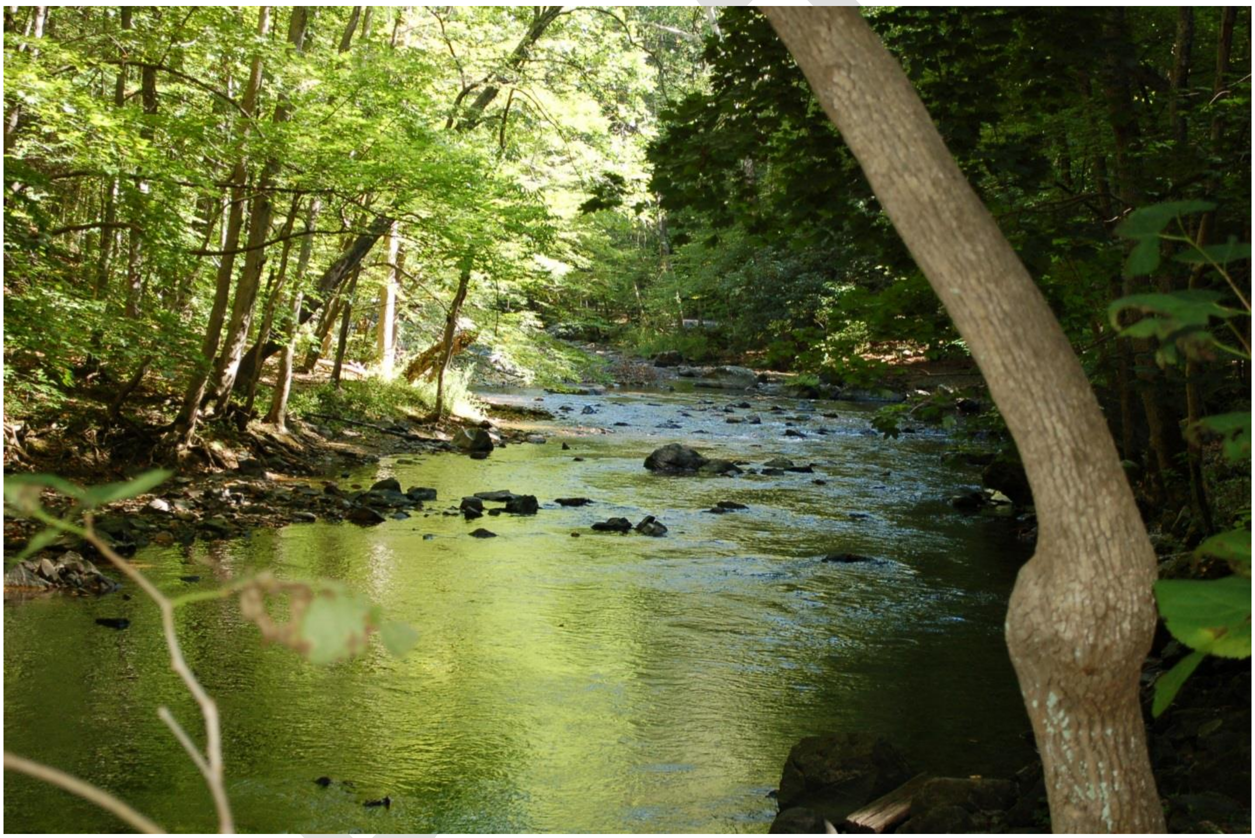
Stream Health in the North and South Branch Raritan Watershed (WMA8), New Jersey, USA, 1992-2017, Part 1: Temporal Trends and Regional Patterns in Benthic Macroinvertebrate Community Metrics



Prepared by Kristi MacDonald, Ph.D.

Raritan Headwaters Working Paper #3, July 2019

About Raritan Headwaters

We are a 501(c)3 non-profit conservation organization, formed by the 2011 merger of Upper Raritan and South Branch watershed associations (URWA and SBWA), both founded in 1959 to engage New Jersey residents in safeguarding water and natural ecosystems. As one of the largest watershed associations in New Jersey, Raritan Headwaters protects, preserves and improves water quality and other natural resources of the Raritan River headwaters region.

Major programs include surface and ground water monitoring, ecological research, habitat restoration, land preservation and stewardship, policy and advocacy as well as extensive public education and outreach. Through our long-established Stream Monitoring and Well Testing programs, we have become a trusted source of data on the health of surface and ground water. We work to identify and address stressors on water quality including pollutants, land use practices, and factors associated with climate change. We monitor the effectiveness of various restoration practices for improving water quality and insuring resilience of these systems into the future as the impacts of climate change become more pronounced. We preserve land to protect water quality including properties we own and manage (10 wildlife preserves encompassing 450 acres, plus 32 conservation easements protecting 880 acres). Our stewardship efforts include riparian restoration, invasive plant removal and forest management. Our work engages community residents and decision-makers, including more than 3,200 volunteers and citizen scientists annually, in efforts to protect land, water and natural habitat in our region. www.raritanheadwaters.org

Acknowledgements

This effort was made possible through the passion and hard work of RHA's talented staff, interns, and citizen scientists who have waded into our streams each June to collect valuable data on benthic macroinvertebrates, habitat and chemical conditions. There are far too many to name but we thank them all. A special note of thanks goes to Angela Gorczyca who managed the stream monitoring program from 2010-2018. She not only helped to continue expanding and improving the rigor of RHA's stream monitoring program and the sharing of data with the public and our partners but she greatly helped in compiling the data for this analysis. Melissa Mitchell Thomas, RHA GIS Specialist, created all the maps in this report. George Christian, Normandeau Associates Environmental Consulants, provided expert identification of benthic macroinvertebrate samples. Thanks to those who carefully reviewed the report including RHA Watershed Scientists Maria Berezin and Mara Tippett, and members of RHA's Water Quality Committee. This draft is currently under external peer review. Funding for this project was generously provided by the Leavens Foundation.

Cite as: MacDonald, K. 2019. Stream Health in the North and South Branch Raritan Watershed (WMA8), New Jersey, USA, 1992-2017, Part 1: Temporal Trends and Regional Patterns in Benthic Macroinvertebrate Community Metrics. Raritan Headwaters Working Paper #3, www.raritanheadwaters.org, 71 pages.

Executive Summary

- Over several decades, Raritan Headwaters Association (RHA), a non-profit environmental group, has conducted annual biological, chemical, and habitat monitoring at sites throughout the North and South Branch Raritan River Region (WMA8). Monitoring has included collection of high quality data using NJ Department of Environmental Protection (NJDEP) protocols on the benthic macroinvertebrate communities of streams and rivers over several decades allowing for the analysis of trends in water quality with time and exploration of patterns by watershed region.
- Benthic macroinvertebrates, including insects, crustaceans, worms, and mollusks, are used as indicators of water quality because taxa vary in their tolerance of pollution and the presence of sensitive species such as mayflies, stoneflies and caddisflies (EPT species) indicates clean, oxygen-rich, cold water. The High Gradient Macroinvertebrate Index (HGMI) and New Jersey Impairment Score (NJIS) are two indices calculated from benthic macroinvertebrate data used in New Jersey to measure water quality and ecological health of streams.
- Temporal trends and geographic patterns were explored using RHA's data on benthic macroinvertebrates collected from 105 monitoring sites for two long-term periods (1992-2017 and 2000-2017), and 4 shorter time-periods in between, for the watershed overall and combinations of major river (North Branch vs. South Branch) and physiographic province/region (Highlands vs. Piedmont) using Spearman Rank correlation. In addition, relationships of macroinvertebrate metrics to local habitat, chemical, and land use-land cover parameters were explored.
- A total of 3,608 Spearman Rank correlation analyses of time with 15 macroinvertebrate community metrics were run using site-level data and results were tallied.
- Most of the sites (83% and 89%, respectively) did not exhibit significant trends in HGMI during the 2 longterm periods, 1992-2017 and 2002-2017. Most (89%) of the sites included in the recent, short-term analysis did not exhibit a trend in HGMI over time.
- Macroinvertebrate metrics were categorized based on whether they are indicating improvements to water quality (positive impact trends) versus trends indicating declines in water quality (negative impact trends), There were slightly more longterm and recent positive impact trends for sites than negative impact trends.
- Two hundred sixty-five (7%) positive and 145 (4%) negative trends were detected, ($P<0.05$). When community parameters were categorized based on whether they are indicators of improving or declining water quality, 232 trends (6%) indicated an impact of improved water quality whereas 178 (5%) indicated a decline in water quality ($p<0.05$).
- When <u>all</u> macroinvertebrate metrics were tallied for trends indicating improvements to water quality (positive impact trends) versus trends indicating declines in water quality

(negative impact trends), the longterm pattern was different than what was detected in recent years (2010-2017). Longterm, 19% of the sites had ≥1 parameter indicating declines in water quality while 29% of the sites had ≥1 parameter indicating an improvement in water quality. Whereas in recent years, 26% of the sites had ≥1 indicator of a decline in water quality while 18% had ≥1 indicator of improvements.

- There has been a trend of increasing proportion of impaired sites watershed-wide since about 2010. This trend is most pronounced in the North Branch, especially in the Highlands region but also in the Piedmont. The South Branch also demonstrated recent increases in the amount of impaired sites but in 2017 the number dropped drastically in both the Highlands and Piedmont.
- Over the longterm, there was a pronounced decline in HGMI and NJIS in the North Branch-Highlands and NJIS in the South Branch-Highlands. In recent years, the North Branch-Highlands also had a trend of declining HGMI and NJIS and declining HGMI in the South Branch-Piedmont.
- Negative water quality impact trends included increases in pollution-tolerant taxa and non-insect taxa, and decreases in sensitive EPT taxa.
- HGMI was positively correlated with dissolved oxygen, stream depth, number of stream depth-velocity regimes, epifaunal substrate, % forest cover, % open water and % barren land in the catchement and negatively correlated with temperature and embeddedness.
- NJIS was positively correlated with % open water in the catchement and stream depth and negatively correlated with % urban land use.
- This study identifies specific sites and regions where preservation of forest and/or restoration should be targeted. Sites that have shown improvement or have not changed need protection. Sites that have declined likely require restoration. Preliminary analysis shows that both local stream conditions as well as catchment-level land use are impacting the benthic macroinvertebrate community.
- The RHA stream data will be analyzed for more specific trends and patterns in benthic macroinvertebrate community composition; climate change and severe weather impacts; and local and landscape-scale factors influencing stream health. These analyses will be presented in subsequent Raritan Headwaters Working Papers.

Introduction

Ecological function and services provided by stream ecosystems are heavily altered by human activities on the landscape (Kratzer et al. 2006; Paul and Meyer 2001; Allan and Johnson 1997). Human impacts on streams and rivers affects drinking water supplies (Fitzhugh and Richter 2003; Dudley and Stolton 2003). In addition to point sources of pollution such as industrial and wastewater discharges, there are ubiquitous non-point sources of pollution and stream alteration that impact stream health and water quality. Human alterations to the landscape including agricultural and urban land uses and forest loss increase stormwater runoff (Arnold and Gibbons 1996); disrupt natural disturbance and flow regimes (Paul and Meyer 2004); modify channel morphology and substrate (Poff et al. 1997); alter temperature regimes (Sweeney 1993); alter pollutant inputs including nutrients, sediments, and other pollutants (Phillips et al. 2002; Meador and Goldstein 2003; Dodds and Whiles 2004); and affect primary energy inputs in headwater streams (Wallace et al. 1999; England and Rosemond 2004). Identifying natural and human anthropogenic environmental factors that influence biological communities in streams is an important step in effective watershed management (Wang and Kanehl 2003).

With enactment of The Clean Water Act (1970), NEPA, and other environmental regulations protecting water, we would expect to see mainly improvements in water quality over time. However, many of the stressors that impact water quality including increases in urban land use and loss of forest and wetland could counteract the positive impacts. In addition, while it is assumed regulations have greatly helped with point source pollution, many non-point sources are difficult to regulate.

Benthic Macroinvertebrates are invertebrates that occupy lotic or stream and rivers and are typically the most diverse and abundant organisms in these ecosystems (Giller and Malmqvist 2004; Voshell 2002; McCafferty 1981; Figure 1.). They serve many important roles in stream ecosystems as predators, herbivores, and detritivores, prey for other species of invertebrates and vertebrates such as fish and salamanders, and as recyclers of nutrients. Because of their important role in stream ecosystems they are widely used as biological indicators of water quality and overall stream health (Rosenberg and Resh 1993; Barbour et al. 1999). Some macroinvertebrates (freshwater mussels) have complicated life cycles tied to specific species of fish. Many benthic macroinvertebrates require low temperatures and high oxygen levels. PH closer to neutral and other chemical parameters below certain tolerance thresholds is important for many species. To avoid being swept away in strong currents, these species often live in the interstitial spaces under and around cobbles and boulders and thus are sensitive to deposition of fine and sandy sediments around larger substrate (i.e., embeddedness). A diversity of habitat structure and composition are associated with a diversity of organisms. And land use and land cover both locally, within stream buffers as well as at larger landscape scales such as the catchement-level have an impact on these ecological characteristics. Replacement of forests with high levels of urban development and agriculture result in higher levels of stormwater runoff and pollutants including sediments, nutrients, and pesticides in streams. Loss of forested buffers and riparian wetlands results in the loss of ecosystem services including shade, bank stabilization, nutrient filtration and storage of water during floods. All of these factors impact and shape the benthic macroinvertebrate community.

