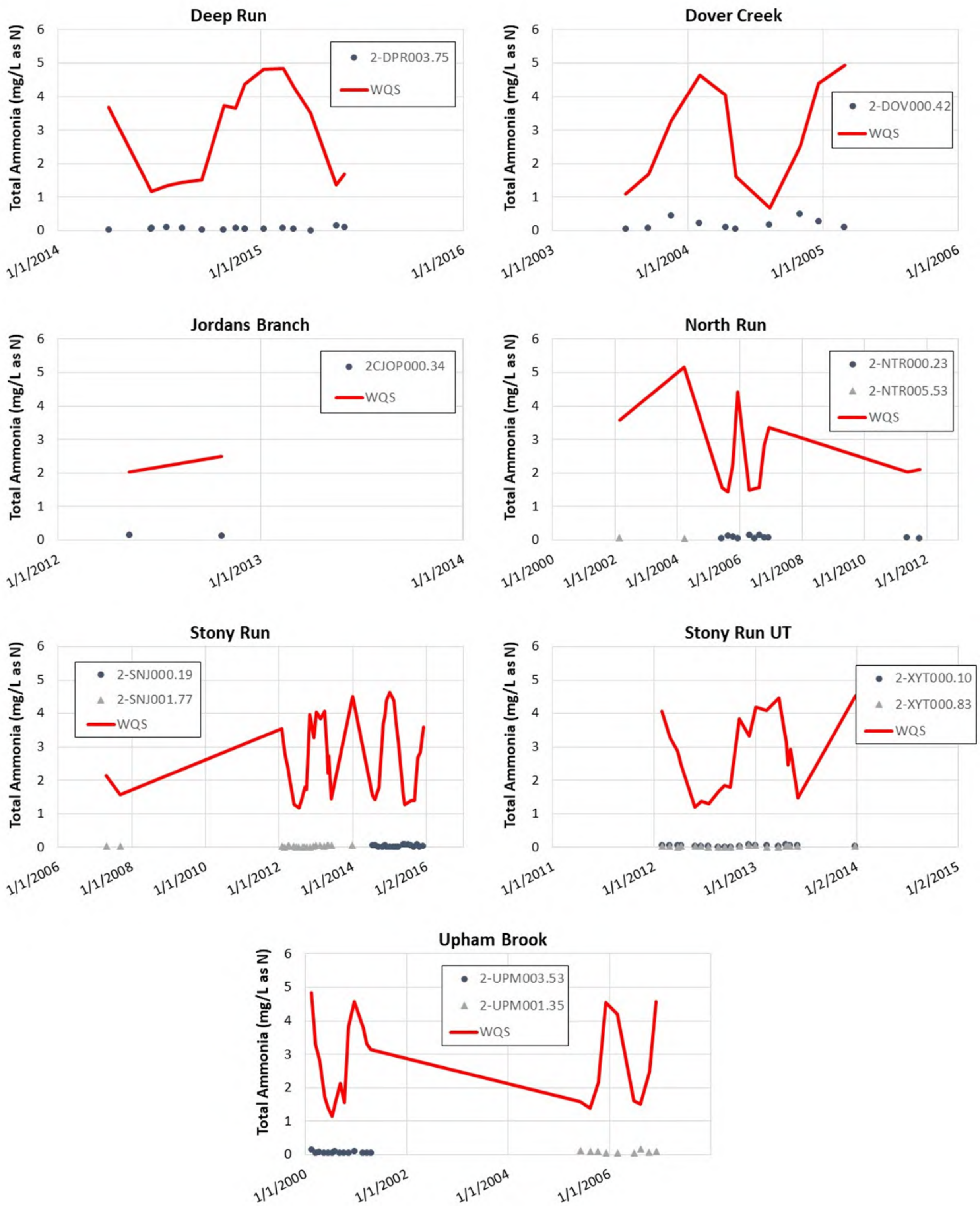

Figure 36. Ammonia levels in Goochland and Henrico Project streams. The red line represents the calculated water quality standard based on temperature and pH at the time of sampling.

2.4.11. Dissolved Metals

Dissolved metals were measured in each of the Goochland and Henrico Project streams on at least one occasion. Table 11 shows the range and average values of eight metals in each stream along with the associated water quality standard (9VAC25-260-140). Virginia's water quality standards for dissolved metals depends upon the hardness of the water (except for arsenic and selenium), so standards were calculated specifically for each stream based on hardness values measured at the time of sampling. All average dissolved metals concentrations were below the respective water quality standards, indicating that these metals do not pose a risk to aquatic life.

For toxic metals that do not have chronic water quality criteria for aquatic life use in Virginia (aluminum, antimony, barium, beryllium, silver, and thallium), toxicity reference values (TRVs) were obtained from the literature. TRVs are threshold values below which toxic freshwater effects are not expected. Table 12 shows the range and average values of these six metals at each of the stations along with the associated TRVs. None of the stations exceeded TRVs in any of the samples, indicating that these metals are not expected to pose a risk to aquatic life.

To investigate the combined effects of dissolved metals, a criterion unit was calculated for each sample as the ratio of measured values to the chronic water quality criterion. In cases where the measured value was censored at the detection limit, half the detection limit was used for the criterion unit calculation. The criterion unit values for each of the eight metals subject to Virginia water quality standards were then summed to obtain a cumulative criterion unit (CCU) for each sampling event. The cumulative criterion unit represents the additive effect of the metals in total. A value greater than one indicates that the combined effects of the metals acting additively could be toxic. The CCUs ranged from 0.043 in Deep Run to 0.44 in North Run (Table 13). The CCU values calculated for the Goochland and Henrico Project streams fall into the range of no probability of causing stressor effects, according to VDEQ's stressor threshold analysis (VDEQ, 2017).

To investigate the combined effects of dissolved metals that do not have chronic water quality criteria for aquatic life in Virginia, a toxicity reference value (TRV) quotient was calculated for each sample as the ratio of measured values to the literature-based TRV. In cases where the measured value was censored at the detection limit, half the detection limit was used for the TRV quotient. The TRV quotient values for each of the six metals were then summed to obtain a TRV index for each sampling event. The TRV index is similar to the CCU and represents the additive effect of the metals in total. A value greater than one indicates that the combined effects of the metals acting additively could be toxic. The TRV index values ranged from 0.015 in Deep Run to 0.45 in North Run and Stony Run (Table 13). All of the TRV index values were below 1.0, indicating that these six dissolved metals are not likely a stressor to the benthic community.

Table 11. Average dissolved metals concentrations and corresponding water quality standards for Goochland and Henrico Project streams.

Metal	Water Quality Standard[1] (µg/L)	Average Conc. (Range)[2] in µg/L							
		Genito Creek Reference	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook
Arsenic	150	0.2	0.30 (0.28-0.31)	0.2	0.40 (0.34-0.46)	1.1 (0.62-1.7)	0.55 (0.5-0.59)	0.41	0.33
Cadmium	0.41 (0.22-0.59)	0.1	0.065 (0.03-0.10)	0.1	0.065 (0.03-0.10)	0.08 (0.02-0.1)	0.1 (0.1-0.1)	0.1	0.1
Chromium	41 (21-60)	0.3	0.25 (0.20-0.30)	0.3	0.37 (0.30-0.43)	1.1 (0.3-1.6)	0.25 (0.2-0.3)	0.3	0.3
Copper	4.8 (2.4-7.2)	0.27	1.3 (1.2-1.4)	0.31	1.8 (1.6-1.9)	2.2 (1.5-3.5)	2 (1.7-2.2)	2.2	1.6
Lead	4.9 (1.9-8.0)	0.1	0.045 (0.02-0.07)	0.1	0.03 (0.03-0.03)	0.7 (0.34-1.1)	0.13 (0.1-0.16)	0.1	0.13
Nickel	11 (5.4-16)	0.2	0.51 (0.29-0.72)	0.2	1.6 (1.3-1.9)	1.2 (0.68-1.8)	0.47 (0.44-0.5)	0.43	1.1
Selenium	5	0.3	0.21 (0.14-0.27)	0.4	0.28 (0.21-0.34)	0.32 (0.1-0.5)	0.32 (0.13-0.5)	0.13	0.1
Zinc	64 (31-95)	0.5	5.6 (1.6-9.7)	0.92	18 (14-22)	9.1 (4.5-13)	3.7 (3.5-3.9)	4.7	9.3

[1] Water quality standards for all metals except for arsenic and selenium are hardness based, so standards varied with individual samples.
[2] No range information is given for sites with only a single metals sample.

Table 12. Average dissolved metals concentrations and corresponding toxicity reference values for Goochland and Henrico Project streams.

Metal	Toxicity Reference Value (µg/L)	Average Conc. (Range)[1] in µg/L							
		Genito Creek Refer-ence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook
Aluminum[2]	1000 (600-1300)	5.96	10 (4.7-15)	11	5.9 (4.1-7.7)	100 (30-210)	19 (18-19)	20	5
Antimony[3]	30	0.02	0.1 (0.09-0.11)	0.02	0.53 (0.42-0.63)	0.19 (0.11-0.24)	0.36 (0.21-0.5)	0.2	0.42
Barium[4]	1700	32.9	56 (43-69)	32	73 (71-75)	31 (22-35)	45 (39-52)	53	61
Beryllium[5]	5.3	0.1	0.08 (0.03-0.13)	0.2	0.04 (0.04-0.04)	0.13 (0.06-0.25)	0.095 (0.09-0.1)	0.12	0.02
Silver[3]	0.12	0.02	0.0035 (0.003-0.004)	0.02	0.017 (0.004-0.03)	0.052 (0.004-0.1)	0.052 (0.004-0.1)	0.004	0.004
Thallium[3]	40	0.01	0.015 (0.01-0.02)	0.02	0.03 (0.02-0.04)	0.11 (0.01-0.2)	0.055 (0.01-0.1)	0.01	0.02

[1] No range information is given for sites with only a single metals sample.
[2] Toxicity reference value was based on pH, hardness, and dissolved organic carbon as specified in USEPA, 2018b.
[3] Toxicity reference value from USEPA, 1987.
[4] Toxicity reference value from Golding et al., 2018.
[5] Toxicity reference value from USEPA, 1980.

Table 13. Cumulative criterion units and toxicity reference value index scores for dissolved metals in Goochland and Henrico Project streams.

Stream	Station	Date	CCU[1]	TRV Index[2]
Deep Run	2-DPR003.75	4/2/2014	0.043	0.015
	2-DPR003.75	9/24/2020	0.14	0.022
Dover Creek	2-DOV003.55	4/10/2017	0.42	0.11
Jordans Branch	2CJOP000.34	5/9/2012	0.099	0.13
	2CJOP000.34	9/29/2020	0.12	0.023
North Run	2-NTR000.23	5/19/2011	0.074	0.024
	2-NTR000.23	10/5/2020	0.19	0.023
	2-NTR005.53	6/3/2003	0.36	0.45
	2-NTR005.53	3/22/2004	0.44	0.45
Stony Run	2-SNJ001.77	4/23/2007	0.35	0.45
	2-SNJ001.77	10/1/2020	0.19	0.023
Stony Run UT	2-XYT000.29	10/1/2020	0.19	0.023
Upham Brook	2-UPM005.26	10/6/2020	0.13	0.023

[1] Cumulative criterion unit (CCU) is the sum of the dissolved metal concentration to water quality standard ratio for each metal. Values in blue are in the no probability range of stressor effects.
[2] Toxicity reference value (TRV) index is the sum of the dissolved metal concentration to toxic threshold value ratio for each metal.

2.4.1. Toxic Organics

A list of 55 toxic organic compounds were analyzed in the water column of Jordans Branch (2-JOP002.23) on one occasion (7/22/2013). None of the 55 compounds were detected. Data on toxic organic compounds were not available for the other impaired streams in the Goochland and Henrico Project.

2.4.2. Sediment Toxics - PAHs

Polycyclic aromatic hydrocarbons (PAHs) are a class of chemicals that occur naturally in coal, oil, and gasoline and can be generated when organic fuels are burned. PAHs in the aquatic environment are commonly associated with oil or fuel leaks or spills, but PAHs can also be elevated in urban areas from the runoff of deposited fossil fuel combustion byproducts. Many PAH compounds are toxic and can adversely impact benthic aquatic communities when they build up in sediments. PAHs were analyzed in sediments collected from North Run (2-NTR005.53) on 3/22/2004. A total of 17 PAH compounds were analyzed, and 10 were below detection. For those that were above detection limits, none exceeded threshold effect concentrations (TEC) or probable effect concentrations (PEC) reported by MacDonald *et al.* (2000). As a result, PAHs are likely a non-stressor in North Run. PAH data were not available for the other impaired streams in the Goochland and Henrico Project.

2.4.3. Sediment Toxics - PCBs

Polychlorinated biphenyls (PCBs) are a group of man-made chlorinated organic compounds that were widely used in electrical equipment and other applications from the 1930s to 1970s. While their manufacturing has been banned in the US for decades, these compounds are extremely persistent in the environment and can continue to produce toxicity in aquatic sediments. PCBs were analyzed in sediments collected from North Run (2-NTR005.53) on 3/22/2004. A total of 19 individual or co-eluting PCB congeners and total PCBs were analyzed, and all but one were below detection. PCB 1 was detected but was below the quantification level and estimated at a concentration of 6 ug/kg. This value and the non-detect total PCB value are well below the probable effect concentration (PEC) of 676 ug/kg reported by MacDonald *et al.* (2000), so PCBs are likely a non-stressor in North Run. PCB data were not available for the other impaired streams in the Goochland and Henrico Project.

2.4.4. Sediment Toxics - Pesticides

A total of 83 different pesticide compounds were analyzed in the sediments of North Run (2-NTR005.53) on two occasions (2/21/2002 and 3/22/2004). Of the 83 compounds, 77 were below detection levels and only 6 were detected. Aldrin, alpha-chlordane, gamma-chlordane, diazinon, dibromochloropropane, and tokuthion were detected in sediments but were at levels too low to quantify. Pesticide data were not available for the other impaired streams in the Goochland and Henrico Project.

2.4.5. Sediment Toxics - Metals

A total of 16 metals were measured in the sediments of North Run (at 2-NTR000.23 and 2-NTR005.53) and Stony Run. Levels of the eight more toxic metals were compared to threshold effect concentrations (TECs) and probable effect concentrations (PECs) from MacDonald *et al.* (2000). TECs are levels below which toxic effects are unlikely, and PECs are levels above which toxic effects are likely. Selected metals with published effect thresholds are shown in Table 14.

All metal concentrations in sediments of all streams were below both the TEC and PEC values. This indicates that sediment metals are likely a non-stressor in these streams. Sediment metals data were not available for the other impaired streams in the Goochland and Henrico Project.

Table 14. Metals concentrations in sediments from Goochland and Henrico Project streams.

Metal	TEC[1] (mg/kg)	PEC[2] (mg/kg)	Concentration (mg/kg)		
			North Run (2-NTR000.23)	North Run[3] (2-NTR005.53)	Stony Run (2-SNJ001.77)
Arsenic	9.79	33	0.98	<5	<5
Cadmium	0.99	4.98	<0.02	<1	<1
Chromium	43.4	111	2.04	5.6 (<5-6.7)	<5
Copper	31.6	149	<0.4	5.1 (<5-5.3)	<5
Lead	35.8	128	8.81	15.1 (<5-26.1)	<5
Mercury	0.18	1.06	0.017	<0.1	<0.1
Nickel	22.7	48.6	0.25	<5	<5
Zinc	121	459	11.1	25.3 (7.8-45.1)	10

[1] TEC is the consensus-based Threshold Effect Concentration from MacDonald *et al*., 2000.
[2] PEC is the consensus-based Probable Effect Concentration from MacDonald *et al*., 2000.
[3] Value represents the average of three samples with range in parentheses.

2.4.1. Water Quality Regressions

To investigate the potential role of various water quality parameters impacting the benthic macroinvertebrate community, SCI scores at each station were regressed against water quality parameter values at those sites. Table 15 shows the results of these regressions ordered from most significant to least significant. The only parameters that exhibited a statistically significant regression (at the alpha = 0.05 level) were temperature and dissolved ion parameters (conductivity, total dissolved solids, chloride, sodium, and sulfate). Each of these parameters is associated with urbanization and impervious area. Temperature typically increases and the wash-off of dissolved solids increases as watersheds urbanize. While episodic excursions of dissolved ions during wintertime deicing events may be a possible short-term stressor, the observed water quality correlations among average conditions are likely due more to cross correlations with imperviousness than to causal relationships between dissolved ion parameters and benthic health. Temperatures were all well within water quality standards, and median conductivities were in the no- to low probability range for stressor effects in each of the impaired streams.

Table 15. Regression relationship between water quality parameters and stream condition index (SCI) scores.

Parameter	Regression Significant (Y/N)	r^2	p-value
Conductivity	Y	0.8	0.000097
Total Dissolved Solids	Y	0.69	0.0014
Chloride	Y	0.69	0.0028
Sodium	Y	0.65	0.0029
Sulfate	Y	0.69	0.0031
Temperature	Y	0.47	0.014
Total Suspended Solids	N	0.39	0.071
Total Volatile Solids	N	0.46	0.095
Dissolved Oxygen	N	0.19	0.16
Turbidity	N	0.3	0.26
pH	N	0.11	0.29
Phosphorus	N	0.085	0.36
Habitat	N	0.034	0.57
Nitrogen	N	0.0029	0.87
Ammonia	N	0.0025	0.89
Potassium	N	0.000021	0.99

3.0 CAUSAL ANALYSIS

JMU conducted this stressor identification analysis according to EPA's Stressor Identification Guidance Document (USEPA, 2000b) using the Causal Analysis/Diagnosis Decision Information System (CADDIS) (USEPA, 2018a). The CADDIS approach provides guidance on evaluating various lines of evidence to determine the cause of biological impairments. In the case of the Goochland and Henrico Project, JMU used the available data collected from the site, published water quality standards and threshold values, and available literature from other cases to investigate the potential causes of impairment in each of the impaired streams. Table 16 shows the lines of evidence suggested by the CADDIS approach, an explanation of the concept, and examples of how these lines of evidence were analyzed in this project. Some lines of evidence were not applicable, such as the analysis of biomarkers, field manipulations, or laboratory experiments. The majority of the lines of evidence, however, were investigated for this project.

Table 16. Lines of evidence used in the causal analysis approach.

Evidence	The Concept	Examples from this Project
Data from the Case		
Spatial Co-occurrence	The biological effect must be observed where the cause is observed, and must not be observed where the cause is absent.	Analysis of water quality and habitat data across stations
Temporal Co-occurrence	The biological effect must be observed when the cause is observed, and must not be observed when the cause is absent.	Analysis of temporal trends in benthic data
Evidence of Exposure or Biological Mechanism	Measurements of the biota show that relevant exposure to the cause has occurred, or that other biological mechanisms linking the cause to the effect have occurred.	NA
Causal Pathway	Steps in the pathways linking sources to the cause can serve as supplementary or surrogate indicators that the cause and the biological effect are likely to have co-occurred.	Development and analysis of causal pathways for stressors
Stressor-Response Relationships from the Field	As exposure to the cause increases, intensity or frequency of the biological effect increases; as exposure to the cause decreases, intensity or frequency of the biological effect decreases.	Correlation of water quality data with benthic score
Manipulation of Exposure	Field experiments or management actions that increase or decrease exposure to a cause must increase or decrease the biological effect.	NA
Laboratory Tests of Site Media	Controlled exposure in laboratory tests to causes (usually toxic substances) present in site media should induce biological effects consistent with the effects observed in the field.	NA
Temporal Sequence	The cause must precede the biological effect.	Analysis of temporal trends in benthic data
Verified Predictions	Knowledge of a cause's mode of action permits prediction and subsequent confirmation of previously unobserved effects.	NA
Symptoms	Biological measurements (often at lower levels of biological organization than the effect) can be characteristic of one or a few specific causes.	Analysis of benthic metrics, community composition, and functional feeding groups
Data from Elsewhere		
Stressor-Response Relationships from Other Field Studies	At the impaired sites, the cause must be at levels sufficient to cause similar biological effects in other field studies.	Water quality comparison with reference stations and stressor probability thresholds
Stressor-Response Relationships from Laboratory Studies	At the impaired sites, the cause must be at levels associated with related biological effects in laboratory studies.	Water quality comparison with VA water quality standards and literature threshold values
Stressor-Response Relationships from Simulation Models	At the impaired sites, the cause must be at levels associated with effects in mathematical models simulating ecological processes.	Confirmation through use of TMDL model
Mechanistically Plausible Cause	The relationship between the cause and biological effect must be consistent with known principles of biology, chemistry and physics.	Development and analysis of causal pathways for stressors
Manipulation of Exposure at Other Sites	Field experiments or management actions at other sites that increase or decrease exposure to a cause must increase or decrease the biological effect.	Confirmation through literature
Analogous Stressors	Agents similar to the causal agent at the impaired site should lead to similar effects at other sites.	Confirmation through literature

Multiple Types of Evidence		
Consistency of Evidence	Confidence in the argument for or against a cause is increased when many types of evidence consistently support or weaken it.	Weight of evidence approach
Explanation of the Evidence	Confidence in the argument for a candidate cause is increased when a post hoc mechanistic, conceptual, or mathematical model reasonably explains any inconsistent evidence.	Confirmation through use of TMDL model

For each impairment and for each potential candidate cause, the applicable lines of evidence were evaluated. For each line of evidence, the candidate cause was scored on a 3-point positive and negative scale (Table 17). This scale represents the strength of the evidence for or against each candidate cause. A weight of evidence approach was then used to sum the respective scores and classify candidate causes as either non-stressors, possible stressors, or probable stressors. If the summed scores for candidate causes were ≤0, the cause was classified as a non-stressor. If scores were 1-3, the cause was classified as a possible stressor. If scores were >3, the cause was classified as a probable stressor (Table 18).

Table 17. Scoring criteria used to evaluate candidate stressors.

Score	Explanation
+3	The line of evidence **strongly supports** the candidate stressor as the cause of the impairment
+2	The line of evidence **moderately supports** the candidate stressor as the cause of the impairment
+1	The line of evidence **weakly supports** the candidate stressor as the cause of the impairment
0	The line of evidence **does not support or refute** the candidate stressor as the cause of the impairment
-1	The line of evidence **weakly refutes** the candidate stressor as the cause of the impairment
-2	The line of evidence **moderately refutes** the candidate stressor as the cause of the impairment
-3	The line of evidence **strongly refutes** the candidate stressor as the cause of the impairment

Table 18. Scheme for classifying candidate causes based on causal analysis.

Total Score	Classification
<-2	Non-Stressor
-1	
0	
+1	Possible Stressor
+2	
+3	
+4	Probable Stressor
+5	
>+6	

3.1. Temperature

Table 19 shows the causal analysis results for temperature across Goochland and Henrico Project streams. Total causal analysis scores ranged from -10 to -5, indicating that there is strong evidence that temperature is a non-stressor in these streams. No violations of the temperature standard were observed at any of the benthic monitoring stations even during summertime diurnal monitoring, when critical conditions should be observed. For this reason and others explained in Table 19, temperature was categorized as a non-stressor.

Table 19. Causal analysis results for temperature as a stressor.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-3	-3	-2	-3	-1	-3	-3	At the benthic station in each impaired stream, SCI scores were impaired, but temperature values were within water quality standards. One station on Stony Run exceeded temperature water quality standards on one date. Temperature was significantly higher in Stony Run and Jordans Branch than the reference.
Temporal Co-occurrence	-3	-3	-3	-3	-3	-3	-3	At the time of benthic sample collection, temperature at all sites met water quality standards.
Causal Pathway	2	-2	2	2	2	2	2	The pathway from high imperviousness to increased temperature is intact for all streams except for Dover Creek.