Figure 1. Benthic macroinvertebrates, including insects, crustaceans, worms, and mollusks, are used as indicators of water quality because taxa vary in their tolerance of pollution and the presence of sensitive species such as mayflies, stoneflies and caddisflies (EPT species) indicates clean, oxygen-rich, cold water. The HGMI and NJIS are two indices calculated from benthic macroinvertebrate data used in New Jersey to measure water quality. Examples of benthic macroinvertebrate a. Flatworm/Planaria; b. Crane fly larvae; c. Crayfish; d. Case maker caddisfly ; e. Netspinner Caddisfly; f. Aquatic sow bug; g. Odonate/Dragonfly and Damselflies; h. Bithyniid snail; i. Midge larvae; j. Scud; k. Black fly larvae; l. Water Penny; m. Clam; n. Riffle beetle; o. Leech; p. Physid snail (note opening should be on the left); q. Helgrammite/Dobsonfly larvae; r. Planorbid snail; s. Stonefly; t. Aquatic earthworm; u. Mayfly.

Benthic macroinvertebrate communities have long been used as a biological indicator of stream health for a variety of reasons outlined in Barbour et al. 1999. They are limited in their movement and thus are well-suited to assessing local, site-level conditions; the overall community responds slowly to changes in water quality; they are diverse and abundant serving important roles in the ecosystem, representing a broad range of trophic levels and pollution tolerances for which there is ample scientific literature.

With the knowledge that stream taxa vary in their physiological requirements and range of tolerance to chemical parameters and physical conditions, several indices of water quality have been developed utilizing samples of stream macroinvertebrate communities. From the sample, species composition, richness, relative abundance and dominance of pollution tolerant and sensitive taxa are used to calculate indices of biotic integrity or IBIs. Three families of aquatic macroinvertebrates are particularly sensitive to poor water quality, the Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies) or EPT taxa. Two indices developed for New Jersey include the New Jersey Impairment Score (NJIS; Kurtenbach 1990; Poretti et al. 2007; Appendix A), which is a state-wide metric based on family-level data, and the more sensitive High Gradient Macroinvertebrate Index (HGMI; Jessup 2007a; Appendix A), which is a metric developed for the types of streams that occur in northern regions of NJ and is based on genus-level data.

RHA's parent organizations, Upper Raritan Watershed Association (URWA) and South Branch Watershed Association (SBWA), have been monitoring water quality in the region's streams and rivers since 1959. The current stream monitoring program, which utilizes strict protocols and a team of citizen scientists trained by RHA scientists, conducts annual monitoring at permanent locations since 1992 in the South Branch and 1999 in the North Branch. This robust program allows RHA to monitor 63-70 stream sites throughout the 470 mi^2 (1,217 km^2) Upper Raritan Region that includes the North and South branches of the Raritan River. Data spanning 25 years (1992-2017), provide rare opportunities to explore a variety of questions pertaining to trends and spatial patterns in water quality indices as well as underlying mechanisms and predictions given different land use and climate change scenarios.

Goals of Trend Analysis of Benthic Macroinvertebrate Community:

The macroinvertebrate community, when studied over long periods of time, may be used to study short-term fluctuations due to rare events and provide insights into positive and negative trends in water quality occurring in streams and rivers. Thus, measuring this community of organisms is a summary of many changes that may have occurred in chemistry, habitat, and landscape-scale factors over time. Because the data are collected using the same or similar methods and at the same sites each year, it is possible to look for temporal trends and regional patterns, among other things. Long-term trend analyses allow us to study changes that occur slowly, study changes due to multiple stressors, and study response and recovery from rare or extreme events (Dodds et al. 2012).

By examining changes in the macroinvertebrate community indices over time we can: (1) define baseline conditions and underlying annual variations and cycles; (2) target specific sites, streams, and regions in the watershed where problems exist for more detailed monitoring and restoration; (3) identify areas for investigation of point and non-point causes of water quality or habitat decline and/or improvement; (4) identify trends associated with extreme weather events such as floods and droughts that occur periodically; (5) detect the signature of more subtle longterm changes such as those due to climate change; and (6) improve the prediction of future trends.

The current study will focus on identifying temporal trends in benthic macroinvertebrate community metrics and geographic patterns in those trends.

Questions for the current trend analysis:

1. Have the macroinvertebrate community indicators of water quality changed over time? If so, which community indices have changed in the watershed overall and at which particular sites or geographic areas (streams or regions) of the watershed?

2. Which local or catchement-level conditions are contributing to improvements and declines in water quality? Which contribute to stable conditions?

3. Based on the findings of this trend analysis, what targets are recommended for protecting and restoring stream health in the Upper Raritan?

Methods

Study area

The drainage basin of the entire Raritan River covers approximately 1,100 square miles, making it the largest river basin located entirely within the State of New Jersey along the mid-Atlantic coast of the United States. The study area is the Upper Raritan region, which includes the North and South Branch Raritan River Watershed Region (WMA8) covered in this report is 43% of the entire Basin. The South and North branches of the Raritan eventually meet in Branchburg at the confluence with the Lower Raritan and the river flows into Raritan Bay on the Atlantic Ocean.

The North and South Branch Raritan Watershed (WMA8; Figure 2) is the largest watershed within the Raritan River Basin and is part of the New Jersey Highlands Region. The 470 $mile^2$ (1,217 km^2) watershed, which comprises the Raritan Headwaters region, provides drinking water to 300,000 watershed residents of 38 municipalities in Hunterdon, Morris and Somerset counties and drinking water to more than 1.5 million residents that live beyond our watershed, in the state's more urban areas. The South Branch of the Raritan River is 51 miles long, from its source in Budd Lake to its confluence with the North Branch. The North Branch originates as a spring-fed stream in Morris County and flows south approximately 23 miles to its confluence with the South Branch in Branchburg. The watershed holds a rich variety of flora and fauna and contains some 1,400 miles of stream, including many wild trout production streams. Two large reservoirs, Spruce Run and Round Valley, and a variety of large protected public lands including Ken Lockwood Gorge, Hacklebarney State Park, and the Black River Wildlife Management Area are all within the Raritan Headwaters region. Under the surface, are the fractured-rock aquifers of the Newark Basin including mainly the Brunswick aquifer, Lockatong and Stockton formations, along with some limestone aquifers and buried valley aquifers where glaciers deposited sand, gravel and clay materials. These resources are threatened by continued degradation caused by numerous stressors associated with human activities.

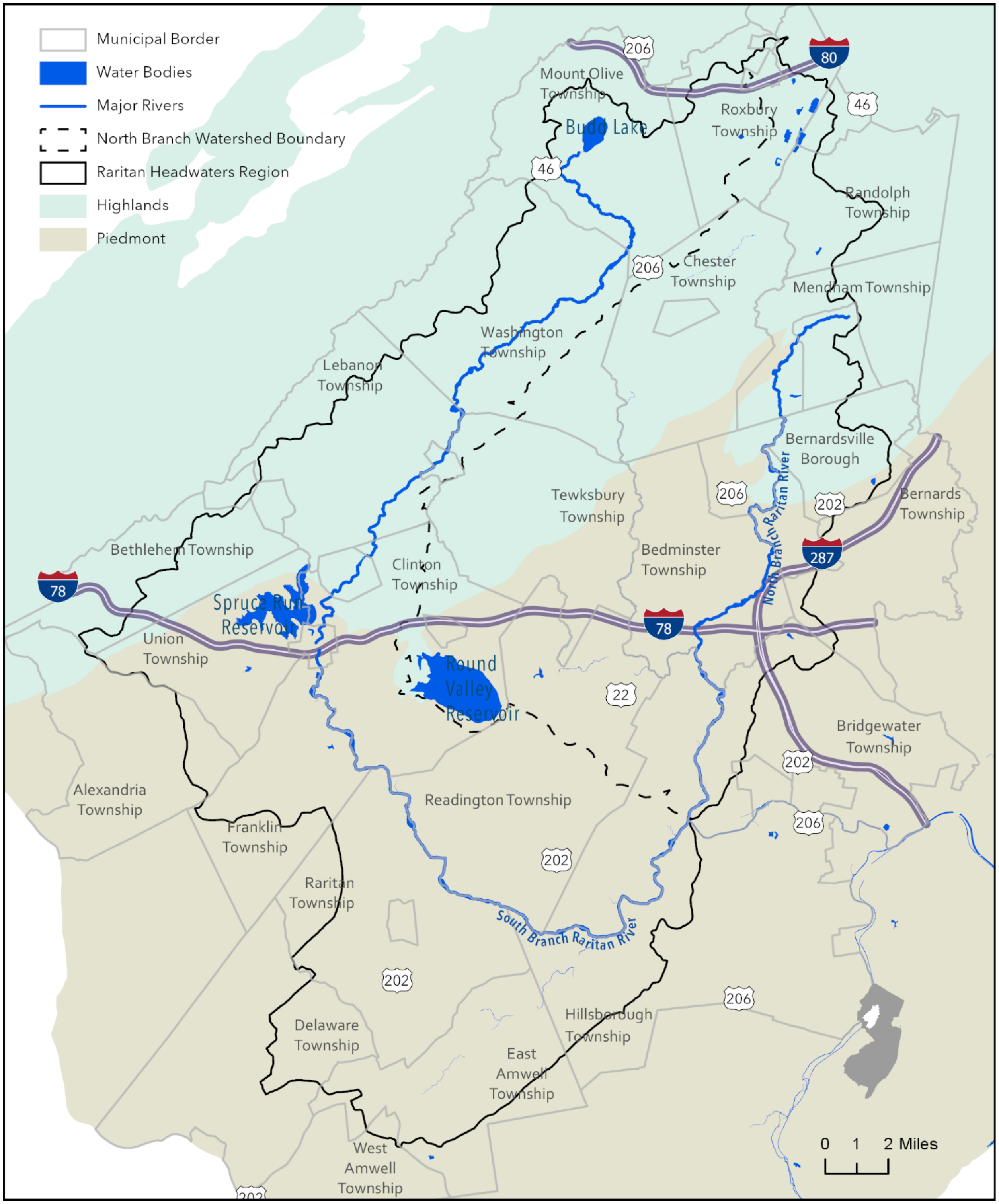


Figure 2. Map of the North and South Branch Watershed Region (WMA8) depicting major waterbodies, waterways, roads, and the Highlands and Piedmont physiographic provinces.

Water quality conditions and trends: In 2007, South Branch Watershed Association contracted with U.S. EPA and Tetra Tech, Inc. to produce a report, "South Branch Raritan River: 12-Year Trend (1994-2005) in Water Quality Using Macroinvertebrate Data," (Jessup 2007b). The report included an analysis of annual macroinvertebrate data collected from 12 sites on the South Branch Raritan River and Neshanic River for temporal trends and longitudinal patterns of macroinvertebrate water quality indices. The results showed roughly that temporal trends were related (positively) to discharge/flows whereas longitudinal patterns were roughly related (negatively) to differences in the percent of managed land in the catchement associated with each site. RHA will be exploring all these areas in subsequent papers. However, the current study will focus on identifying temporal trends in benthic macroinvertebrate community metrics and geographic patterns in those trends.

In addition to the Raritan Headwaters stream monitoring program, NJDEP AMNET data are collected from sites throughout New Jersey, including the Upper Raritan, to assess biological, habitat and chemical conditions in streams. Based on data from NJDEP (unpublished presentation), the most common causes for a waterway being in non-attainment for designated uses under the Clean Water Act , in order of most number of highest to lowest number of impacted areas are pathogens (E. *coli* or Enterococcus), arsenic (mostly from naturally occurring sources), total phosphorous, dissolved oxygen, pH, unknown (impact on aquatic life), temperature, mercury, PCBs, and DDT.

Nutrients including nitrate and phosphate concentration at sites monitored by NJDEP and/or USGS between 1971 and 2011 demonstrate that most sites either did not exhibit a trend or exhibited a decrease in these chemical parameters (Hickman and Hirsch 2017). This includes 3 locations in WMA8.

Land use – land cover conditions and trends: Figure 3 is a map of 2012 land use and land cover in the watershed (NJDEP, Bureau of GIS). Land use-land cover and other trends are described in Table 1. There have been great changes in land use in the watershed over the past two decades, which included an increase in urban/suburban land use replacing farmland and forestland. Protection of remaining forest and wetlands in this headwater region is critical to maintaining surface and groundwater quality.