Stressor-Response Relationships from the Field	3	3	3	3	3	3	3	Temperature was significantly correlated with benthic health across sites.
Temporal Sequence	-3	-1	-1	-1	-3	-3	-1	Temperatures are generally highest in the late summer, however, fall benthic scores were higher than spring scores in Deep Run, Stony Run, and Stony Run UT. Seasonal benthic SCI trends were not observed in the other streams.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-2	-3	-3	All temperature values at benthic stations were within water quality standards. One station on Stony Run exceeded temperature water quality standards on one date.
Consistency of Evidence	-1	-1	-1	-1	-1	-1	-1	Most evidence refuted temperature as a stressor.
Sum	**-8**	**-10**	**-5**	**-6**	**-5**	**-8**	**-6**	

3.2. pH

Table 20 shows the causal analysis results for pH across Goochland and Henrico Project streams. Total causal analysis scores ranged from -24 to -9 in Deep Run, Dover Creek, Jordans Branch, Stony Run, Stony Run UT, and Upham Brook, indicating that there is strong evidence that pH is a non-stressor in these streams. However, the total causal analysis score in North Run was +6, indicating that pH is a probable stressor in this stream. Four samples and three out of six at the upper North Run benthic station were below the water quality standard of 6.0. The remaining streams did not exhibit violations of the pH standard at benthic monitoring stations (with the exception of 1 sample in Upham Brook). For these reasons and others explained in Table 20, pH was categorized as a probable stressor in North Run and a non-stressor in the remaining streams.

Table 20. Causal analysis results for pH as a stressor.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-3	-3	-3	2	-3	-3	1	In most streams, SCI scores were impaired, but all pH values were within water quality standards and in the low probability range for stressor effects. In North Run, 4 samples (and 3 out of 6 at the benthic station) were

								below the water quality standard of 6. In Upham Brook, 1 sample was below the water quality standard of 6.
Temporal Co-occurrence	-3	-3	-3	2	-3	-3	-3	At the time of benthic sample collection, pH at all sites except for the upper North Run station met water quality standards. pH at the upper North Run station was below the water quality standard on 3 out of 6 benthic collection dates.
Causal Pathway	-3	-3	-3	2	-3	-3	-3	The causal pathway from wetland decomposition to low pH from organic acid formation is intact for upper North Run. This pathway includes ample wetlands within the watershed, high dissolved organic matter, blackwater conditions, and low pH. No other streams exhibited evidence of this pathway.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	-3	pH was not significantly correlated with benthic health across sites.
Temporal Sequence	-1	0	0	0	-1	-1	0	Spring SCI scores were lower than fall scores in Deep Run, Stony Run, and Stony Run UT, however, no seasonal trend in pH was observed. pH values were consistently in the low probability range for stress effects. In all other streams, distinct seasonal trends were not identified in SCI scores or pH.
Symptoms	-2	-2	-2	-2	-2	-2	-2	Biological Condition Gradient analysis did not identify any of the top predominant taxa as increasing in abundance in the presence of acidity (score of 5), and average BCG scores for acidity were ranked low as a stressor.
Stressor-Response Relationships from Other Field Studies	-3	-3	-3	2	-3	-3	1	At the upper North Run benthic station, 3/6 pH values were in the medium probability range for stress effects. At the Upham Brook benthic station, 1/40 pH values were in the medium probability range for stress effects. In all other impaired streams, all pH values were in the low probability range for stress effects.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	2	-3	-3	1	At the upper North Run benthic station, 3/6 pH values were below water quality standards. At the Upham Brook benthic station, 1/40 pH values were below water quality standards. In all other impaired streams, all pH values were within water quality standards.
Consistency of Evidence	-3	-3	-3	1	-3	-3	-1	Evidence consistently supported pH as a stressor in upper North Run, but refuted pH as a stressor in the other streams.
Sum	**-24**	**-23**	**-23**	**6**	**-24**	**-24**	**-9**	

3.3. Dissolved Oxygen

Table 21 shows the causal analysis results for dissolved oxygen across Goochland and Henrico Project streams. Dissolved oxygen was categorized as a non-stressor in Deep Run, Dover Creek, Jordans Branch, and Stony Run UT with total causal analysis scores ranging from -14 to -2. At the benthic stations in these streams, DO was consistently above the 5.0 mg/L average water quality standard (except for one measurement in Deep Run). Dissolved oxygen was categorized as a possible stressor in Stony Run and Upham Brook, where total causal analysis scores were +1 and +3, respectively. In Stony Run, 15% of samples at the downstream benthic station were below 5.0 mg/L, and in Upham Brook, 5%-9% of samples were below the 5.0 mg/L average DO standard. Lastly, in North Run (specifically the upper benthic station), dissolved oxygen was categorized as a probable stressor with a causal analysis score of +13. In North Run, 17% of periodic DO measurements were below 5.0 mg/L, and diurnal DO measurements were consistently below the 4.0 mg/L instantaneous water quality standard. Additional rationale for stressor categorizations is explained in Table 21.

Table 21. Causal analysis results for dissolved oxygen as a stressor.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	1	-3	-2	3	2	-1	2	SCI scores were impaired in each of the streams, but periodic DO values in Dover Creek, Jordans Branch, and Stony Run UT were all above the water quality standard. Less than 10% of periodic DO values were below the 5 mg/L average water quality standard in Deep Run and Upham Brook, and greater than 10% of periodic DO values in North Run and Stony Run were below the 5 mg/L average water quality standard. During diurnal monitoring in the warm summer months, nighttime DO was below the 4 mg/L instantaneous standard in North Run. In Stony Run, Stony Run UT, and Upham Brook, nighttime DO was below the 5 mg/L average standard but not below the 4 mg/L instantaneous standard.
Temporal Co-occurrence	-2	-3	1	2	1	-2	-2	At the time of benthic sample collection, DO was in the high probability range for stressor effects on one occasion in Jordans Branch and four occasions in North Run. DO was in the medium probability range on two

								additional occasions in Jordans Branch and one occasion in Stony Run. DO was below water quality standards in 2/6 samples in North Run.
Causal Pathway	1	2	1	3	2	1	2	In North Run, there is strong evidence of a pathway from connected wetlands to decomposition of dissolved or deposited organic matter. In Dover Creek, Stony Run, and Upham Brook, there is evidence of a pathway through nutrient enrichment. In the other streams, there is weak evidence of a pathway that includes low slope and upstream impoundments.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	-3	DO was not significantly correlated with benthic health across sites.
Temporal Sequence	-2	-1	-1	-1	-2	-2	-1	DO is generally lowest in the late summer, however, fall benthic scores were higher than spring scores in Deep Run, Stony Run, and Stony Run UT. Benthic scores were generally consistent between spring and fall in the other streams.
Symptoms	-2	-2	2	3	-2	-2	2	Biological Condition Gradient analysis identified top predominant taxa in Jordans Branch, North Run, and Upham Brook that increase in abundance in the presence of low DO (score of 5). In North Run, DO was ranked as the top stressor.
Stressor-Response Relationships from Other Field Studies	1	1	2	1	1	1	1	Median DO values were in the low probability range for stress effects in each of the impaired streams, except for Jordans Branch, which was in the medium probability range. All streams had periodic excursions into the high probability range.
Stressor-Response Relationships from Laboratory Studies	1	-3	-2	3	2	-1	2	Periodic DO values in Dover Creek, Jordans Branch, and Stony Run UT were all above the water quality standard. Less than 10% of periodic DO values were below the 5 mg/L average water quality standard in Deep Run and Upham Brook, and greater than 10% of periodic DO values in North Run and Stony Run were below the 5 mg/L average water quality standard. During diurnal monitoring in the warm summer months, nighttime DO was below the 4 mg/L instantaneous standard in North Run. In Stony Run, Stony Run UT, and Upham Brook, nighttime DO was below the 5 mg/L average standard but not below the 4 mg/L instantaneous standard.
Consistency of Evidence	0	-2	0	2	0	0	0	Evidence generally supported DO as a stressor in North Run, refuted DO as a stressor in Dover Creek, and was mixed in other streams.
Sum	**-5**	**-14**	**-2**	**13**	**1**	**-9**	**3**	

3.4. Conductivity and Total Dissolved Solids

Table 22 shows the causal analysis results for conductivity and total dissolved solids across Goochland and Henrico Project streams. Conductivity and total dissolved solids were categorized as non-stressors in Dover Creek and North Run with total causal analysis scores ranging from -11 to -1. Strong evidence suggests that conductivity is a non-stressor in Dover Creek, where all conductivity values were in the no- to low probability range for stressor effects. Weak evidence suggests that conductivity is a non-stressor in North Run, where the median conductivity value was in the no probability range for stressor effects, but some excursions into the high probability range were observed. In the remaining streams (Deep Run, Jordans Branch, Stony Run, Stony Run UT, and Upham Brook), conductivity and total dissolved solids were categorized as possible stressors with total causal analysis scores ranging from +1 to +3. These streams also had conductivity excursions into the high probability range in addition to other rationale explained in Table 22. In all streams (except for Dover Creek), high conductivity and total dissolved solids were observed in the winter months and likely related to the high imperviousness in these watersheds in conjunction with the use of roadway deicing salts.

Table 22. Causal analysis results for conductivity and dissolved solids.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-1	-2	-1	-1	-1	-1	-1	Conductivity was significantly higher in all impaired streams than the reference, but median conductivity values were in the no- to low probability range for stress effects in each stream with no (Dover Creek) or only a few excursions into the high probability range (all other streams).
Temporal Co-occurrence	1	-1	1	-1	1	1	1	At the time of impaired benthic sample collections, conductivity levels were in the medium probability range for stress effects on one occasion in each stream except for North Run and Dover Creek.
Causal Pathway	2	-2	2	2	2	2	2	The causal pathway from imperviousness to runoff of roadway deicing salts is intact for all streams except for Dover Creek.

Stressor-Response Relationships from the Field	1	1	1	1	1	1	1	Conductivity was significantly correlated with SCI scores across sites, however, this correlation is likely due to a cross-correlation with imperviousness.
Temporal Sequence	1	0	0	0	1	1	0	Spring SCI scores were lower than fall scores in Deep Run, Stony Run, and Stony Run UT, and conductivity was generally highest in the winter prior to spring benthic collections. In all other streams, distinct seasonal trends were not identified in SCI scores.
Symptoms	1	-2	1	1	1	1	2	Biological Condition Gradient analysis identified predominant taxa in each stream except for Dover Creek that increase in abundance in the presence of high conductivity (score of 5), and conductivity ranked as the top stressor in Upham Brook (along with %imperviousness), but was ranked 3-6 for all other streams.
Stressor-Response Relationships from Other Field Studies	-1	-2	-1	-1	-1	-1	-1	Median conductivity values were in the no- to low probability range for stress effects with no (Dover Creek) or only a few excursions into the high probability range (all other streams).
Analogous Stressors	-1	-2	-2	-2	-2	-1	-1	The analogous stressor of total dissolved solids (TDS) was in the no- to low probability range for stress effects in all streams with only a few excursions into the medium or high range in Deep Run, Stony Run UT, and Upham Brook.
Consistency of Evidence	0	-1	0	0	0	0	0	Evidence refuted conductivity as a stressor in Dover Creek, but evidence was inconsistent in other streams.
Sum	**3**	**-11**	**1**	**-1**	**2**	**3**	**3**	

3.5. Dissolved Ions

3.5.1. Sodium

Table 23 shows the causal analysis results for dissolved sodium across Goochland and Henrico Project streams. Dissolved sodium was categorized as non-stressors in Dover Creek and North Run with total causal analysis scores of -13 and 0, respectively. Strong evidence suggests that dissolved sodium is a non-stressor in Dover Creek, where all sodium values were in the no- to low probability range for stressor effects. Weak evidence suggests that sodium is a non-stressor in North Run, where the median dissolved sodium value was in the medium probability range for stressor effects, but the literature indicates that sodium toxicity should not be observed at these levels. In the remaining streams (Deep Run, Jordans Branch, Stony Run, Stony Run UT, and Upham Brook), dissolved sodium was categorized as a possible stressor with total causal analysis scores ranging from +1 to +3. These streams had higher sodium levels with medians in the medium to high probability range. Additional rationale for stressor categorizations is explained in Table 23. Like conductivity patterns, sodium levels are likely related to the high imperviousness in these watersheds in conjunction with the use of roadway deicing salts.