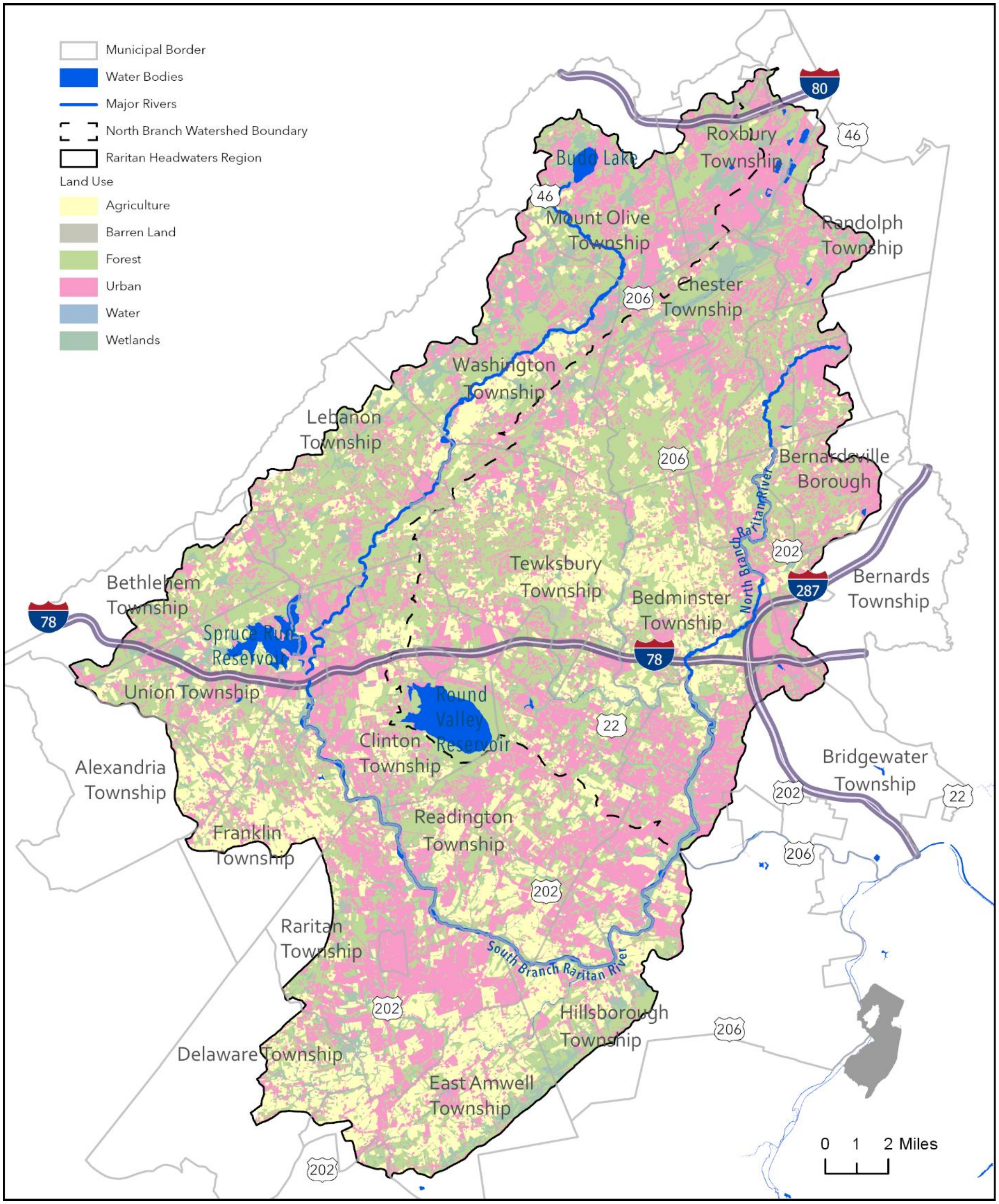


Figure 3. Land use and land cover in the North and South Branch Raritan Watershed Region (WMA8) based on NJDEP analysis of 2012 satellite imagery.

Table 1. Trends in human population, land use and land cover in the Upper Raritan (Sustainable Raritan Initiative 2016, 2018).

Parameter	1990s	2010s	Change	% Change
Human Population	174,516	223,002	+48,485	+27.8
Land Use-Land Cover	**1986**	**2012**	**Change**	**% Change**
Urban Land (acres)	71,727	98,696	+26,969	+37.6
Upland Forest (acres)	107,341	104,734	-2,606	-2.4
Agricultural Land (acres)	89,078	66,235	-22,843	-25.6
Wetlands (acres)	22,902	21,609	-1,293	-5.6
Water (acres)	5,951	7,166	+1,215	+20.4
Barren Land (acres)	2,584	1,162	-1,422	-55.0

Climatic conditions and trends in the region: Weather refers to short-term (days to weeks or months) changes in the atmosphere whereas climate describes what the weather is like over a long period of time (decades to centuries) in a specific area. New Jersey's climate is characterized by moderately cold and occasionally snowy winters and warm, humid summers (Runkle et al., 2017).

NOAA's National Centers for Environmental Information (NCEI) (Formerly the National Climatic Data Center [NCDC]) calculates Climate Normals, three-decade averages of climatological variables, including temperature and precipitation, for over 9,800 stations across the United States. One such station is located at Somerset Airport in Bedminster (Station: SOMERVILLE SOMERSET AIRPORT, NJ US USW00054785), approximately in the center of WMA8. Climate Normals for the 1981 – 2010 period of record at this station indicate that average monthly temperatures ranged from 29.0 °F in January to 73.9 °F in July (Arguez et. al., 2010). Temperature averages by season were 31.3 °F in winter, 49.8 °F in spring, 71.8 °F in summer, 53.8 °F in autumn. Average annual precipitation was 47.39 inches, with monthly averages ranging from 2.17 inches in February to 5.27 inches in July. Precipitation averages by season were 9.06 inches in winter, 12.66 inches in spring, 13.54 inches in summer, 12.13 inches in autumn.

Average temperatures in New Jersey have increased by 3 degrees Fahrenheit over the past century. Heat waves are projected to be more intense while cold waves are projected to become less intense (Runkle et al., 2017). Precipitation has been highly variable but tends toward wetter than average conditions over the last decade (Runkle et al., 2017). Winter and spring precipitation and extreme weather events, be they storms, heat waves, or droughts, are projected to increase by mid-century (Robinson 2014).

For more information on the climate of New Jersey, visit the Office of the State Climatologist's website at https://climate.rutgers.edu/stateclim/?section=njcp&target=NJCoverview.

Data Collection

RHA has annually collected data on benthic macroinvertebrates and habitat, and more recently chemical data, at fixed monitoring sites some of which have been monitored since 1992. Data have typically followed protocols developed by the USEPA (Barbour et al. 1999) and later refined by NJ Department of Environmental Protection (NJDEP; Poretti et al. 2007). In addition, beginning in 2017, Raritan Headwaters began collecting baseline chemical data on water quality parameters at each of its stream monitoring sites. A list of the variables used in this study and their abbreviations is provided in Table 2.

Table 2. Water quality parameters and brief description or source for methods.

Variable (Abbreviation)	**Brief Description/Source**
Biological (Benthic Macroinvertebrate)	Barbour et al. 1999; Poretti et al. 2007; https://www.state.nj.us/dep/wms/bfbm/amnet.html
High Gradient Macroinvertebrate Index (HGMI)	Jessup 2007a
New Jersey Impairment Score (NJIS)	Kurtenbach 1990; Poretti et al. 2007
Family Richness (F_Rich)	No. of Families
Genus_Richness (G_Rich)	No. of Genera
Family-Level Biotic Index (FBI)	An index of pollution tolerant families; Poretti et al. 2007?
Hilsenhoff Biotic Index (HBI), Genus level	An index of pollution tolerant genera; Hilsenhoff 1987
Percent Non-Insect Genera (Non_Insect)	Percentage of the Genera that are non-insect indicating increasing pollution tolerance

Percent Ephemeroptera, Plecoptera, Trichoptera (EPT)	Percentage of pollution intolerant Genera
H2 Genera (H2)	Pollution Sensitive Uncommon Genera
H3 Genera (H3)	Pollution Sensitive Common Genera
Scrapers	
Bacteria	
Escheria coli count	EPA Method Method 1603
Chemical	
Temperature (Temp)	Degrees Celsius: YSI Probe
Turbidity (Turb)	LaMotte Kit
pH	YSI Probe
Dissolved Oxygen (DO)	YSI Probe
Phosphate (P)	LaMotte Kit
Nitrate (N)	LaMotte Kit
Specific Conductance (SPC)	YSI Probe
Habitat Quality	
Total Habitat Score (HAB)	Habitat Score: Ratings of embeddedness, bank structure, stream bottom, woody debris, periphyton, and vegetated buffer are combined into a habitat score (Barbour et al. 1999; NJDEP 2015)
Land Use Land Cover, Catchement (2012)	NJDEP 2012 Land Use Land Cover GIS data used to calculate the percentage of major habitat categories standardized per unit area (acres)
Total Catchement Area	
% Forest (FOR)	
% Wetland (WET)	
% Agriculture (AGR)	
% Urban (URB)	
% Water (WAT)	
% Barren (BAR)	

Biological Data (Benthic Macroinvertebrates): Each year, visual and biological stream assessments have been performed at fixed sites in the Upper Raritan (WMA8; Figure 4) between June 15 and July 10. By using the same sampling window each year the information gathered can be easily compared across years and among sites. Stream monitoring sites have been chosen so that they are suitable to use with the U.S. Environmental Protection Agency's Rapid Bioassessment protocol (Barbour et al. 1999).

To collect a biological sample, a net is used to perform a "kick" in the stream, disturbing the benthic habitat in a riffle within a 100-meter stream segment so that all cobble, sand, and debris flow into the net. Larger rocks are rubbed into the net to remove attached organisms prior to commencing each kick. Kicks are timed for 1 minute at each of 10 riffles or other suitable habitats in the stream. Once completed, volunteers sort through the collected debris, ensuring a minimum of 120 benthic macroinvertebrates was collected. Effort is made to retain all the bugs in the sample. The macroinvertebrates along with most of the substrate and debris are preserved in a jar of 10% ethyl alcohol. As part of QAQC, duplicate samples are taken from 10% of the sites each year. Jars are clearly labeled using stream monitoring site ID numbers. Once completed, samples are sent to Normandeau Labs (Stowe, PA), an EPA certified laboratory, where an expert taxonomist identifies all macroinvertebrates collected down to the lowest taxonomic level possible. Analysis by an independent lab assures that RHA's data is of the highest quality, allowing it to be used by state and federal agencies with the most stringent data quality requirements. As further QAQC, benthic macroinvertebrates from the 100-organism samples are returned to RHA and periodically a subsample is sent for taxonomic verification to a different certified taxonomist for verification. Using the relative abundances and pollution tolerances at the family level (Table 2; NJ Impairment Score and underlying metrics; Poretti et al. 2007) and genus level (Table 2; High Gradient Macroinvertebrate Index and underlying metrics; Jessup 2007a), the macroinvertebrate community can be characterized and compared across sites and years.

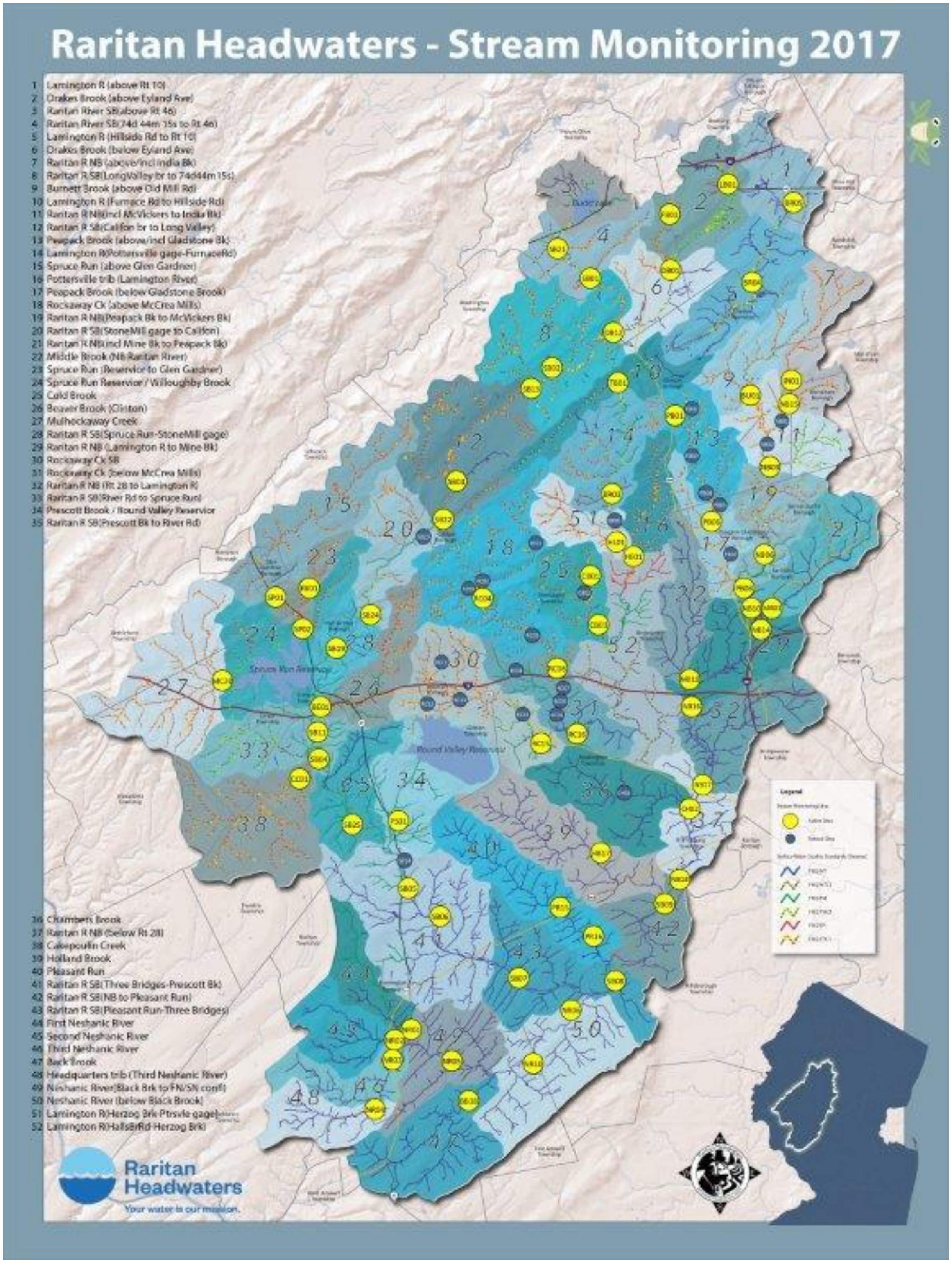


Figure 4. Location of Raritan Headwaters annual stream monitoring sites as of Fall 2017. Map includes current to 2017 as well as retired stream sites included in the trend analysis.