Table 23. Causal analysis results for dissolved sodium.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	3	-3	3	2	2	3	3	All impaired stations except for Dover Creek had significantly higher sodium levels than the reference. Median sodium levels were in the no probability range for stressor effects in Dover Creek, medium range for North Run and Stony Run, and high probability range for the other impaired streams.
Temporal Co-occurrence	1	0	2	1	1	0	0	At or around the time of benthic sampling, dissolved sodium levels were in the high probability range for stressor effects in Jordans Branch and medium range in Deep Run, North Run, and Stony Run.
Stressor-Response Relationships from the Field	1	1	1	1	1	1	1	Dissolved sodium was significantly correlated with benthic health across sites, however, this correlation is likely due to a cross-correlation with imperviousness.
Temporal Sequence	1	0	0	0	1	1	0	Spring SCI scores were lower than fall scores in Deep Run, Stony Run, and Stony Run UT, and sodium was generally highest in the winter prior to spring benthic collections. In all other streams, distinct seasonal trends were not identified in SCI scores.
Stressor-Response Relationships from Other Field Studies	3	-3	3	2	2	3	3	Median sodium levels were in the no probability range for stressor effects in Dover Creek, medium range for North Run and Stony Run, and high probability range for the other impaired streams.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-3	-3	-3	In an analysis of toxicity to major ions (Mount et al., 2016), all LC50s for Ceriodaphnia exposed to sodium salts were well above the sodium levels in Goochland and Henrico project streams.
Mechanistically Plausible Cause	-2	-2	-2	-2	-2	-2	-2	Since sodium levels are well below toxic levels, benthic impacts due to sodium are unlikely.
Analogous Stressors	-1	-1	-1	-1	-1	-1	-1	For the analogous stressor of conductivity, median conductivity values were in the no- to low probability range for stress effects in each stream.
Consistency of Evidence	0	-2	0	0	0	0	0	Evidence strongly refutes sodium as a stressor in Dover Creek, but evidence is inconsistent in other streams.
Sum	**3**	**-13**	**3**	**0**	**1**	**2**	**1**	

3.5.2. Potassium

Table 24 shows the causal analysis results for dissolved potassium across Goochland and Henrico Project streams. Total causal analysis scores ranged from -4 to -1, indicating that there is moderate to weak evidence that potassium is a non-stressor in these streams. Median dissolved potassium values were in the medium probability range for stressor effects, but no excursions were observed into the high range (except for in Dover Creek). Values were also below toxic thresholds reported by Mount *et al.* (2016). Additional rationale for stressor categorizations is explained in Table 24.

Table 24. Causal analysis results for dissolved potassium.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	1	2	1	1	1	1	1	Each of the impaired streams was significantly higher in dissolved potassium than the reference, and median dissolved potassium values were in the medium probability range for stressor effects in each stream, with excursions into the high probability range in Dover Creek.
Temporal Co-occurrence	1	0	1	1	1	0	0	At or around the time of benthic sampling, dissolved potassium levels were in the medium probability range for stressor effects in Deep Run, Jordans Branch, North Run, and Stony Run.
Stressor-Response Relationships from the Field	1	1	1	1	1	1	1	Dissolved potassium was significantly correlated with benthic health across sites, however, this correlation is likely due to a cross-correlation with imperviousness.
Temporal Sequence	-2	-1	0	0	-2	-2	0	Spring SCI scores were lower than fall scores in Deep Run, Stony Run, and Stony Run UT, but potassium was typically highest in the fall in these streams. In all other streams, distinct seasonal trends were not identified in SCI scores, but potassium was highest in the fall or winter (Dover Creek).
Stressor-Response Relationships from Other Field Studies	1	2	1	1	1	1	1	Median dissolved potassium values were in the medium probability range for stressor effects in each stream. Dover Creek had excursions into the high probability range.
Stressor-Response Relationships from Laboratory Studies	-2	-2	-2	-2	-2	-2	-2	In an analysis of toxicity to major ions (Mount et al., 2016), all LC50s for Ceriodaphnia exposed to KCl were

								well above the potassium levels in Goochland and Henrico project streams.
Mechanistically Plausible Cause	-2	-2	-2	-2	-2	-2	-2	Since potassium levels are well below toxic levels, benthic impacts due to potassium are unlikely.
Analogous Stressors	-1	-1	-1	-1	-1	-1	-1	For the analogous stressor of conductivity, median conductivity values were in the no- to low probability range for stress effects in each stream.
Consistency of Evidence	0	0	0	0	0	0	0	Evidence supporting and refuting potassium as a stressor was inconsistent in each stream.
Sum	**-3**	**-1**	**-1**	**-1**	**-3**	**-4**	**-2**	

3.5.3. Chloride

Table 25 shows the causal analysis results for dissolved chloride across Goochland and Henrico Project streams. Total causal analysis scores ranged from -13 to -1, indicating that there is strong to weak evidence that dissolved chloride is a non-stressor in these streams. Median chloride levels ranged from the no probability range for stressor effects in Dover Creek to medium probability range in Deep Run, Jordans Branch, Stony Run UT, and Upham Brook. All chloride levels measured in all streams were well below the water quality standard of 230 mg/L. For this reason and others explained in Table 25, dissolved chloride was categorized as a non-stressor in all streams.

Table 25. Causal analysis results for dissolved chloride.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	2	-2	2	-1	-1	2	2	All impaired stations had significantly higher chloride levels than the reference. Median chloride levels were in the no probability range for stressor effects in Dover Creek, low range for North Run and Stony Run, and medium probability range for the other impaired streams.
Temporal Co-occurrence	2	0	1	1	0	0	0	At or around the time of benthic sampling, dissolved chloride levels were in the high probability range for stressor effects in Deep Run and medium range in Jordans Branch and North Run.
Stressor-Response Relationships from the Field	1	1	1	1	1	1	1	Dissolved chloride was significantly correlated with benthic health across sites, however, this correlation is likely due to a cross-correlation with imperviousness.

Temporal Sequence	1	0	0	0	1	1	0	Spring SCI scores were lower than fall scores in Deep Run, Stony Run, and Stony Run UT, and chloride was generally highest in the winter prior to spring benthic collections. In all other streams, distinct seasonal trends were not identified in SCI scores.
Symptoms	-3	-3	-3	-3	-3	-3	-3	Biological Condition Gradient analysis did not identify any predominant taxa that increase in abundance in the presence of high chloride (score of 5), and chloride was one of the lowest ranked stressors based on average BCG score.
Stressor-Response Relationships from Other Field Studies	2	-2	2	-1	-1	2	2	Median chloride levels were in the no probability range for stressor effects in Dover Creek, low range for North Run and Stony Run, and medium probability range for the other impaired streams.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-3	-3	-3	Chloride levels were all well below the Virginia water quality standard for chloride.
Mechanistically Plausible Cause	-2	-2	-2	-2	-2	-2	-2	Since chloride levels are well below toxic levels, benthic impacts due to chloride are unlikely.
Analogous Stressors	-1	-1	-1	-1	-1	-1	-1	For the analogous stressor of conductivity, median conductivity values were in the no- to low probability range for stress effects in each stream.
Consistency of Evidence	0	-1	0	-1	-1	0	0	Evidence consistently refutes chloride as a stressor in Dover Creek, North Run, and Stony Run, but evidence is inconsistent in the other streams.
Sum	**-1**	**-13**	**-3**	**-10**	**-10**	**-3**	**-4**	

3.5.4. Sulfate

Table 26 shows the causal analysis results for dissolved sulfate across Goochland and Henrico Project streams. Total causal analysis scores ranged from -12 to -9, indicating that there is strong evidence that dissolved sulfate is a non-stressor in these streams. In each stream, median dissolved sulfate values were in the no- to low probability range for stressor effects. Values were also below toxic thresholds reported by Mount *et al.* (2016). For these reasons and others explained in Table 26, dissolved sulfate was categorized as a non-stressor.

Table 26. Causal analysis results for dissolved sulfate.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-1	-3	-1	-2	-2	-2	-1	All impaired stations except for Dover Creek had significantly higher sulfate levels than the reference. Median sulfate levels were in the no- to low probability range for stressor effects in all streams.
Temporal Co-occurrence	-1	0	-1	-1	0	0	0	At or around the time of benthic sampling, dissolved sulfate levels were in the no- to low probability range for stressor effects in Deep Run, Jordans Branch, and North Run.
Stressor-Response Relationships from the Field	1	1	1	1	1	1	1	Dissolved sulfate was significantly correlated with benthic health across sites, however, this correlation is likely due to a cross-correlation with imperviousness.
Temporal Sequence	-1	0	0	0	-1	-1	0	Spring SCI scores were lower than fall scores in Deep Run, Stony Run, and Stony Run UT, but fall sulfate concentrations were generally highest. In all other streams, distinct seasonal trends were not identified in SCI scores.
Symptoms	1	1	-1	-1	1	-1	-1	Biological Condition Gradient analysis identified several of the top predominant taxa in Deep Run, Dover Creek, and Stony Run as increasing in abundance in the presence of high sulfate (score of 5). However, sulfate was one of the intermediate to low ranked stressors in each stream based on average BCG scores.
Stressor-Response Relationships from Other Field Studies	-1	-3	-1	-2	-2	-2	-1	Median sulfate levels were in the no- to low probability range for stressor effects in all streams.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-3	-3	-3	In an analysis of toxicity to major ions (Mount et al., 2016), all LC50s for Ceriodaphnia exposed to sulfate salts were well above the sulfate levels in Goochland and Henrico project streams.
Mechanistically Plausible Cause	-2	-2	-2	-2	-2	-2	-2	Since sulfate levels are well below toxic levels, benthic impacts due to sulfate are unlikely.
Analogous Stressors	-1	-1	-1	-1	-1	-1	-1	For the analogous stressor of conductivity, median conductivity values were in the no- to low probability range for stress effects in each stream.
Consistency of Evidence	-1	-1	-1	-1	-1	-1	-1	Evidence consistently refutes sulfate as a stressor in the Goochland and Henrico project streams.
Sum	**-9**	**-11**	**-10**	**-12**	**-10**	**-12**	**-9**	

3.6. Suspended Solids and Deposited Sediment

Table 27 shows the causal analysis results for suspended solids and deposited sediment across Goochland and Henrico Project streams. Total causal analysis scores ranged from +5 to +12, indicating that there is moderate to strong evidence that sediment is a probable stressor in these streams. While evidence varied slightly among the streams, lines of evidence supporting sediment as a probable stressor in most streams included:

- Total suspended solids concentrations and turbidity were significantly higher in most streams than in the unimpaired reference.
- Total habitat scores and habitat metrics that indicate instream sediment were significantly lower in most streams than in the reference.
- Total habitat scores in all streams except for Deep Run were in the medium probability range for stressor effects.
- Seasonal trends in benthic health in several streams indicated poor health in the spring following high spring flows that typically bring higher sediment loads.
- Imperviousness was high in all streams except for Dover Creek, providing a causal pathway for increased runoff and instability of benthic substrate.
- Total habitat was significantly correlated with benthic health across sites at the alpha = 0.1 level.
- Biological condition gradient analysis identified predominant taxa in all streams except Dover Creek that indicated sediment-associated stressors (total habitat or % imperviousness). Average BCG scores ranked the sediment-associated stressor of % imperviousness as the top stressor in all streams except for Dover Creek and the upstream North Run station.
- Taxonomic community structure indicated shifts to Dipteran-dominated communities that prefer sediment and away from Ephemeroptera, Plecoptera, and Trichoptera, which generally prefer clean substrate.

- Functional feeding group analysis indicated shifts to collectors that prefer sediment conditions and away from shredders and scrapers that prefer clean substrate.
- Relative bed stability analysis showed that the bed substrate in some streams (Deep Run, North Run, and Upham Brook) was unstable, and all streams exhibited significant embeddedness (43-96%).

For these reasons and others explained in Table 27, suspended solids and deposited sediment were categorized as probable stressors.

Table 27. Causal analysis results for suspended solids and deposited sediment.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	1	0	0	1	1	1	1	SCI scores were impaired at each station, and TSS or turbidity was significantly higher than in an unimpaired reference in Deep Run, North Run, Stony Run, Stony Run UT, and Upham Branch.
Temporal Co-occurrence	0	0	0	1	1	1	1	In Stony Run UT and Upham Brook, habitat scores correlated with benthic health scores. In North Run and Stony Run, elevated TSS levels occurred on or around the time of benthic sampling.
Causal Pathway	2	0	2	2	2	2	2	All streams except for Dover Creek had greater than 15% imperviousness, which means that the pathway from imperviousness to increased runoff to erosion and in-stream sediment transport is intact.
Stressor-Response Relationships from the Field	1	1	1	1	1	1	1	TSS was not significantly correlated with benthic health across sites at the alpha = 0.05 level, but was significant at the alpha = 0.1 level (p=0.071).
Temporal Sequence	1	0	0	0	1	1	0	Seasonal trends of lower spring benthic scores observed in Deep Run, Stony Run, and Stony Run UT may indicate excess sediment, as higher spring flows bring increased sediment loads.
Symptoms	3	1	3	2	3	3	3	Biological Condition Gradient analysis identified predominant taxa in each stream except for Dover Creek that increase in abundance in the presence of poor habitat or high % Imperviousness (score of 5), and % Imperviousness ranked as the top stressor in each of the impaired streams except for Dover Creek and the upstream North Run site. Functional feeding group analysis in each of the streams indicated a shift to collectors that thrive in sediment-rich habitats.