Note that in 2011, SBWA’s protocol and URWA’s protocol for collecting their biological samples differed slightly. SBWA used an 18” x 8” kick net with a 900 micron mesh size to sample one riffle for 2 or 5 minutes while URWA used a D-frame dip net with 500 microns mesh size to sample 10 locations, preferably within riffles or other habitat features, at a stream site for 1 minute each. In 2012, volunteers collected biological samples using one unified protocol. All volunteers used a D-frame dip net with a 500 micron mesh size to sample one riffle for five minutes. Subsequently, RHA converted to 10, 1-minute kick samples, within a 100m segment of stream.

The benthic macroinvertebrate samples are scored using the New Jersey Impairment Scoring (NJIS) Criteria for Rapid Bioassessments (Poretti et al. 2007) and the more sensitive High Gradient Macroinvertebrate Index (HGMI; Jessup 2007a). Both protocols evaluate a 100 organism subsample and are described in detail in Appendix A.

NJIS is based on five criteria:

- Taxa Richness
- EPT genera
- Percent Dominance
- Percent EPT
- Family Biotic Index (FBI)

Each of the five metrics is given a score of 0, 3, or 6 depending on where it falls on the scale, and then all are totaled for a final NJIS index score. The possible scores range from 0 to 30, where 30 indicates the high end of non-impaired and 0 indicates a site which is severely impaired.

HGMI is based on 7 criteria:

- Total number of genera
- Percent of genera that are not insects
- Percent of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (EPT; three orders of aquatic insects that are common in the benthic macroinvertebrate community) individuals (excluding Hydropsychidae, including Diplectrona)
- Number of scraper genera
- Hilsenhoff Biotic Index (HBI)
- Number of attribute 2 genera (highly sensitive and uncommon taxa)
- Number of attribute 3 genera (sensitive and common taxa)

For more detailed information regarding metric parameters and scoring, please see Appendix A.

In order to assure that our methods are up to date, RHA submits a Quality Assurance and Acceptance Procedure (QAPP) to the NJDEP Division of Water Monitoring and Standards for review and approval annually. Our current QAPP is approved at Tier D, meaning the data are considered high enough quality to be used for regulatory decisions by state and federal agencies. Before the monitoring season, all monitoring equipment is inventoried, calibrated, and replaced if necessary.

Citizen Science Program: Each spring, RHA holds an intensive stream monitoring training for new volunteers and a separate refresher that returning volunteers repeat every other year. Trainings reviews the purpose of the stream monitoring program and assures the standardization of sample and data collection by explaining and demonstrating the biological sampling and visual assessment protocols. New volunteers are required to work with either a staff member or an experienced volunteer during their first season.

For each stream monitoring site RHA provides to all volunteers GPS coordinates, verbal descriptions of collection (riffle) areas, and photographic records. This further assures that comparable data is gathered from one year to the next. GPS coordinates and site descriptions are available on RHA's website at http://www.raritanheadwaters.org/protect/stream-monitoring-program/stream-monitoring-map/.

Visual Habitat: The suitability of the riparian habitat is assessed through a visual site assessment and calculating stream flow. A total habitat score is calculated (Table 2; Barbour 1999; NJDEP 2015). Staff and volunteers characterize the health of the riparian habitat by completing a visual site assessment and calculating stream flow.

Chemical Data: Chemical parameters are collected annually in June at each of our monitoring sites. Parameters include temperature, pH, dissolved oxygen, nitrogen, phosphorous, specific conductance and turbidity.

Bacterial Data: The current primary contact recreation use surface water quality standard (SWQS) for freshwater in New Jersey is based on Escherichia coli (E. coli) bacteria levels. In 2016, the RHA monitoring program expanded to include more potential stressors including counts of E. *coli* at sites impaired for 2 years and at unregulated swimming areas on our rivers and streams. Each summer, RHA collects water samples at our impaired stream sites and known swimming holes in the watershed to determine if E. *coli* levels are above the surface water standard for safe recreational use. The sites are sampled 5 times over a 30 day period between July and August using NJDEP protocols (https://www.nj.gov/dep/wms/bfbm/QAPPs/SummerAmbientBacteriology2016QAPP.pdf). The results from 2016-2018 indicate that E. *coli* levels often exceed the surface water quality standard for a single sample and/or for the geometric mean especially within 3 days of rain. Garden State Labs (GSL), an NJDEP-certified water testing lab, determines E. *coli* count/100ml using USEPA Method 1603.

Land Use Land Cover*:* Data on land use land cover (referred to as land use going forward) were obtained from NJDEP (Bureau of GIS) and analyzed by catchment area for each site ArcGIS(ESRI). The major land use categories in WMA8 are mapped in Figure 3. For each site, cathement-level variables were calculated from the data including total area of the catchement, percent land use land cover type (forest, wetland, agriculture, urban and barren), and percentage change for each land use land cover type between 1986 and 2012.

Statistical Analysis

Indices of biotic integrity based on benthic macroinvertebrates (Table 3) collected from 105 monitoring sites between 1992 and 2017, and shorter speriods in between, were analyzed for trends over time for the watershed overall and combinations of major river (North Branch vs. South Branch) and physiographic province (Highlands vs. Piedmont). In addition, relationships to local habitat, chemical, bacterial and land use-land cover parameters were explored.

As part of the process of analyzing the data, several issues had to be addressed because along with the opportunities associated with long-term data, there are often obstacles including changing locations, time periods, goals, and methods. One solution was that sites be grouped based on the length of time in the program as well as their location in the watershed. Two long-term analyses included sites that spanned 1992-2017 and 2002-2017 and 4 short term periods within those time frames were analyzed (1992-1999, 2000-2004, 2005-2009, and 2010-2017). In addition, sites were categorized into one of two main branches (North and South Branch Raritan) and by physiographic province/region (Highlands, Piedmont, and Border). Border accounted for sites located right on the border between the Highlands and Piedmont. Combinations of branches and regions were used to obtain a finer understanding of geographic patterns in benthic macroinvertebrate trends.

Descriptives: Descriptive statistics of community metrics summarized by site, the watershed overall, by Branch-Regions, and by year were calculated and reported as box plots and in tabular format (SPSS, 2017).

Trend Analysis: Presence of significant temporal trends in macroinvertebrate community metrics was determined by assessing the significance of Spearman's rank correlation coefficients for pairings of X (Year) and Y (community metric) using methods described by

Scarsbrook et al. (2000; SPSS Statistics 2017). In addition, strength of significant trends were determined. Sites with ≥ 5 years, close to beginning and end of period, for long term and ≥3 years for short-term time periods were included in analyses. Spearman's rank correlation coefficient has an advantage over parametric correlation techniques in that the relationship between X and Y does not necessarily have to be linear, and data does not need to come from a normal population (Iman and Conover 1983). In the analysis, both variables are first ranked, then the correlation coefficient is calculated for the ranks. In the present study, Year was ranked (separate analyses for the 2 long term and 4 short term time periods), with the first year being ranked as 1 and subsequent years given sequential numbers (2, 3, 4, …). A significant relationship between Year and an individual community metric indicated a trend and the sign of the relationship indicated weather the metric increased or decreased temporally. The level of significance was set *a priori* at $p<0.05$.

Data were explored for significant trends (positive or negative Spearman rank correlations) in long term and shorter time periods by site, in the overall watershed, as well as by watershed Branch-Regions. Analyses included reporting proportions and numbers of sites with significant trends, the direction of trends and their strength in all categories as well as comparing percentage of trends within each time period and among Branch-Regions.

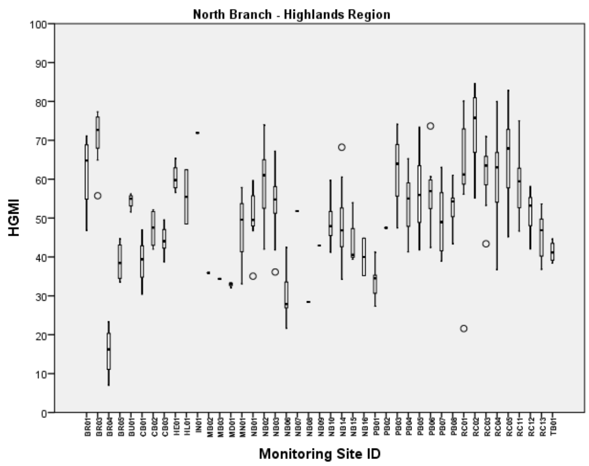
Results

Descriptives

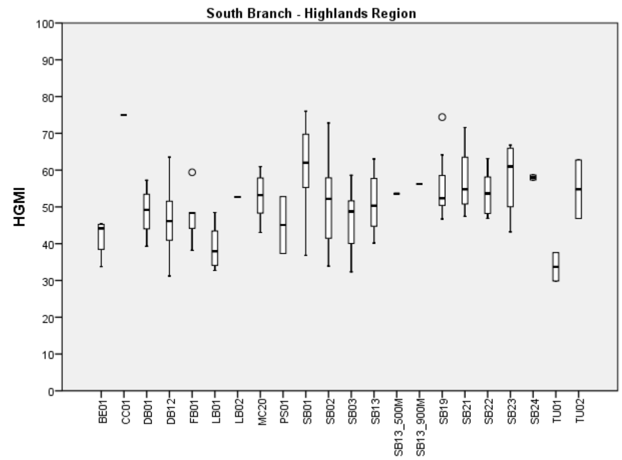
Box plots (Figure 5, a-f) of HGMI by year for all 105 stream monitoring sites studied by RHA between 1992 and 2017. Sites are grouped geographically by their Branch-Region on each graph. Means and standard deviations for all benthic macroinvertebrate metrics summarized by Branch-Region are in Appendix B. Graphs of HGMI by year for individual sites is in Appendix C. Box plots of all data combined for all 15 macroinvertebrate metrics is in Appendix D.

Figure 5 (a-f). Box Plots of all stream monitoring site results depicting HGMI median, 1st quartile, 3rd quartile, max and min for all years combined for each site.

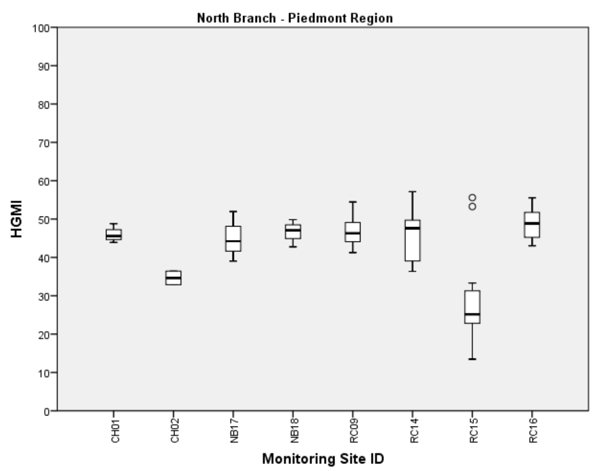
a.



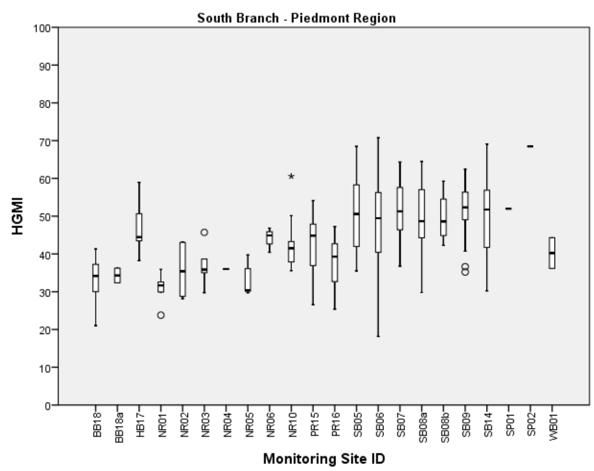
b.