Stressor-Response Relationships from Other Field Studies	-1	2	3	3	3	3	2	Median total habitat scores were in the medium probability range for stress effects in all streams except for Deep Run. Habitat scores were significantly lower than the reference in Jordans Branch, North Run, Stony Run, and Stony Run UT.
Analogous Stressors	2	0	-1	1	-1	-1	1	Relative Bed Stability analysis showed values in the high probability range for stressor effects in Deep Run and medium probability range in North Run and Upham Brook. RBS values were in the no- to low probability range in Jordans Branch, Stony Run, and Stony Run UT.
Consistency of Evidence	1	1	1	1	1	1	1	Most evidence weakly supported sediment as a stressor.
Sum	**10**	**5**	**9**	**12**	**12**	**12**	**12**	

3.7. Organic Matter

Table 28 shows the causal analysis results for organic matter across Goochland and Henrico Project streams. In North Run, the total causal analysis score was +12, indicating that organic matter is a probable stressor in this stream, particularly at the upstream station (2-NTR005.53). In North Run, total organic carbon was much higher than in the reference, and dissolved organic carbon was above the 80th percentile of Mid-Atlantic coastal plain streams. High organic matter in this stream is also consistent with observations of blackwater conditions and contributes to a causal pathway from connected wetlands to high dissolved organic matter to low pH and low DO. In the remaining streams, total causal analysis scores ranged from -2 to 0, indicating that there is weak evidence that organic matter is a non-stressor in these streams. Additional rationale for stressor categorizations is explained in Table 28.

Table 28. Causal analysis results for organic matter.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	1	0	1	2	1	0	1	Total volatile solids and total organic carbon were higher in Deep Run, Jordans Branch, North Run, Stony Run, and Upham Brook than in the unimpaired reference stream. Total organic carbon in North Run averaged approximately seven times higher than the reference. No

								organic matter data were available for Dover Creek and Stony Run UT.
Temporal Co-occurrence	-1	0	-1	1	-1	0	0	At or around the time of benthic sampling, dissolved organic carbon in North Run was above the upper 80th percentile of Mid-Atlantic Coastal Plain streams. DOC levels in Deep Run, Jordans Branch, and Stony Run were near the median.
Causal Pathway	-2	-2	-2	2	-2	-2	-2	Causal pathway indicative of blackwater conditions was present for North Run. This pathway leads from wetlands to high organic matter to low pH and low dissolved oxygen. This pathway was not present in other streams.
Stressor-Response Relationships from the Field	1	1	1	1	1	1	1	Total volatile solids were not significantly correlated with benthic health across sites at the alpha = 0.05 level, but were significant at the alpha = 0.1 level (p=0.095).
Temporal Sequence	-1	0	0	0	-1	-1	0	Seasonal trends of lower spring benthic scores observed in Deep Run, Stony Run, and Stony Run UT are inconsistent with organic matter enrichment, since organic matter from primary productivity would increase in the summer and fall.
Symptoms	1	1	-1	1	1	1	-1	Functional feeding group analysis in Deep Run, Dover Creek, North Run, Stony Run, and Stony Run UT indicated an increase in filterers that thrive in organic-rich habitats, while filterers decreased in Jordans Branch and Upham Brook.
Stressor-Response Relationships from Other Field Studies	1	0	1	2	1	0	1	Total volatile solids or total organic carbon were higher than an unimpaired reference site in all streams except Dover Creek and Stony Run UT.
Stressor-Response Relationships from Laboratory Studies	-1	0	-1	2	-1	0	0	DOC in North Run was above the 80th percentile of Mid-Atlantic coastal plain streams, while Deep Run, Jordans Branch, and Stony Run were near the median.
Consistency of Evidence	0	0	0	1	0	0	0	Evidence consistently supported organic matter as a stressor in North Run, but was inconsistent in other streams.
Sum	**-1**	**0**	**-2**	**12**	**-1**	**-1**	**0**	

3.8. Nutrients

3.8.1. Total Phosphorus

Table 29 shows the causal analysis results for total phosphorus across Goochland and Henrico Project streams. In Deep Run and Stony Run UT, total causal analysis scores were -2, indicating that there is weak evidence that phosphorus is a non-stressor in these streams. In Jordans Branch and North Run, total causal analysis scores were +2 and +3, respectively, indicating that phosphorus is a possible stressor in these streams. In Dover Creek, Stony Run, and Upham Brook, total causal analysis scores ranged from +5 to +11, indicating that there is moderate to strong evidence that phosphorus is a probable stressor in these streams. Lines of evidence supporting phosphorus as a probable stressor in Dover Creek, Stony Run, and Upham Brook included:

- Median phosphorus levels in Stony Run and Upham Brook were in the medium probability range for stressor effects, and phosphorus levels in Dover Creek were in the high probability range.
- On or around the time of benthic sampling, phosphorus levels in Dover Creek and Stony Run were in the high probability range for stressor effects.
- Seasonal trends of lower spring benthic scores in Stony Run indicate possible nutrient enrichment.
- Large diurnal swings in DO in Upham Brook may indicate nutrient enrichment.
- Biological condition gradient analysis identified predominant taxa in each of these streams that indicate nutrient enrichment. Average BCG scores ranked nutrients as the top stressor in Dover Creek and second stressor in Stony Run and Upham Brook.
- Streams exceeded EPA-recommended phosphorus criterion for the ecoregion.

For these reasons and others explained in Table 29, phosphorus was categorized as a probable stressor in Dover Creek, Stony Run, and Upham Brook, a possible stressor in Jordans Branch and North Run, and a non-stressor in Deep Run and Stony Run UT.

Table 29. Causal analysis results for total phosphorus.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-1	3	2	2	2	-1	2	Dover Creek had significantly higher phosphorus levels than the reference stream, and median levels were in the high probability range for stressor effects. Median phosphorus levels were in the low probability range in Deep Run and Stony Run UT. All other streams were in the medium probability range for stressor effects.

Temporal Co-occurrence	0	2	1	0	1	0	0	At or near the time of benthic sample collection, total phosphorus levels were in the high probability range for stressor effect on two occasions in Dover Creek, one occasion in Jordans Branch and Stony Run, and no occasions in Deep Run and North Run, where values were in the medium probability range.
Causal Pathway	-2	-2	-2	-2	-2	-2	3	Diurnal DO measurements in most streams did not show strong fluctuations from daytime to nighttime indicating that the causal pathway from nutrient enrichment to low DO is weak or not intact. Only Upham Brook had large daily fluctuations in DO indicative of nutrient enrichment.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	-3	Phosphorus was not significantly correlated with benthic health across sites.
Temporal Sequence	1	0	0	0	1	1	0	Seasonal trends of lower spring benthic scores observed in Deep Run, Stony Run, and Stony Run UT may indicate nutrient enrichment, as higher spring flows bring increased nutrient loads.
Symptoms	1	3	-1	1	1	1	1	Biological Condition Gradient analysis identified top predominant taxa in each of the streams except for Jordans Branch that increase in abundance in the presence of nutrients (score of 5). Based on average BCG scores, nutrients ranked as the highest ranked stressor in Dover Creek and second to fourth highest ranked stressor in all other streams.
Stressor-Response Relationships from Other Field Studies	-1	3	2	2	2	-1	2	Median phosphorus levels were in the low probability range in Deep Run and Stony Run UT, high range in Dover Creek, and medium probability range in all other streams.
Stressor-Response Relationships from Laboratory Studies	1	2	1	1	1	1	1	Total phosphorus levels averaged 0.04 to 0.37 mg/L at impaired stations, which is above the EPA-recommended criterion for the respective Piedmont or Southeastern Plains ecoregions.
Mechanistically Plausible Cause	2	2	2	2	2	2	2	Nitrogen to phosphorus ratios indicate that phosphorus is the limiting nutrient in these streams.
Consistency of Evidence	0	1	0	0	0	0	1	Evidence consistently supported phosphorus as a stressor in Dover Creek and Upham Brook, but was inconsistent in other streams.
Sum	**-2**	**11**	**2**	**3**	**5**	**-2**	**9**	

3.8.2. Total Nitrogen

Table 30 shows the causal analysis results for total nitrogen across Goochland and Henrico Project streams. Total causal analysis scores ranged from -11 to -8 in Deep Run, North Run, Stony Run, and Stony Run UT, indicating that there is strong evidence that nitrogen is not a stressor in these streams. In Dover Creek, Jordans Branch, and Upham Brook, total causal analysis scores ranged from +1 to +3, indicating that nitrogen is a possible stressor in these streams. While some lines of evidence indicate nutrient enrichment as a stressor in these streams, nitrogen to phosphorus ratios showed that phosphorus (and not nitrogen) is the limiting nutrient. Additional rationale for stressor categorizations is explained in Table 30.

Table 30. Causal analysis results for total nitrogen.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-2	2	3	-1	-1	-1	2	Nitrogen levels at impaired Dover Creek, Jordans Branch, and Upham Brook stations were significantly higher than the unimpaired reference. Median nitrogen levels were in the low probability range for stressor effects in Deep Run, North Run, Stony Run, and Stony Run UT. Median nitrogen levels were in the medium probability range in Dover Creek and Upham Brook, and high probability range for stressor effects in Jordans Branch.
Temporal Co-occurrence	-1	1	2	0	-1	0	0	At or near the time of benthic sample collection, total nitrogen levels were in the high probability range for stressor effects on two occasions in Jordans Branch, one occasion in Dover Creek, and no occasions in Deep Run, North Run, and Stony Run. Values at the time of benthic sampling were in the medium probability range in North Run.
Causal Pathway	-2	-2	-2	-2	-2	-2	3	Diurnal DO measurements in most streams did not show strong fluctuations from daytime to nighttime indicating that the causal pathway from nutrient enrichment to low DO is weak or not intact. Only Upham Brook had large daily fluctuations in DO indicative of nutrient enrichment.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	-3	Nitrogen was not significantly correlated with benthic health across sites.
Temporal Sequence	1	0	0	0	1	1	0	Seasonal trends of lower spring benthic scores observed in Deep Run, Stony Run, and Stony Run UT may indicate nutrient enrichment, as higher spring flows bring increased nutrient loads.
Symptoms	1	3	-1	1	1	1	1	Biological Condition Gradient analysis identified top predominant taxa in each of the streams except for Jordans Branch that increase in abundance in the presence of nutrients (score of 5). Based on average

								BCG scores, nutrients ranked as the highest ranked stressor in Dover Creek and second to fourth highest ranked stressor in all other streams.
Stressor-Response Relationships from Other Field Studies	-2	2	3	-1	-1	-1	2	Median nitrogen levels were in the low probability range for stressor effects in Deep Run, North Run, Stony Run, and Stony Run UT. Median nitrogen levels were in the medium probability range in Dover Creek and Upham Brook, and high probability range for stressor effects in Jordans Branch.
Stressor-Response Relationships from Laboratory Studies	1	2	2	1	1	1	1	Total nitrogen levels averaged 0.67 to 3.7 mg/L at impaired stations, which is above the EPA-recommended criterion for the respective Piedmont or Southeastern Plains ecoregions.
Mechanistically Plausible Cause	-3	-3	-3	-3	-3	-3	-3	The nitrogen to phosphorus ratios in Goochland and Henrico Project streams ranged from 10 to 40, indicating that phosphorus, and not nitrogen, is the limiting nutrient controlling algae growth.
Consistency of Evidence	-1	0	0	-1	-1	-1	0	Evidence consistently refuted nitrogen as a stressor in Deep Run, North Run, Stony Run, and Stony Run UT, while evidence was inconsistent in the other streams.
Sum	**-11**	**2**	**1**	**-9**	**-9**	**-8**	**3**	

3.9. Ammonia

Table 31 shows the causal analysis results for ammonia across Goochland and Henrico Project streams. Total causal analysis scores ranged from -15 to -12, indicating that there is strong evidence that ammonia is not a stressor in these streams. All samples in all streams were well below the water quality standard for ammonia. Based on multiple lines of evidence explained in Table 31, ammonia was categorized as a non-stressor in all Goochland and Henrico Project streams.