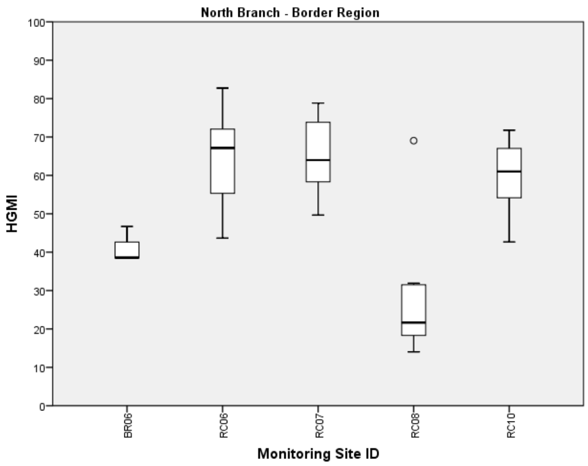
c.



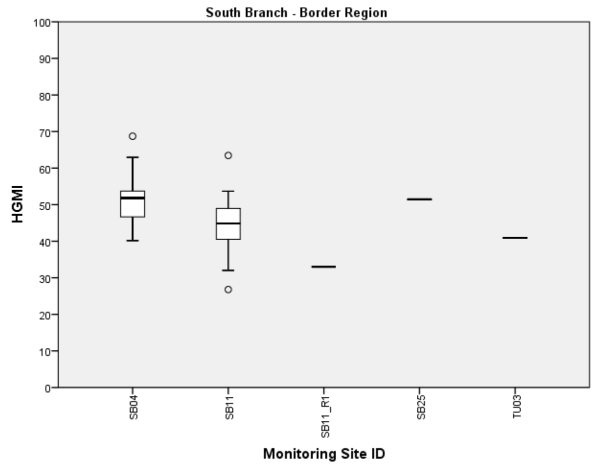
d.



e.



f.



Trends

Trends with Time by Site: Appendix D contains graphs of HGMI over time for each of the sites analyzed. A total of 3,608 Spearman's rank correlation analyses of time with benthic macroinvertebrate community metrics were run using site-level data in two long term and 4 short term time periods. A detailed summary tallying the site-level results is in Table 4 and Figure 7. Two hundred sixty-five (7%) positive and 145 (4%) negative trends were detected, ($p<0.05$). The remaining analyses did not indicate statistically significant trends over time for their respective community metrics. However, when community parameters were categorized based on whether they are indicators of improving or declining water quality (i.e., water quality impact), 232 (6%) of the significant trends indicated improved water quality and 178 (5%) indicated decreased water quality ($p<0.05$). Again, most sites did not demonstrate a significant trend with time.

The two long-term analyses (1992-2017 and 2002-2017) including all sites in the watershed indicated most of the sites (83%, and 89%, respectively) showed no trend in HGMI or NJIS, 14% and 9% showed a positive trend, and 9% and 4% showed a negative trend in water quality, respectively (Table 3). Long term, 19% of the sites had >1 metric indicating declines in water quality while 29% of the sites had >1 metric indicating an improvement in water quality. In recent years (2010-17), 26% of the sites had >1 indicator of a decline in water quality while 18% had >1 indicator of improvements (Table 3). Thus, in the longterm analysis, there were more trends indicating improvements than declines in water quality but in the last few years there were more trends indicating a decline in water quality than improved water quality.

Table 3. Summary of Percentage and number of sites exhibiting Positive, Negative and No Trend in HGMI or NJIS as well as other Benthic Macroinvertebrate Parameters based on Water Quality Impact for each Long Term and Short Term Time Period.

Time Period	n	Percentage and number of Sites with Each Trend in HGMI (or NJIS)			# of Sites with a count of ≥1 community parameter trend based on Water Quality Impact (other than HGMI, NJIS, or Richness)				Total # analyses run
		Positive	Negative	No Trend	Improving	Declining	Both	No Trend	
Longterm 1992-2017	35	14.3(5)	8.6(3)	82.9(29)	21.6(8)	40.5(15)	18.9(7)	18.9(7)	
Longterm 2002-2017	47	8.5(4)	4.3(2)	89.4(42)	29.1(14)	18.8(9)	10.4(5)	41.7(20)	
1992-1999	13	15.4(2)	0(0)	84.6(11)	23.0(3)	0(0)	0(0)	76.9(10)	
2000-2004	43	11.6(5)	9.3(4)	79.1(34)	25.6(11)	25.6(11)	11.6(5)	37.2(16)	
2005-2009	41	14.6(6)	7.3(3)	78.0(32)	18.4(9)	29.3(12)	2.4(1)	46.3(19)	
2010-2017	62	6.4(4)	4.8(3)	88.7(55)	17.7(11)	25.8(16)	8.1(5)	48.4(30)	

When site-level results for each respective metric were expressed as proportions of sites with no trend, positive trend and negative trend , the metrics with the greatest trends were increases in taxa richness (genus and family levels), increasing non-insect taxa, and increasing pollution tolerant taxa (HBI and FBI) with decreases in sensitive EPT (Figure 7).

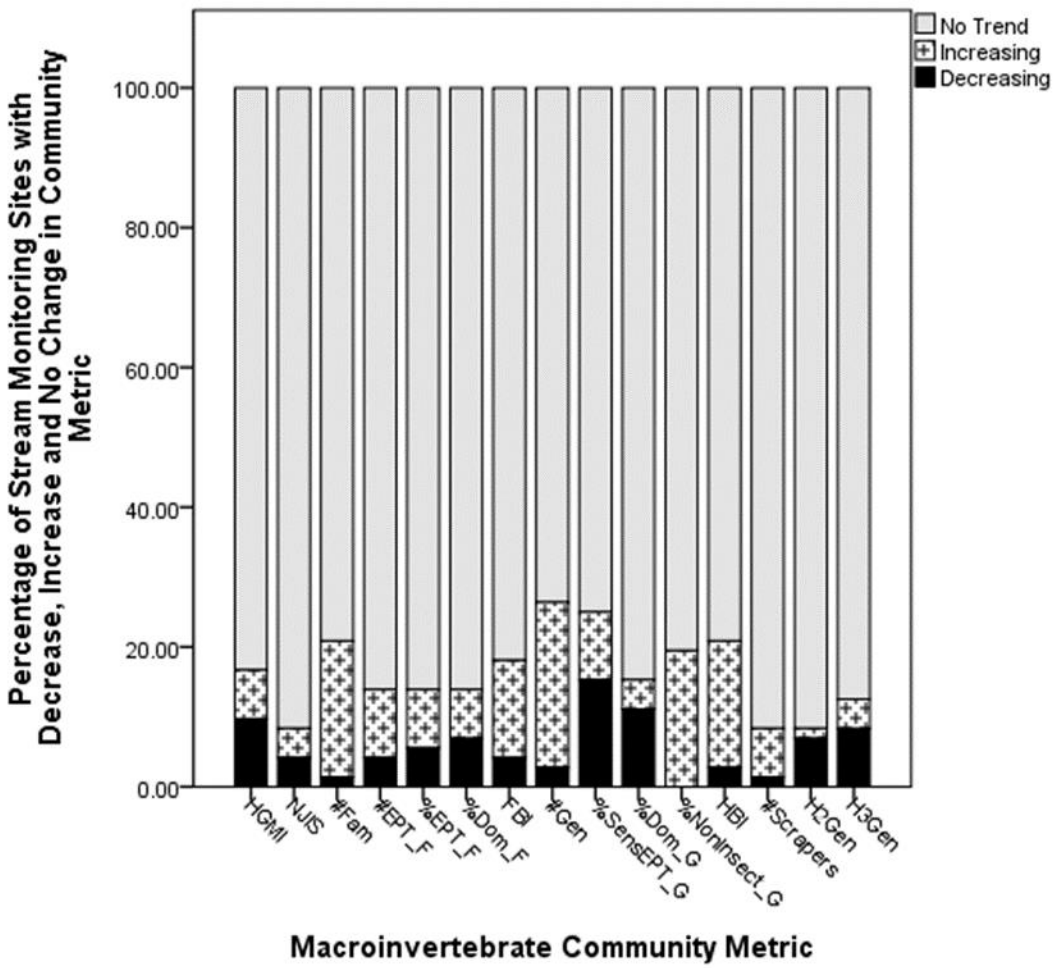


Figure 6. Percentage of stream monitoring sites exhibiting no trend, increasing (positive) or decreasing (negative) trends for each benthic macroinvertebrate community metric (based on longterm 2002-2017 data).

Six sites had long term positive trends in HGMI and/or NJIS (PR15, RC04, SB05, SB09, SB14; Figure 7, a and b) whereas 4 sites had long term negative trends in HGMI and/or NJIS (RC11, PB03, SB01, SB02; Figure 8, a and b). Trend graphs for these sites are presented in Appendix C.

Figure 7 a and b. Maps of long term trends in HGMI (or NJIS) at sites for 1992-2017 (a) and 2002-2017 (b). Green and red arrows indicate positive and negative trends, respectively.

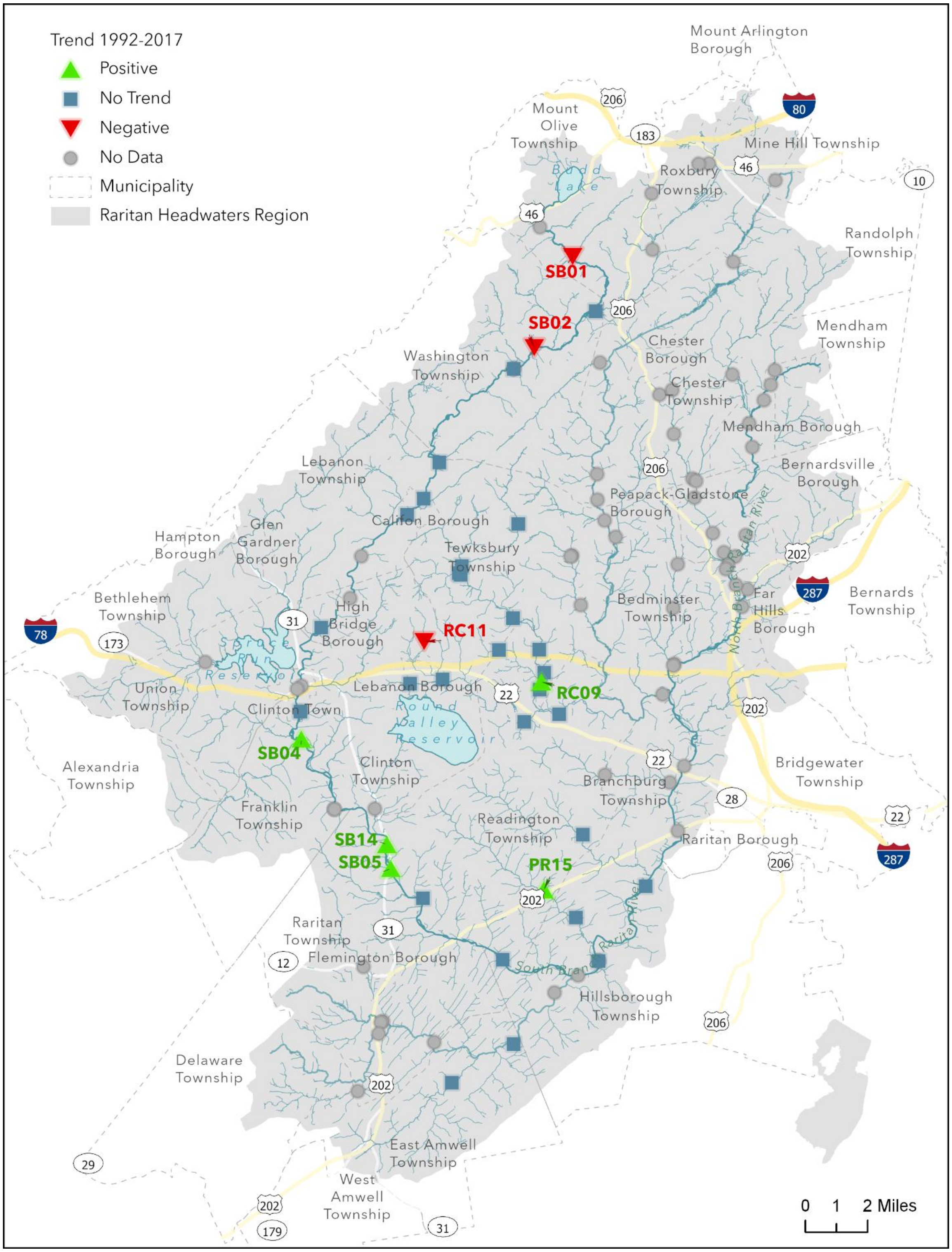


Figure 7a. Map of longterm trends from 1992-2017. **Positive**: PR15, SB04, SB05, SB14; **Negative**: RC11, SB01, SB02