Table 31. Causal analysis results for ammonia.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-3	-3	-3	-3	-3	-3	-3	In all streams, SCI scores were impaired, but ammonia values were well below water quality standards.
Temporal Co-occurrence	-1	0	-1	-1	-1	0	0	At or near the time of benthic sample collection, ammonia levels were well below water quality standards

								in Deep Run, Jordans Branch, North Run, and Stony Run.
Stressor-Response Relationships from the Field	-3	-3	-3	-3	-3	-3	-3	Ammonia was not significantly correlated with benthic health across sites.
Temporal Sequence	-2	0	0	0	-2	-2	0	Ammonia levels are generally highest in the late summer when water temperatures are highest, however, fall benthic scores were higher than spring scores in Deep Run, Stony Run, and Stony Run UT.
Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-3	-3	-3	All ammonia values in all streams were well below water quality standards.
Consistency of Evidence	-3	-3	-3	-3	-3	-3	-3	Evidence consistently refuted ammonia as a stressor.
Sum	**-15**	**-12**	**-13**	**-13**	**-15**	**-14**	**-12**	

3.10. Dissolved Metals

Table 32 shows the causal analysis results for dissolved metals across Goochland and Henrico Project streams. Total causal analysis scores ranged from -13 to -12, indicating that there is strong evidence that dissolved metals are not a stressor in these streams. In all streams, the CCU was in the no probability range for stressor effects. All metals in all streams were below water quality standards and reference toxicity values. For these reasons and others explained in Table 32, dissolved metals were categorized as non-stressors in all Goochland and Henrico Project streams.

Table 32. Causal analysis results for dissolved metals.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	-3	-3	-3	-3	-3	-3	-3	In all streams, SCI scores were impaired but dissolved metal cumulative criteria units (CCU) were in the no probability range for stressor effects.
Temporal Co-occurrence	-1	-1	-1	-1	-1	0	-1	At or near the time of benthic sample collection, metals CCU values were well below one in Deep Run, Dover Creek, Jordans Branch, North Run, Stony Run, and Upham Brook.
Stressor-Response Relationships from Other Field Studies	-3	-3	-3	-3	-3	-3	-3	CCU values for dissolved metals were in the no probability range for stressor effects in all streams.

Stressor-Response Relationships from Laboratory Studies	-3	-3	-3	-3	-3	-3	-3	All dissolved metals values were below water quality standards and published effect thresholds.
Consistency of Evidence	-3	-3	-3	-3	-3	-3	-3	Evidence consistently refuted dissolved metals as a stressor in all streams.
Sum	**-13**	**-13**	**-13**	**-13**	**-13**	**-12**	**-13**	

3.11. Sediment Toxics

Table 33 shows the causal analysis results for sediment metals across Goochland and Henrico Project streams. Total causal analysis scores ranged from -8 to -2, indicating that there is weak to strong evidence that sediment toxics are a non-stressor in these streams. In all streams with sediment toxics data, all parameters were below published effect thresholds. For streams that did not specifically have sediment toxics data, water column toxics data indicated that toxics were not a stressor. For these reasons and others explained in Table 33, sediment toxics were categorized as a non-stressor in all Goochland and Henrico Project streams.

Table 33. Causal analysis results for sediment toxics.

Evidence	Deep Run	Dover Creek	Jordans Branch	North Run	Stony Run	Stony Run UT	Upham Brook	Explanation
Spatial Co-occurrence	0	0	-1	-2	-1	-1	0	In North Run and Stony Run, SCI scores were impaired, but sediment toxics (metals, PAHs, PCBs, and pesticides) were below published effect thresholds. No sediment toxics data were available for the other streams; however, water column toxics were sampled in Jordans Branch and none were detected. In addition, if sediment toxics were present in Stony Run UT, they would likely be identified downstream in Stony Run.
Temporal Co-occurrence	0	0	0	-1	-1	0	0	At or around the time of benthic sampling, sediment toxics levels in North Run and Stony Run were well below published effect thresholds.
Stressor-Response Relationships from Laboratory Studies	0	0	-1	-2	-1	-1	0	All sediment toxics that were measured (metals, PAHs, PCBs, and pesticides) were below published effect thresholds. No sediment toxics data were available for the other streams; however, water column toxics were sampled in Jordans Branch and none were detected. In addition, if sediment toxics were present in Stony Run

								UT, they would likely be identified downstream in Stony Run.
Analogous Stressors	-2	-2	-2	-2	-2	-2	-2	In all streams, levels of dissolved metals were below WQS and toxic thresholds.
Consistency of Evidence	0	0	-1	-1	-1	-1	0	Evidence consistently refuted sediment toxics as a stressor in streams where data were available.
Sum	**-2**	**-2**	**-5**	**-8**	**-6**	**-5**	**-2**	

4.0 CAUSAL ANALYSIS SUMMARY

4.1. Probable Stressors

The total causal analysis scores for each candidate stressor are shown in Table 34. Candidate stressors with causal analysis scores ≤0 were classified as non-stressors, candidate stressors with causal analysis scores of 1-3 were classified as possible stressors, and candidate stressors with scores >3 were classified as probable stressors. Table 35 shows the non-stressors, possible stressors, and probable stressors identified for each impaired stream. The results indicate that sediment was identified as a probable stressor in all of the Goochland and Henrico Project streams, with causal analysis scores ranging from +5 to +12. In addition, phosphorus, was identified as a probable stressor in Dover Creek, Stony Run, and Upham Brook with causal analysis scores ranging from +5 to +11. Dissolved oxygen, pH, and organic matter were additional probable stressors in North Run, with causal analysis scores of +13, +6, and +12, respectively.

Table 34. Total causal analysis scores by stream and by candidate stressor. Green indicates non-stressors, orange indicates possible stressors, and red indicates probable stressors.

Candidate Stressor	**Deep Run**	**Dover Creek**	**Jordans Branch**	**North Run**	**Stony Run**	**Stony Run UT**	**Upham Brook**
Temperature	-8	-10	-5	-6	-5	-8	-6
pH	-24	-23	-23	6	-24	-24	-9
Dissolved Oxygen	-5	-14	-2	13	1	-9	3
Conductivity/Total Dissolved Solids	3	-11	1	-1	2	3	3
Dissolved Sodium	3	-13	3	0	1	2	1
Dissolved Potassium	-3	-1	-1	-1	-3	-4	-2
Dissolved Chloride	-1	-13	-3	-10	-10	-3	-4

Dissolved Sulfate	-9	-11	-10	-12	-10	-12	-9
Sediment	10	5	9	12	12	12	12
Organic Matter	-1	0	-2	12	-1	-1	0
Phosphorus	-2	11	2	3	5	-2	9
Nitrogen	-11	2	1	-9	-9	-8	3
Ammonia	-15	-12	-13	-13	-15	-14	-12
Dissolved Metals	-13	-13	-13	-13	-13	-12	-13
Sediment Toxics	-2	-2	-5	-8	-6	-5	-2

Table 35. Non-stressors, possible stressors, and probable stressors in Goochland and Henrico Project streams.

Stream	Non-Stressors	Possible Stressors	Probable Stressors	TMDL Target
Deep Run	Temperature, pH, Dissolved Oxygen, Dissolved Potassium, Dissolved Chloride, Dissolved Sulfate, Organic Matter, Phosphorus, Nitrogen, Ammonia, Dissolved Metals, and Sediment Toxics	-Conductivity/Total Dissolved Solids -Dissolved Sodium	-Sediment	-Sediment
Dover Creek	Temperature, pH, Dissolved Oxygen, Conductivity/Total Dissolved Solids, Dissolved Sodium, Dissolved Potassium, Dissolved Chloride, Dissolved Sulfate, Organic Matter, Ammonia, Dissolved Metals, and Sediment Toxics	-Nitrogen	-Sediment -Phosphorus	-Sediment -Phosphorus
Jordans Branch	Temperature, pH, Dissolved Oxygen, Dissolved Potassium, Dissolved Chloride, Dissolved Sulfate, Organic Matter, Ammonia, Dissolved Metals, and Sediment Toxics	-Conductivity/Total Dissolved Solids -Dissolved Sodium -Phosphorus -Nitrogen	-Sediment	-Sediment
North Run	Temperature, Conductivity/Total Dissolved Solids, Dissolved Sodium, Dissolved Potassium, Dissolved Chloride, Dissolved Sulfate, Nitrogen, Ammonia, Dissolved Metals, and Sediment Toxics	-Phosphorus	-pH -Dissolved Oxygen -Sediment -Organic Matter	-Sediment
Stony Run	Temperature, pH, Dissolved Potassium, Dissolved Chloride, Dissolved Sulfate, Organic Matter, Nitrogen, Ammonia, Dissolved Metals, and Sediment Toxics	-Dissolved Oxygen -Conductivity/Total Dissolved Solids -Dissolved Sodium	-Sediment -Phosphorus	-Sediment -Phosphorus
Stony Run UT	Temperature, pH, Dissolved Oxygen, Dissolved Potassium, Dissolved Chloride, Dissolved Sulfate, Organic Matter, Phosphorus, Nitrogen, Ammonia, Dissolved Metals, and Sediment Toxics	-Conductivity/Total Dissolved Solids -Dissolved Sodium	-Sediment	-Sediment
Upham Brook	Temperature, pH, Dissolved Potassium, Dissolved Chloride, Dissolved Sulfate,	-Dissolved Oxygen	-Sediment -Phosphorus	-Sediment -Phosphorus

	Organic Matter, Ammonia, Dissolved Metals, and Sediment Toxics	-Conductivity/Total Dissolved Solids -Dissolved Sodium -Nitrogen		

4.1.1. Sediment

Sediment was identified as a probable stressor in all of the Goochland and Henrico Project streams. Multiple lines of evidence supported this determination including habitat metrics, relative bed stability measurements, seasonal trends, biological condition gradient analysis, taxonomic community structure, and functional feeding group analysis (Section 3.6). Based on the observed data and causal analysis, a conceptual model was developed to describe the causal relationships between the sources of sediment in the watershed, increased suspended sediment loads, and the observed loss of benthic macroinvertebrates (Figure 37). In this conceptual model, sources of sediment are derived from point sources, the erosion of watershed soils, the wash-off of accumulated sediment on impervious surfaces, the erosion of streambanks, and the resuspension of channel sediments. These sources and other contributing factors lead to an increased particulate load (i.e., suspended sediment) in the stream. The increased particulate load then acts to biologically impair the stream through two pathways: a change in feeding niches to favor filter feeders and deposit feeders, and the filling of interstitial spaces that reduces available habitat. Benthic taxa data provide evidence of these pathways with an observed increase in filter and deposit feeders and a decrease in taxa richness. Habitat assessments and relative bed stability analysis also provide evidence of interstitial filling. The combined weight of evidence documented in the causal analysis supports this conceptual model of sediment as a stressor in the Goochland and Henrico Project streams. A TMDL developed to reduce sediment loads in the watershed will address the benthic impairments in these streams through the pathways described in Figure 37. In addition, efforts to address several contributing factors that exacerbate the impact of the sediment stressor will also be effective at reducing the impairment.

4.1.1.1. Contributing Factors

Several factors contribute to the impact of sediment in Goochland and Henrico Project streams, including crop and pasture management (in Dover Creek watershed), the underlying geology and soils of the region, land disturbance, high percent imperviousness in the watersheds, and poor riparian vegetation. In general, the underlying geology of the Piedmont and Southeastern Plains ecoregions naturally produce sandy stream bottoms of often unconsolidated material that is very mobile. This creates reduced habitat conditions for benthic macroinvertebrates that require more stable benthic substrate.

In the Dover Creek watershed, there is a modest amount of cropland (4.80%) and a large amount of pasture (25.89%) that is managed for livestock, primarily horses. The management practices on these agricultural lands play a significant role in the amount of sediment and agricultural wastes that are transported to the stream. Practices on these lands that result in exposed soil increase erosion and can contribute excess sediment to streams. Alternatively, best management practices on pasture and croplands that reduce erosion can be beneficial in reducing sediment loads. Agricultural best management practices such as livestock exclusion fencing, off-stream watering, cover crops, riparian buffers, rotational grazing, and others will likely be an important part of implementation plans to fully restore aquatic life in Dover Creek.

Land disturbance from development is another contributing factor to sediment impairment in the Goochland and Henrico Project streams. While most of the watersheds (except for Dover Creek) are already well developed, redevelopment and infilling can produce short-term land disturbance conditions. Land disturbance greatly increases the rates of watershed erosion, and while land disturbance is addressed in the TMDL through general permits, other actions can reduce the impact of this contributing factor. This includes proper enforcement of erosion and sediment control practices and regional planning and zoning practices that protect stream corridors.

Imperviousness is a significant factor contributing to sediment impairment in the Goochland and Henrico Project streams. As watersheds develop and the percentage of impervious surfaces increases, runoff during precipitation events increases. As the amount of runoff increases, peak flows in local streams increase causing streambank erosion and stream bed scouring. This scenario causes unstable habitat conditions for benthic macroinvertebrates and increased sediment loads. Brabec *et al.* (2002), found that fish and macroinvertebrate diversity decreased when watersheds exceeded 3.6 to 15% imperviousness, and Goochland and Henrico Project streams (excluding Dover Creek) range from 18% to 54% impervious. Land cover analysis in these watersheds revealed that % imperviousness was highly correlated with benthic health. As imperviousness increased, benthic health decreased. While the TMDL does not directly address the percentage of imperviousness in watersheds, efforts to reduce imperviousness and increase infiltration can support the TMDL and assist in reducing the impact of sediment. Practices such as rain gardens, green roofs, rain barrels, and pervious pavers can all reduce runoff. Regional planning, zoning practices, and building codes can also be implemented to discourage imperviousness and reduce runoff.

In association with increased imperviousness in the watershed, wintertime roadway deicing salt applications are another contributing factor to impairment in Goochland and Henrico Project streams. Conductivity/total dissolved solids and dissolved sodium were identified as possible stressors in all streams except for Dover Creek and North Run. Conductivity excursions into the high probability range for stressor effects range were observed during the winter in each of these streams. Depending on the magnitude and duration of these excursions, conductivity spikes can create toxic conditions for freshwater species (Corsi *et al*. 2010).

Lastly, poor riparian vegetation is a contributing factor to sediment impairments in some Goochland and Henrico Project streams. Riparian vegetation stabilizes stream banks and reduces bank erosion, which can often be a primary contributor to in-stream sediment loads. Practices such as riparian plantings, greenways, conservation easements, and regional planning and zoning practices that protect stream corridors can be effective mechanisms for reducing sediment loads from streambank erosion.

4.1.2. Phosphorus

Phosphorus was identified as a probable stressor in Dover Creek, Stony Run, and Upham Brook. Multiple lines of evidence supported this determination including periodic phosphorus measurements, diurnal monitoring, seasonal trends, and biological condition gradient analysis (Section 3.8.1). Based on the observed data and causal analysis, a conceptual model was developed to describe the causal relationships between the sources of phosphorus in the watershed, increased nutrient loads, decreased DO, and the observed loss of benthic macroinvertebrates (Figure 38). In this conceptual model, sources of phosphorus include runoff of fertilizers and other diffuse sources, point sources, exfiltration and overflows from sewer systems, and failure of septic systems. In the Dover Creek watershed, the application and deposit of manure from livestock on pasture is also a significant source. These sources and other contributing factors lead to increased nutrient load in the stream, which can act to biologically impair the stream through two pathways. Increased nutrient availability increases algae growth, which can directly alter macroinvertebrate feeding niches and competition or indirectly limit sensitive species through oxygen decreases as algae respire or are decomposed. Benthic taxa data provide evidence of these pathways with an observed increase in filterers and a decrease in taxa richness. Large DO swings in diurnal DO monitoring also provided evidence of these pathways. The combined weight of evidence documented in the causal analysis supports this conceptual model of phosphorus as a stressor in Dover Creek, Stony Run, and Upham Brook. A TMDL developed to reduce phosphorus loads in the watershed will address the benthic impairments in these streams through the pathways described in Figure 38. In addition, efforts to address several contributing factors that exacerbate the impact of nutrient enrichment will also be effective at reducing the impairment.

4.1.2.1. Contributing Factors

Several factors contribute to the impact of nutrient enrichment and low dissolved oxygen in Dover Creek, Stony Run, and Upham Brook. In Dover Creek, pasture accounts for 25.89% of the watershed, and cropland accounts for 4.80% of the watershed. The management of manures on crop and pasture lands within the watershed plays a large role in determining the loading of nutrients from these land uses to the stream. Practices that limit application, avoid overcrowding, maintain turf health, and utilize buffer zones can be instrumental in reducing nutrients loads from agricultural lands. In Stony Run and Upham Brook, high imperviousness, aging sewer systems, and stormwater inflow and infiltration increase the sources and movement of phosphorus. Impervious areas provide direct conduits for diffuse nutrient sources to be quickly transported to streams through storm sewer networks. For instance, pet waste or fertilizers inadvertently applied to impervious surfaces can wash directly into streams without any chance for retention and uptake from soils. In addition, sewer systems that are aging and susceptible to inflow and infiltration of stormwater can provide routes for exfiltration during dry periods and increase the likelihood of sewer overflows during wet periods. Practices and programs to reduce stormwater inflow and infiltration can reduce nutrient loads and protect human health from sanitary sewer overflows.

In Dover Creek, Stony Run, and Upham Brook, the presence of upstream lakes and impoundments are an additional contributing factor that increases the impact of nutrient enrichment downstream.

These impoundments decrease velocity and increase depth, which decreases oxygen reaeration and overall dissolved oxygen levels. In addition, the impoundments increase water temperature and increase residence time, which increases nutrient cycling and the production of algae.

4.1.3. pH, Dissolved Oxygen, and Organic Matter

Low pH, dissolved oxygen, and organic matter were identified as probable stressors in North Run (particularly at the upstream station). Multiple lines of evidence supported these determinations including periodic pH and DO measurements, diurnal DO monitoring, taxonomic community structure, Biological Condition Gradient analysis, and causal pathway analysis. Based on the observed data and causal analysis, a conceptual model was developed to describe the causal relationships between the prevalence of connected wetlands in the watersheds, anaerobic decomposition, high organic matter, low pH, low DO, and the observed loss of benthic macroinvertebrates (Figure 39). In this conceptual model, the low pH and DO in North Run result from the stream's natural connection to low-lying wetlands. In the upper North Run watershed, 14% of the land area is forested/shrub wetland (Figure 40), many of which are hydrologically connected to the main stream. In these permanently or periodically flooded wetlands, oxygen is quickly depleted and decomposition of dense organic matter proceeds through alternative anaerobic pathways (Inglett *et al.*, 2005). Some of these pathways, such as fermentation, can lead to the production of organic acids. Others, such as sulfate reduction and methanogenesis, can produce hydrogen ions as a biogeochemical byproduct. The result can be an increase in acidity and decrease in pH. The low pH can be toxic to some sensitive macroinvertebrates and limit the diversity of the benthic community. Flushing of dissolved organic matter from connected wetlands can also provide microbes with a constant source of organic matter, and decomposition can further lower dissolved oxygen.

The low pH, low DO, and high organic matter conditions in North Run were determined to be a natural condition resulting from the prevalence of connected wetlands. The stream also exhibited the characteristic dark tannin color of blackwater swamps. This color is the result of organic tannins and other dissolved organic matter from the decomposition of wood and leaf litter material. Since these conditions were determined to be natural, no TMDL will be developed to address pH, DO, and organic matter in this stream.

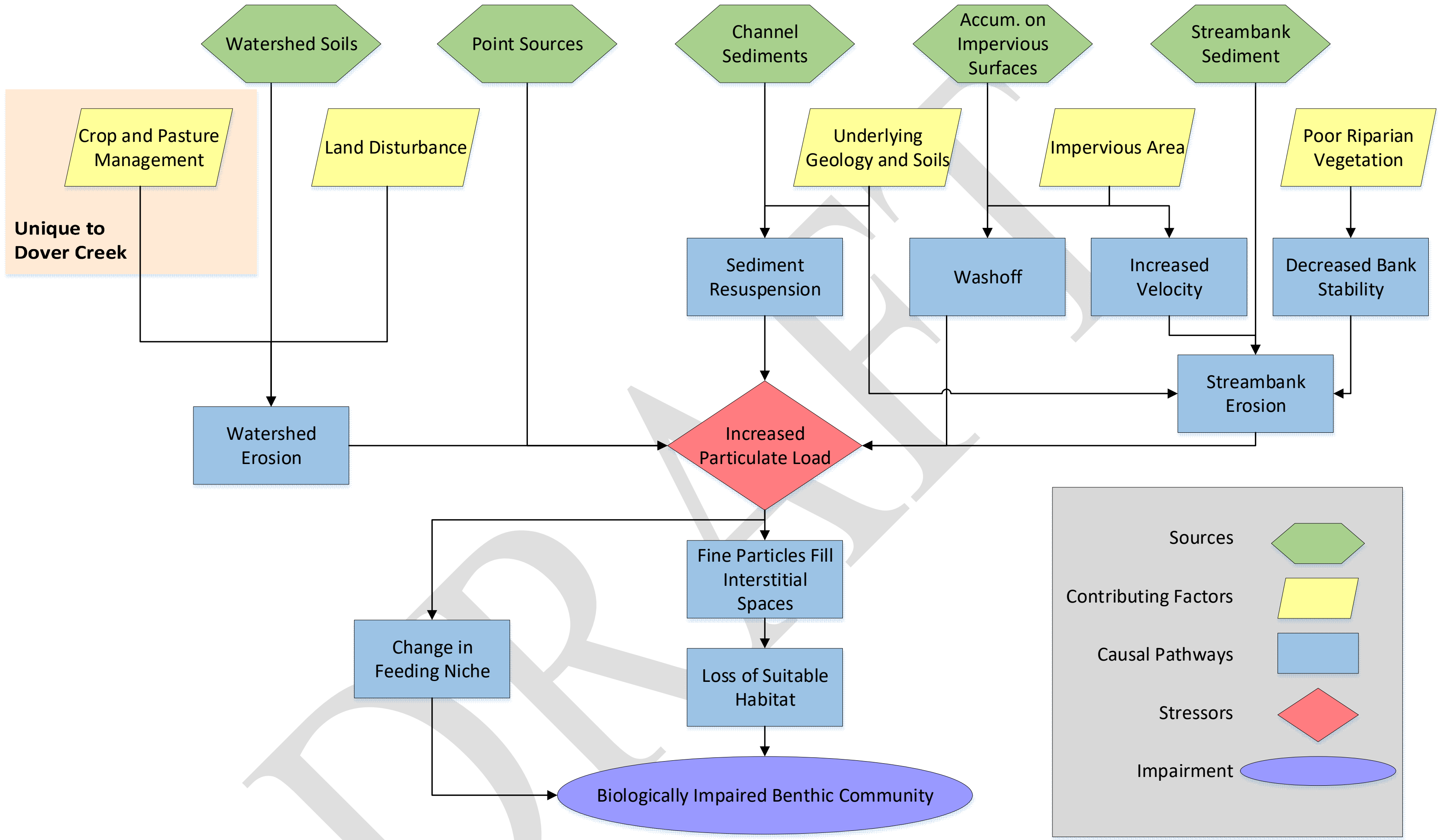

Figure 37. Conceptual model for the causal pathway of sediment impacts on benthic macroinvertebrates in Goochland and Henrico Project streams.