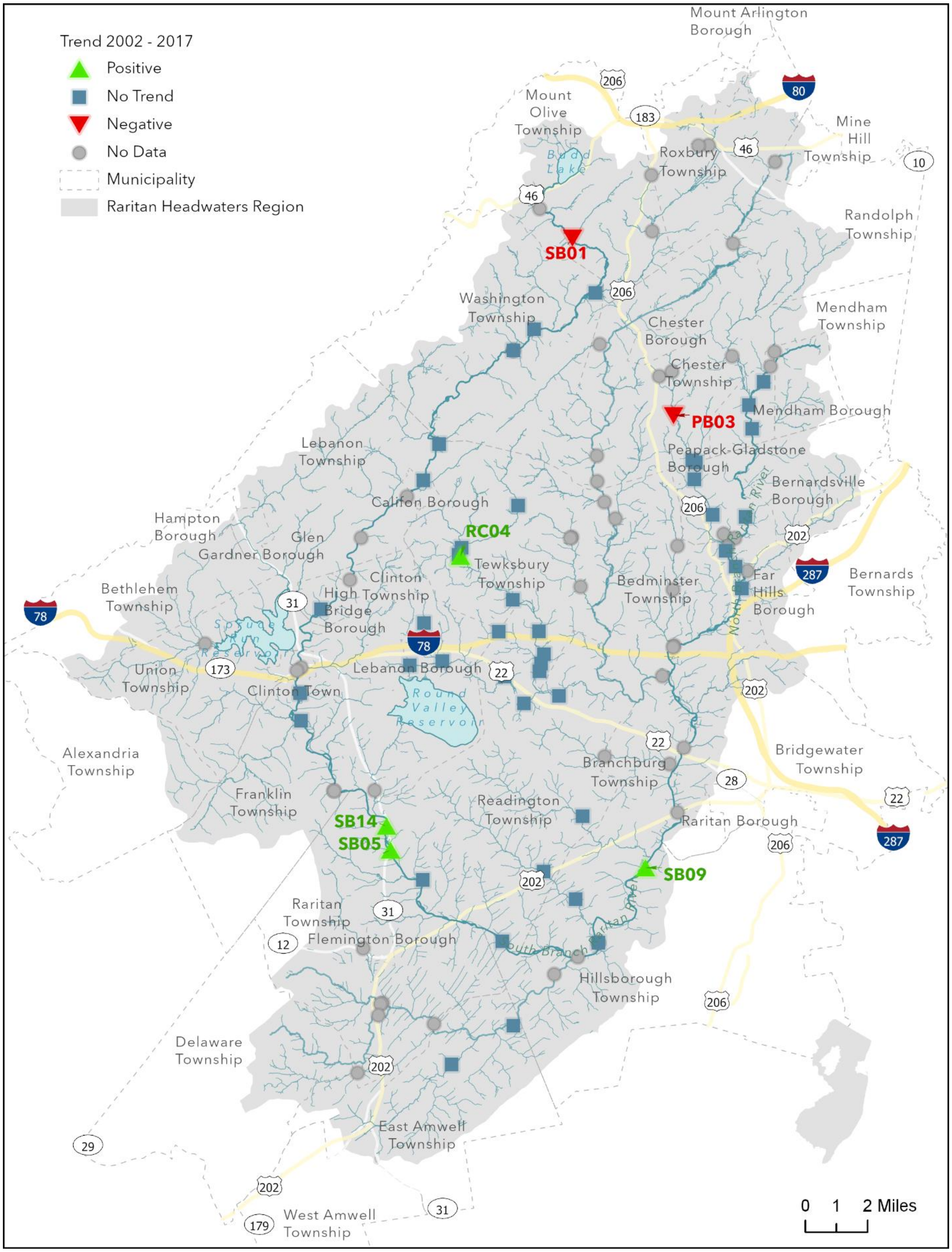


Figure 7b. Map of longterm trends from 2002-2017. **Positive**: RC04, SB05, SB09, SB14; **Negative**: PB03, SB01

Only 2 sites exhibited significant trends in HGMI, both positive, between 1992 and1999 (DB12, SB19; Figure 9a). In the 2000 to 2004 time period there were 5 sites with positive HGMI (or NJIS) trends (NB01, RC09, SB03, SB07, SB11) and 4 sites with negative trends (PB03, PB04, RC03, RC09; Figure 9b). In the 2005-2009 time period, 6 sites had positive trends (BB18, PB05, PB06, PR15, SB06, RC16) while 3 sites had negative trends (DB12, NB10, RC14; Figure 9c). In recent years, 2010-2017, there were 3 sites with positive trends (RC01, SB07, SB21) and 4 with negative trends (PB05, NB01, SB06, SB11; Figure 9d). Trend graphs for all sites are included in Appendix C.

Figure 8 a-d. Maps of short term trends in HGMI at sites included in trend analyses for 1992-1999 (a), 2000-2004 (b), 2005-2009 (c), and 2010-2017 (d). Green and red arrows indicate positive and negative trends, respectively.

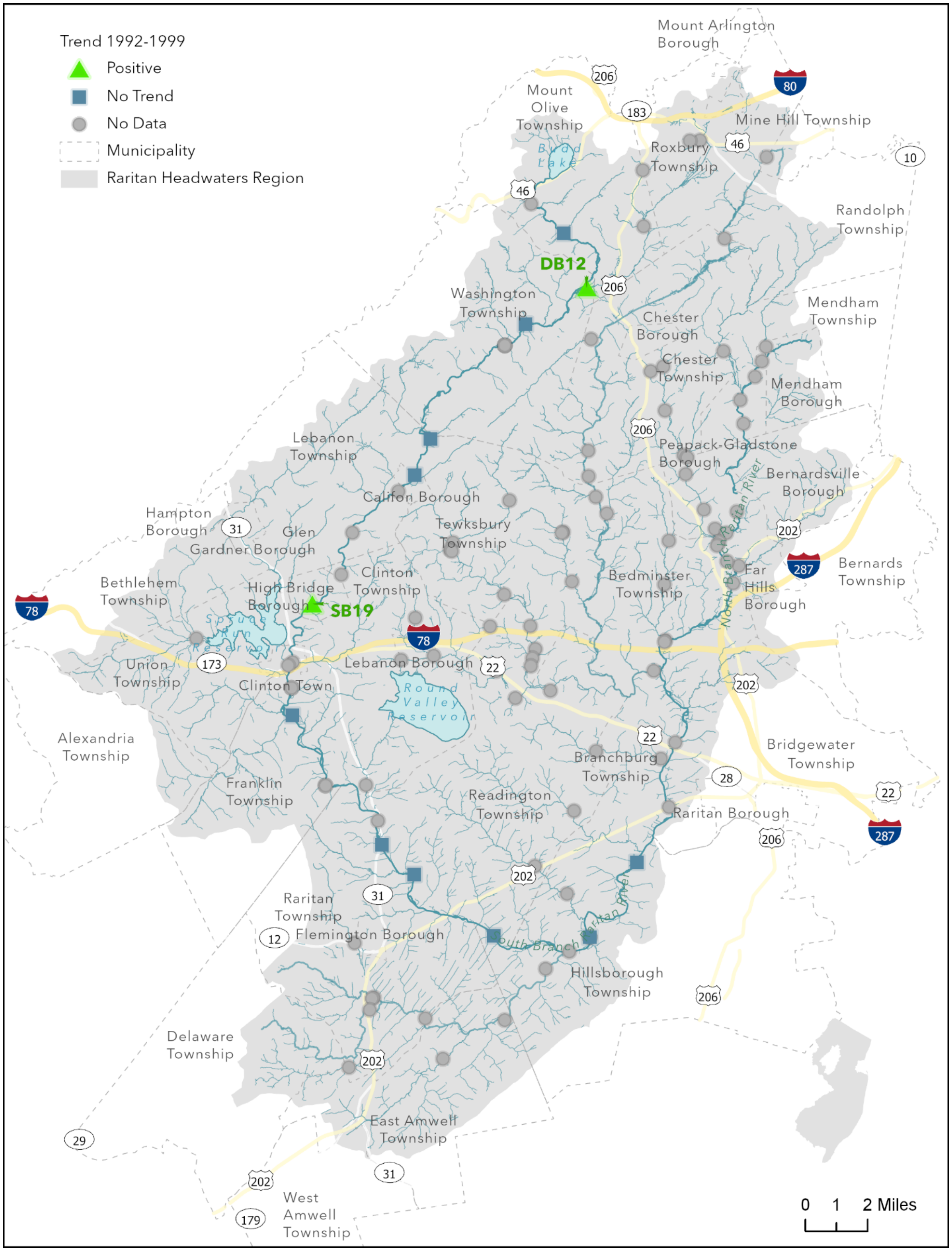


Figure 8a. Map of shortterm trends from 1992-1999. **Positive**: DB12 and SB19

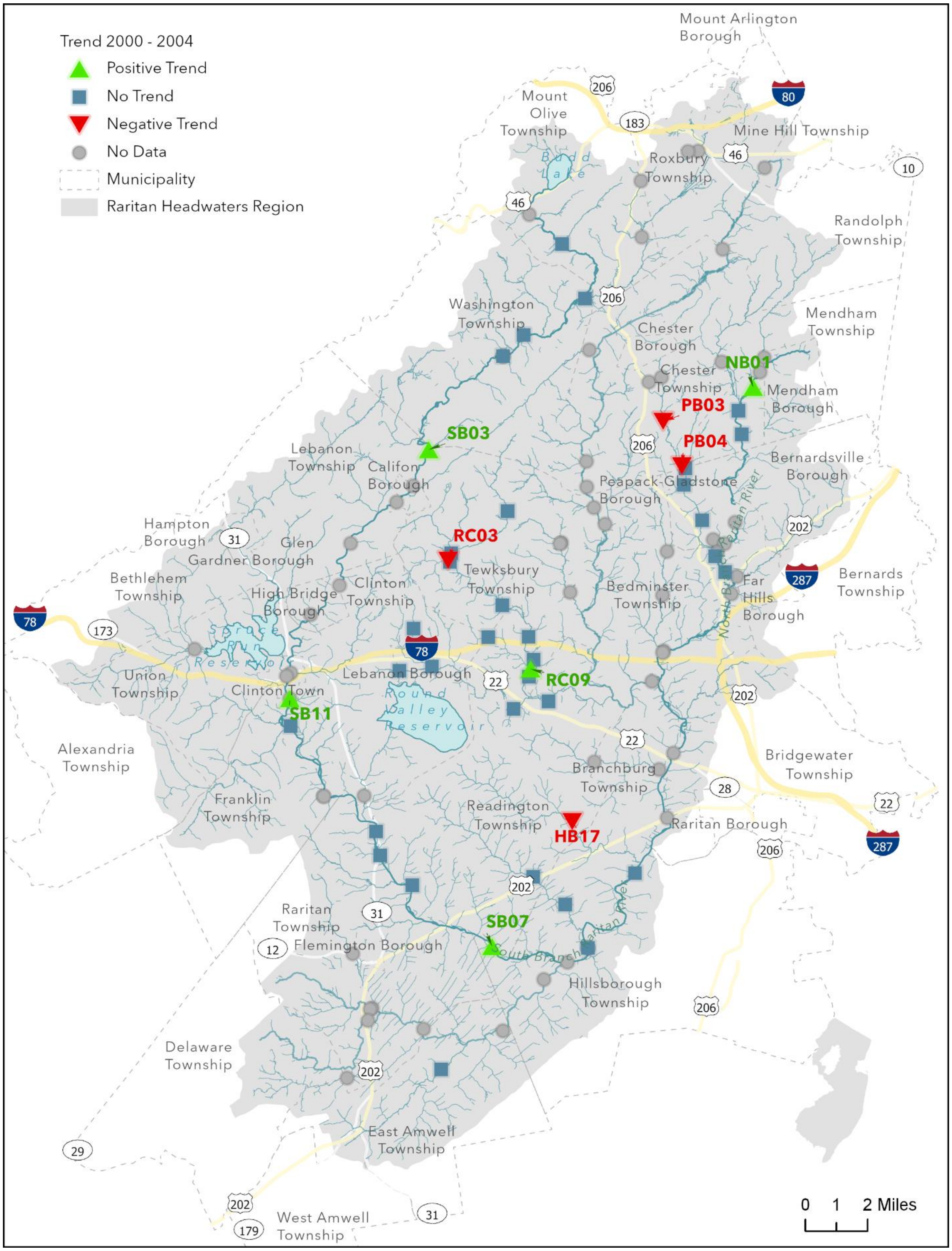


Figure 8b. Map of shortterm trends from 2000-2004. **Positive**: NB01, RC09, SB03, SB07, SB11; **Negative**: PB03, PB04, RC03, RC09

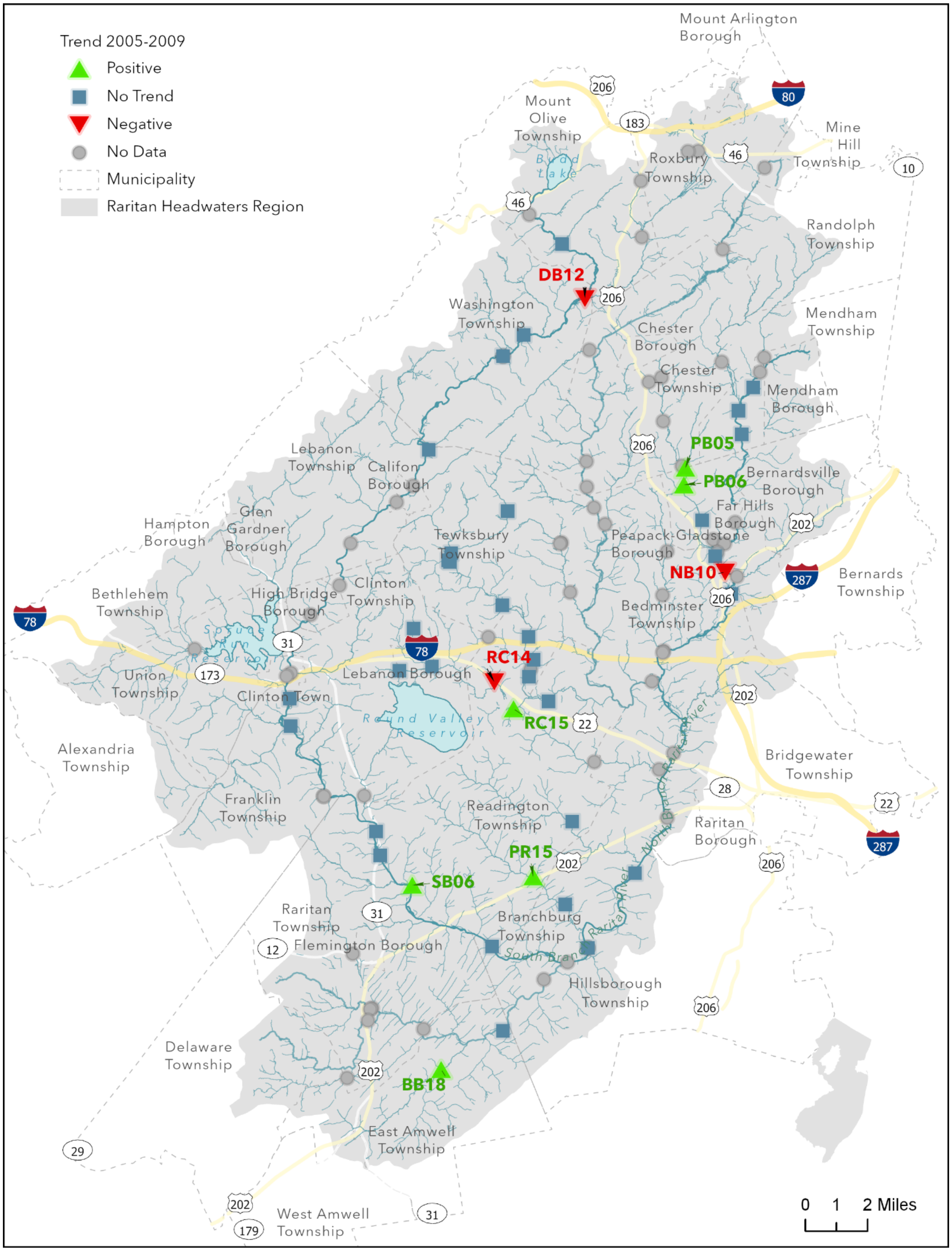


Figure 8c. Map of shortterm trends from 2005-2009. **Positive**: BB18, PB05, PB06, PR15, SB06, RC15; **Negative**: DB12, NB10, RC14

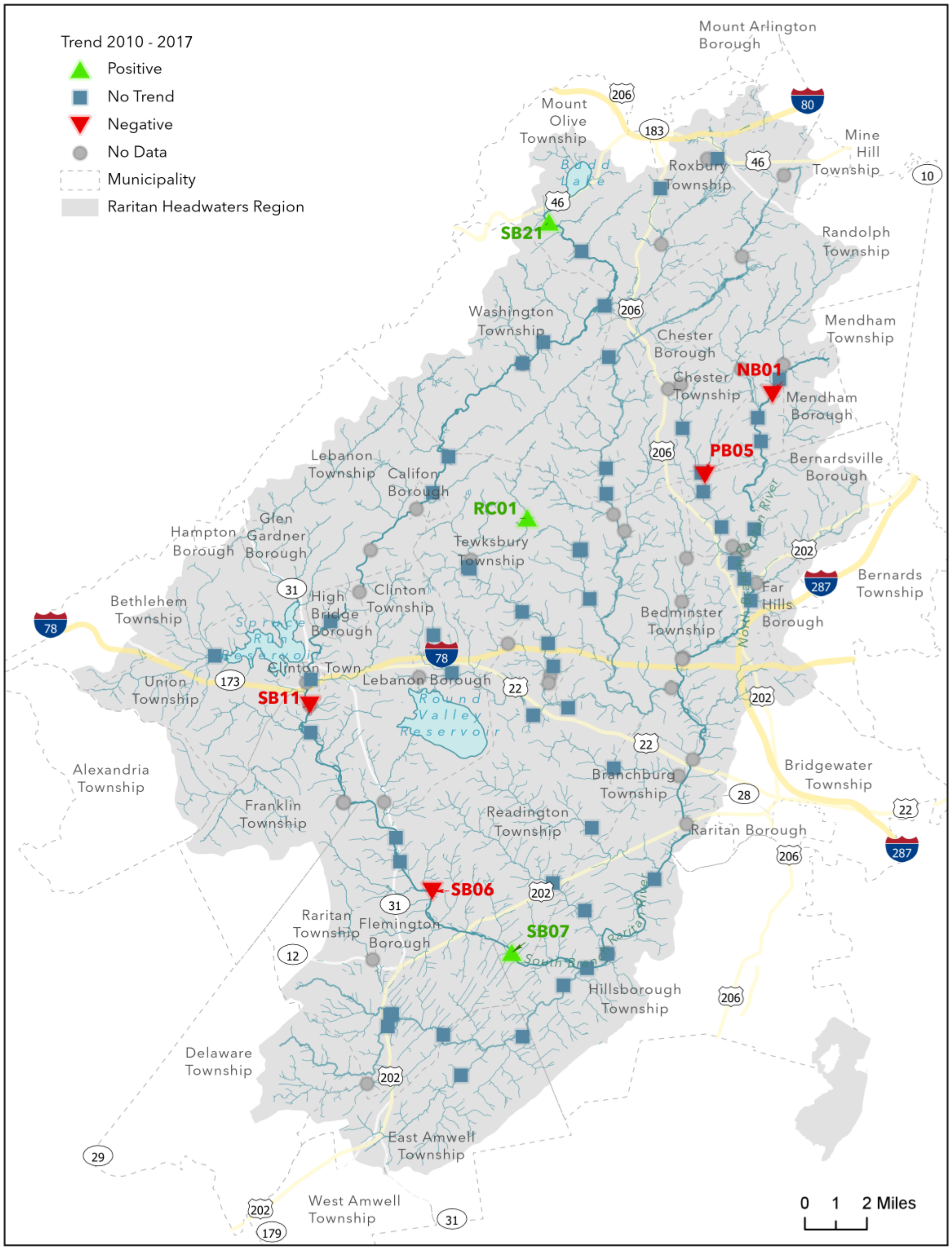
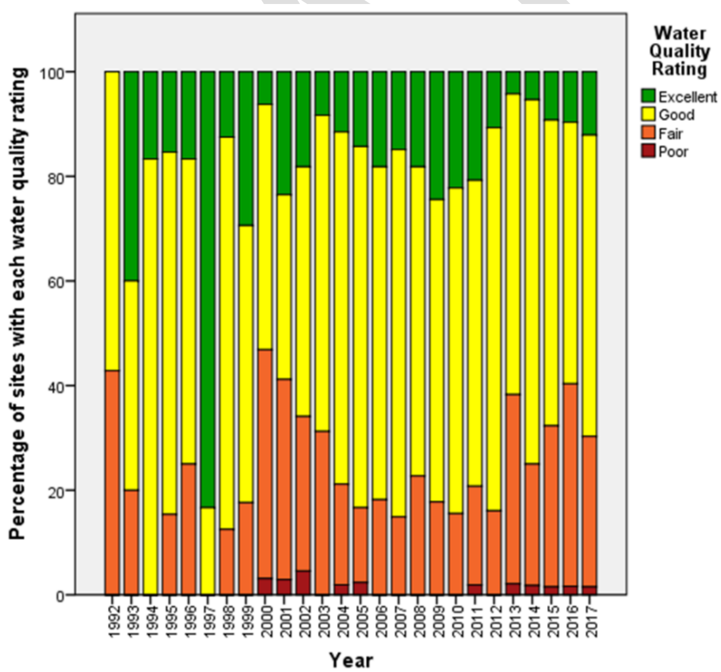


Figure 8d. Map of shortterm trends from 2010-2017. **Positive**: RC01, SB07, SB21; **Negative**: PB05, NB01, SB06, SB11

Overall Watershed Trends

Figure 9 shows the proportions of sites by year with Excellent, Good, Fair and Poor water quality rating based on HGMI for the watershed overall. While the proportion of sites that are non-impaired (Excellent and Good) has fluctuated over time, it appears there has been an increase in the proportion of impaired (Fair and Poor) sites in recent years. Appendix C provides individual box plots for each of the 15 community parameters for all areas of the watershed combined by year. While a large proportion of sites are not impaired in the watershed and have not shown a decline in stream health over time, few sites are achieving an excellent water quality rating. In 2017 about 28% of the sites were impaired; in 2010, only 18% were impaired.

Figure 9. Proportions of sites over time with Excellent, Good, Fair and Poor water quality rating based on HGMI for the watershed overall.



North Branch-Highlands: North Branch-Highlands Region experienced the most monotonic and pronounced increase in proportion of impaired sites (fair and poor HGMI rating) and decrease in proportion of non- impaired sites (good or excellent HGMI rating; Figure 10a). Sites with poor ratings began to appear for the first time in 2014. In 2017, about 50% of the sites were impaired but in 2010 only about 10% were impaired. In the North Branch-Highlands, ten of fifteen macroinvertebrate metrics showed significant negative longterm trends ($p<0.05$; Tables 4 and 5); all of the trends were associated with negative water quality impacts. HGMI and NJIS both showed weak declines. There was a moderate increase in % non-insect genera, which was the strongest trend detected and is associated with a decline in water quality. There were also weak declines in % EPT (family and genus-level), # EPT Families, and # of H2 and H3 Genera; there were increases in pollution tolerant families and genera. A very similar pattern was seen in recent years (2010-2017).

South Branch-Highlands: A trend in greater proportion of sites with impaired HGMI was not as strongly apparent in the South Branch-Highlands Region because proportions of impaired and non-impaired sites tended to fluctuate (Figure 10b). Interestingly, there were no poor sites detected in this region. In 2016, about 30% of sites were impaired but in 2017 none were impaired. South Branch-Highlands had a weak decline in NJIS but no trend in HGMI was detected (Tables 4 and 5). There was a moderate increase in genera richness and HBI (# pollution tolerant genera) and weak increases in family richness, FBI (# pollution tolerant families), % non-insect genera and # H2 genera. There were declines in % EPT families and genera. Recent trends (2010-2017) include weak increases in family and genera richness and % non-insect genera.

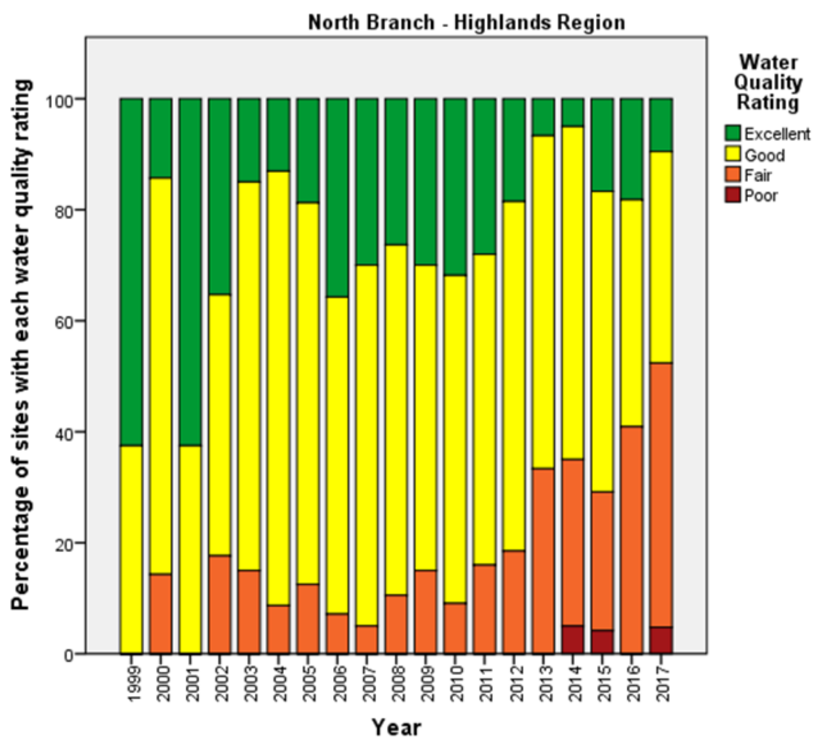
North Branch-Piedmont: The proportion of impaired sites in the North Branch Piedmont (Figure 10c) has fluctuated but appears to have always tended to be higher than other Branch-Regions; there have been no excellent ratings recorded for this Branch-Region since the beginning of monitoring there. In the past few years, the proportion of impaired sites has increased. In 2017, about 60% were impaired. Moderately strong increases in family richness, % non-insect genera and # HBI and #FBI were detected (Tables 4 and 5). There was a weak increase in genera richness. North Branch Piedmont did not exhibit any significant recent trends.