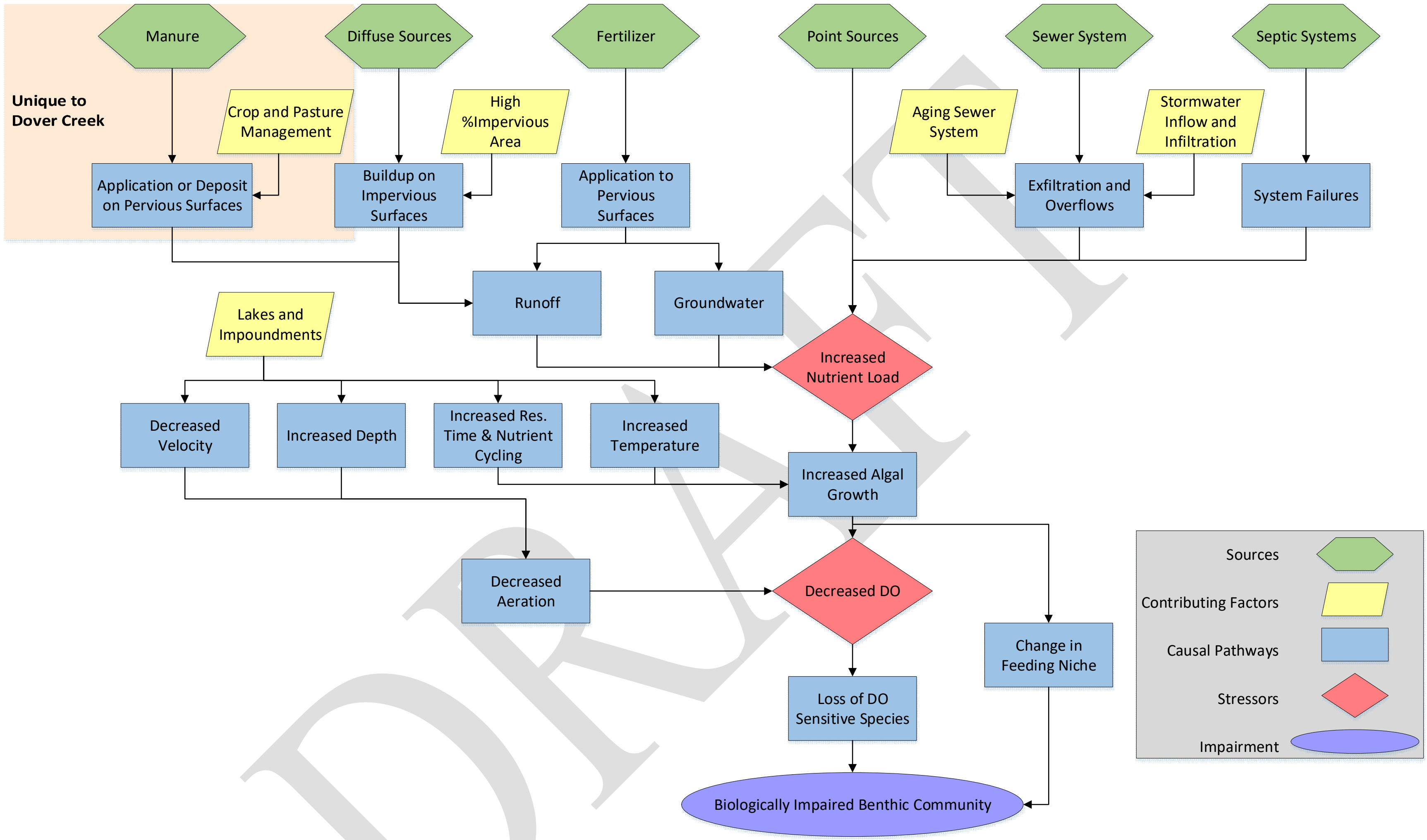

Figure 38. Conceptual model for the causal pathway of nutrient impacts on benthic macroinvertebrates in Dover Creek, Stony Run, and Upham Brook.

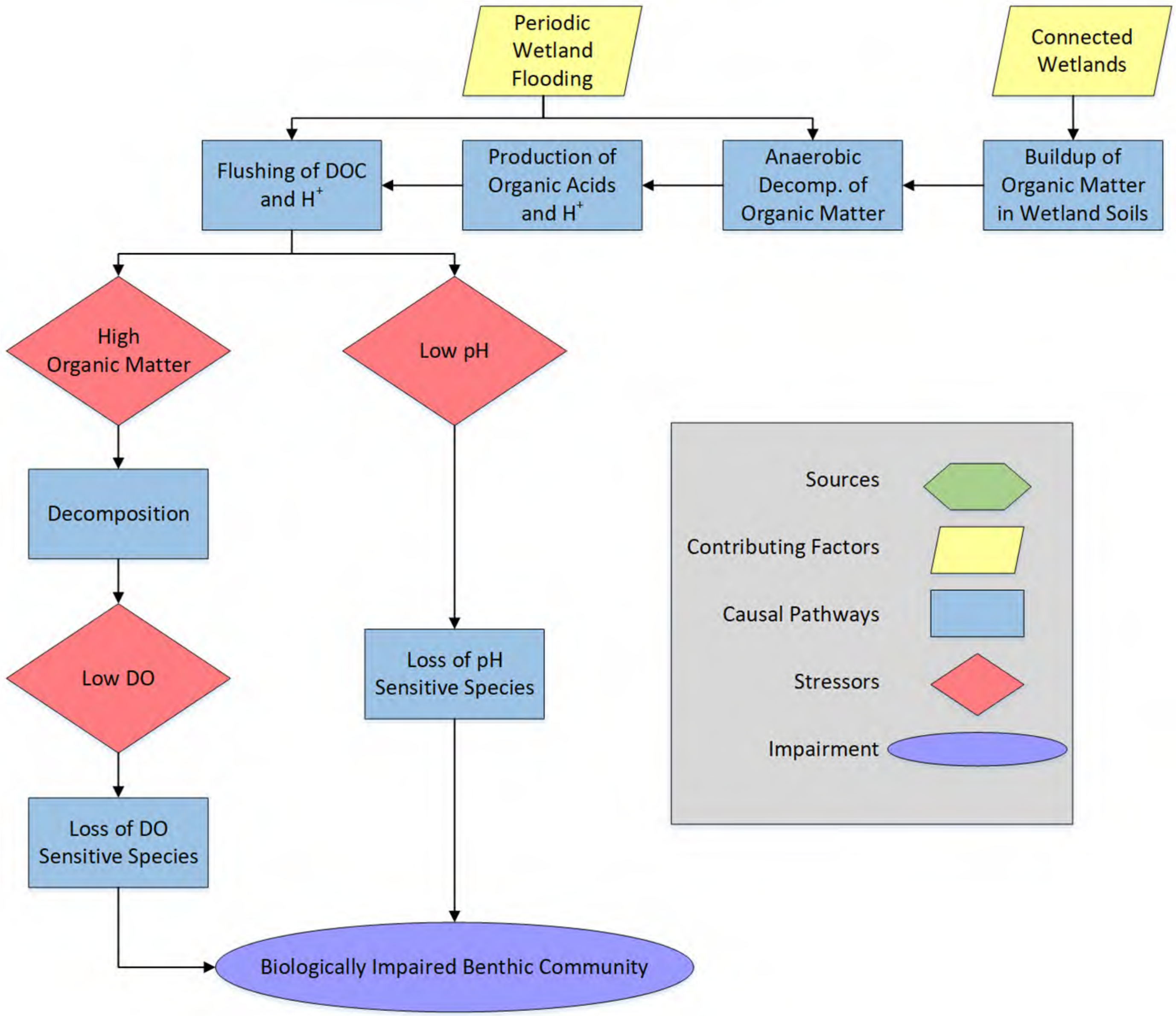

Figure 39. Conceptual model for the causal pathway of organic matter, pH, and DO impacts on benthic macroinvertebrates in North Run.

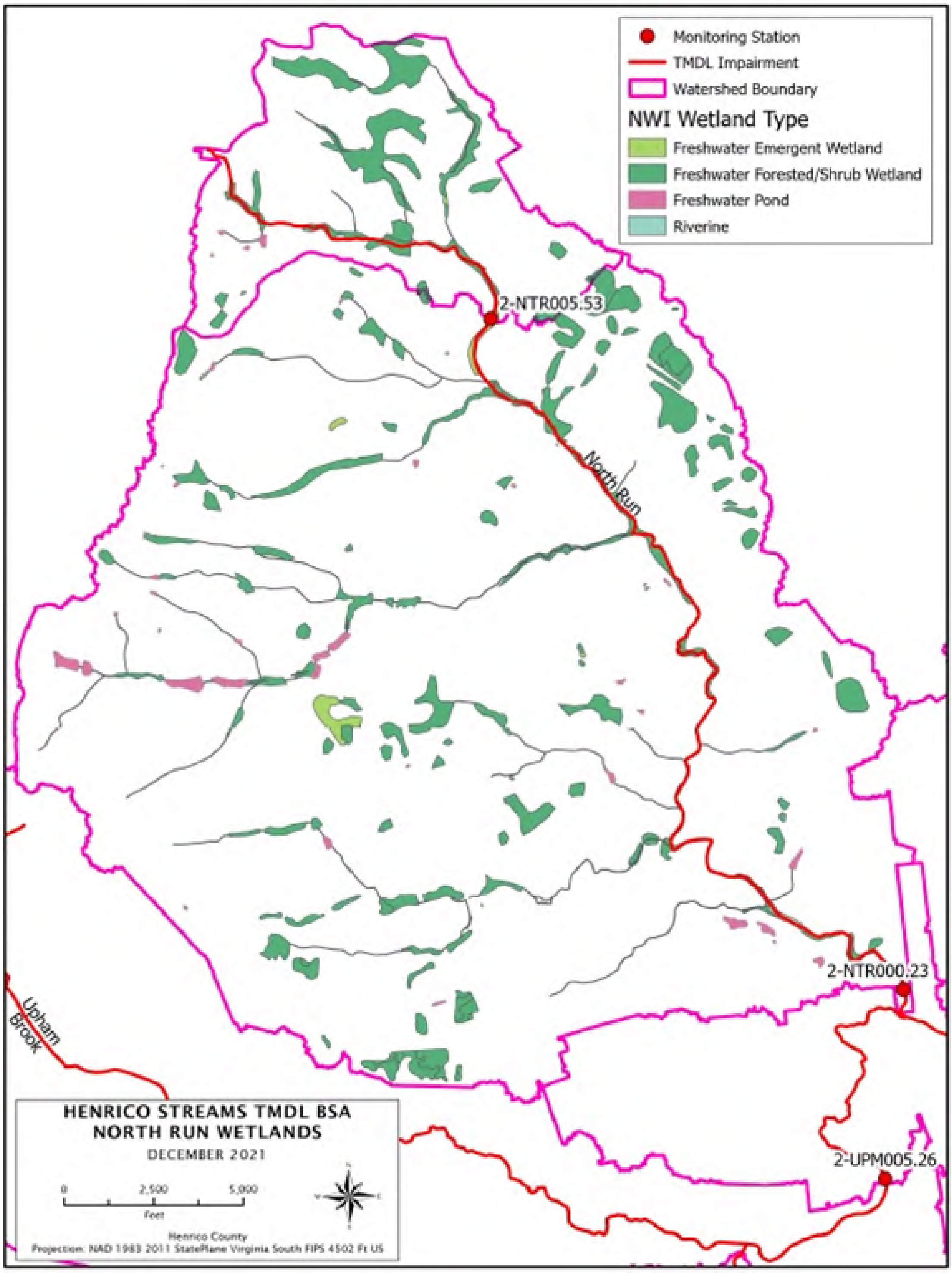

Figure 40. Wetlands in North Run watershed.

4.2. Conclusions

Following causal analysis and the determination of probable stressors, target pollutants for the TMDL were selected. TMDL target pollutants are the physical or chemical substances that will be controlled and allocated in the TMDL to result in restored aquatic life (measured by benthic macroinvertebrate health). TMDL targets must be pollutants that are controllable through source reductions, such as sediment, phosphorus, nitrogen, or other substances. Physical factors or environmental conditions, such as flow regimes, hydrologic modifications, or physical structures (like dams) cannot be TMDL target pollutants. Even though these conditions influence ecological communities and may be sources of stress, they do not represent substances that originate from point and nonpoint sources, they cannot be quantified, summed, and allocated to respective sources, and they cannot be controlled through source reductions. Other stressors and contributing factors that are natural, such as the low pH and DO conditions in North Run, also cannot be the target of TMDL development, because there is no controllable anthropogenic source.

TMDL target pollutants were selected by analyzing the causal pathways of probable stressors and identifying the primary substance responsible for controlling the pathway. For each of the Goochland and Henrico Project streams, the TMDL target pollutant was sediment. For Dover Creek, Stony Run, and Upham Brook, a second TMDL target pollutant of phosphorus was also identified (Table 36).

Table 36. TMDL targets for each impaired stream.

Stream	TMDL Target
Deep Run	Sediment
Dover Creek	Sediment Phosphorus
Jordans Branch	Sediment
North Run	Sediment
Stony Run	Sediment Phosphorus
Stony Run UT	Sediment
Upham Brook	Sediment Phosphorus

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