South Branch-Piedmont: South Branch-Piedmont water quality ratings have fluctuated over the years with some periods with decreasing and some with increasing water quality (Figure 1d).

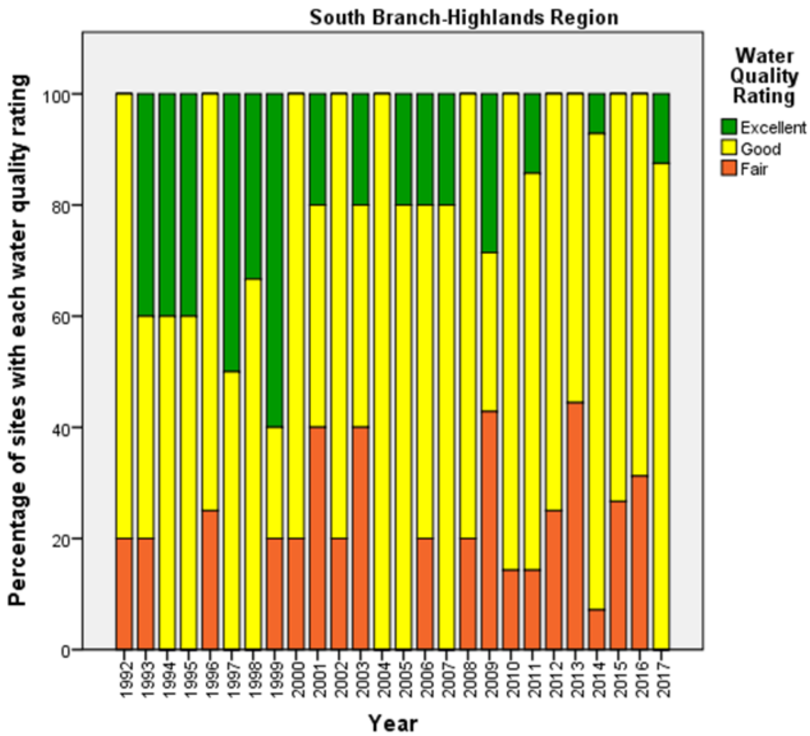
The South Branch Piedmont tends to have a higher proportion of sites with good and excellent ratings than the North Branch-Piedmont in general. The percentage of impaired sites has been increasing over the past few years. However, in 2016 about 50% were impaired but this number dropped to about 28% in 2017. The South Branch-Piedmont had a moderate increase in genera richness and weak increases in family richness, # FBI, % non-insect and % sensitive EPT genera over the longterm (Tables 4 and 5). However in recent years, there have been mainly negative trends in the South Branch-Piedmont including weak declines in HGMI, EPT family richness, and # H3 genera with weak increases in % non-insect taxa.

Figure 10, a-d. Proportion of sites over time with Excellent, Good, Fair and Poor water quality rating based on HGMI grouped by Branch-Region (Border region sites excluded). Excellent and Good rating are Non-impaired whereas Fair and Poor are Impaired.

a.

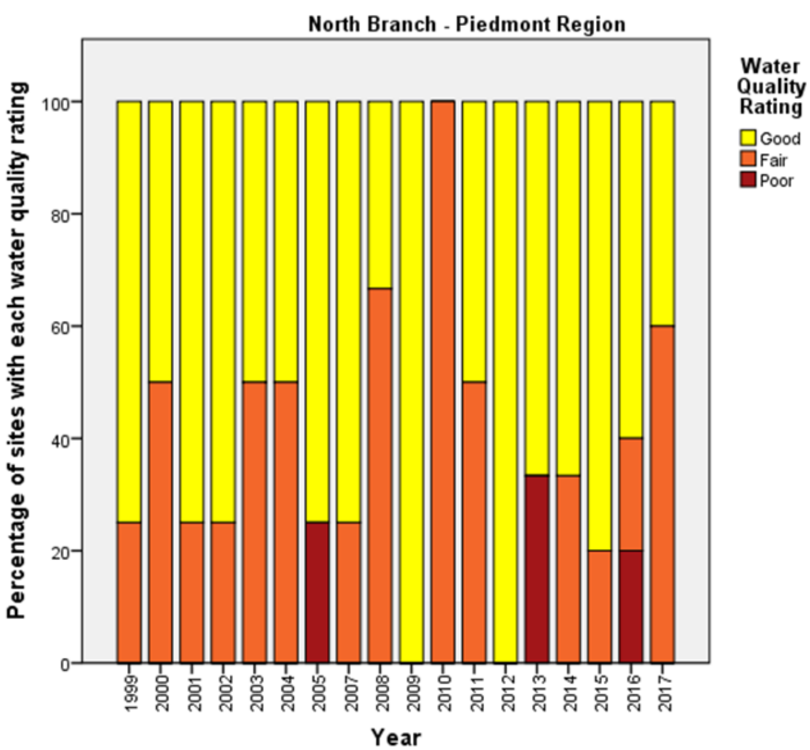


b.



South Branch-Highlands Region
Percentage of sites with each water quality rating
Year
Water Quality Rating
Excellent
Good
Fair

c.



North Branch - Piedmont Region
Percentage of sites with each water quality rating
Year
Water Quality Rating
Good
Fair
Poor

d.

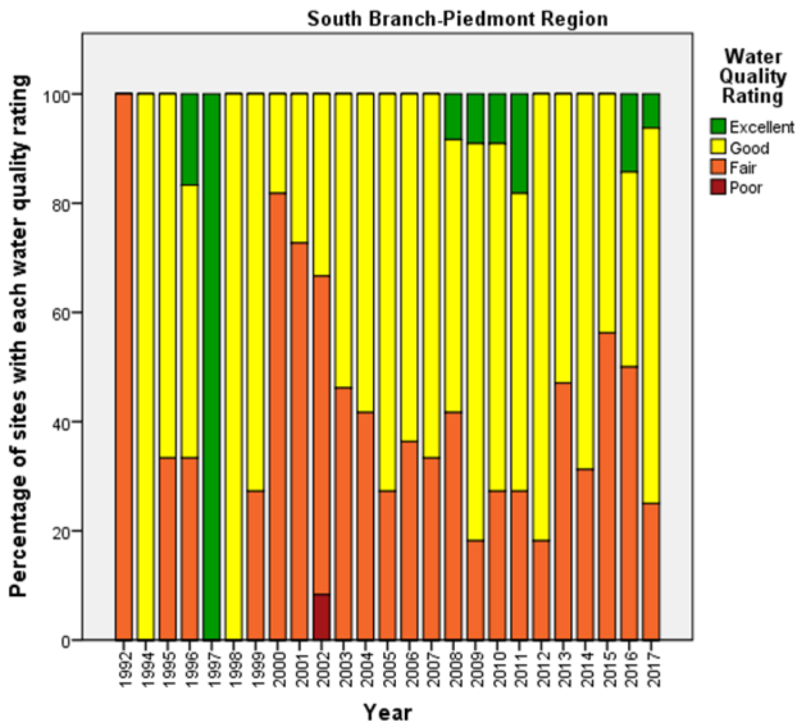


Table 4. Key to Spearman rank strength of significant (p<0.05) positive and negative correlation coefficients and color indicators of whether the trend impacts water quality in a positive (green) or negative (red) way. Saturation of color indicates strength of correlation. White indicates no significant correlation.

Indicator Associated with	–	–	–		+	+	+
Trend	Moderate	Weak	Very Weak	No Trend	Very Weak	Weak	Moderate
Range of Spearman Rank Correlations	-0.40-0.59	-0.20- -0.39	-0.00 - -0.19		0.00 – 0.19	0.20 – 0.39	0.40 – 0.59
Color saturation indicates strength of correlation(Reds=decreasing water quality; Greens indicate improving water quality);							

Table 5. All Sites Combined watershed-wide for each time period, respectively, Spearman Rank Correlation Coefficients at p<0.05 and p<0.01.

	Longterm 1992-2017 (all sites watershed-wide)				Recent 2010-2017			
Region >	Highlands		Piedmont		Highlands		Piedmont	
Branch >	North	South	North	South	North	South	North	South
HGMI	-0.271**				-0.238**			-0.241*
NJIS	-0.193**	-0.152*			-0.253**			
Family Richness		0.214**	0.412**	0.309**	0.178*	0.267*		
EPT Family Richness	-0.170**				-0.209*			-0.213*
% EPT Families	-0.133**	-0.366**			-0.282**			
FBI	0.311**	0.374**	0.414**	0.261**	0.261**			
% Dominance Family								
Genera Richness		0.469**	0.373**	0.399**		0.260*		
%Dominant Genera		-0.324**		-0.281**				
%Non-insect Gen.	0.449**	0.382**	0.571**	0.186**	0.399**	0.256*		0.265**
% Sensitive EPT Gen.	-0.231*	-0.184*		0.217**	-0.354**			
HBI Genera	0.339**	0.409**	0.509**		0.328**			
# Scrapers			0.310*		0.202*			-0.199*
H2 Genera	-0.294**	0.208**			-0.353**			
H3 Genera	-0.135*							-0.233*

Relationship of HGMI & NJIS with Local Habitat, Chemical, & Bacterial Parameters and Land Use-Land Cover

HGMI was positively correlated with dissolved oxygen, stream depth, number of stream depth-velocity regimes, epifaunal substrate, embeddedness, % forest cover, % open water and % barren land and negatively correlated with temperature (Table 6). NJIS was positively correlated with stream depth and % open water, and negatively correlated with % urban land use (Table 6).

Table 6. Table of significant ($p<0.05$) Spearman's Rank Correlations of HGMI and NJIS with local and catchement-level parameters.

Benthic Macroinvertebrate Water Quality Metric	**Positive correlates**	**Negative correlates**
HGMI	FOR +0.205* WAT +0.210* BAR +0.279** DO +0.172* Epifaunal substrate +0.209 * Vel/Depth regimes +0.267* Depth +0.234* Embeddedness +0.179*	Temp -0.171*
NJIS	WAT +0.228* Stream depth +0.253*	URB -0.304**

Conclusions and Next Steps

1.Have the macroinvertebrate community indicators of water quality changed over time? If so, which community indices have changed in the watershed overall and at which particular sites or geographic areas (streams or regions) of the watershed?

The majority of stream sites did not exhibit a trend in water quality but several several sites exhibited positive and negative trends in stream health both longterm and in recent years. Furthermore, there has been a trend of increasing impairment watershed-wide since about 2010. This trend is most pronounced in the North Branch, especially in the Highlands region but also in the Piedmont. The South Branch also demonstrated recent increases in the amount of impaired sites but in 2017 the number dropped drastically in both the Highlands and Piedmont.

Over the longterm, there was a pronounced decline in HGMI and NJIS in the North Branch-Highlands and NJIS in the South Branch-Highlands. In recent years, the North Branch-Highlands also had a trend of declining HGMI and NJIS and declining HGMI in the South Branch-Piedmont. Underlying community metrics generally indicated weak declines in EPT taxa and weak to moderate increases in non-insect genera and pollution tolerant taxa. There were also declines in H2 and H3 genera in the North Branch-Highlands over the longerm and H2 genera. The South Branch Piedmont experienced a decline in H3 genera in the past few years. Over the longterm, there were also weak to moderate increases in family and genera richness in the South Branch (Highlands and Piedmont) and in the North Branch (Piedmont only). In recent years, only the South Branch-Highlands experienced increases in taxa richness.

2.Which local or catchement-level conditions are contributing to improvements and declines in water quality?

Streams in forested catchements, with cooler, oxygen-rich waters and deeper and more diverse habitat structure and composition are associated with healthier macroinvertebrate communities and higher water quality. These conditions are critical for sensitive EPT taxa. Streams in highly urbanized catchements, with low forest cover, higher water temperatures, lower oxygen levels, low diversity habitat with little rock and interstitial space are associated with a poorer community with more pollution-tolerant, non-insect organisms and low numbers of sensitive EPT taxa.

3.Based on the findings of this trend analysis, what targets are recommended for protecting and restoring stream health in the Upper Raritan?

This analysis provides valuable information on specific geographic targets in the Upper Raritan for in need of protection and restoration of stream health through a variety of practices. Several important targets for improvement are:

- Increase the proportion of sites that are non-impaired, especially the proportion of sites rated as excellent, which is in keeping with protection of the headwaters of the Raritan River.
- Increase the proportion of Highlands sites that are rated as excellent in both the North Branch and Piedmont.
- The North Branch-Highlands region, which has shown the most pronounce trend of declining water quality both longterm and in the past 7 years, is of particular concern given the region is has special protections under the Highlands Act and is the drinking water supply for 1.5 million people downstream.
- The North Branch-Piedmont is in need of attention because there is an increasing proportion of impaired sites and this area of the watershed has no excellent sites.
- The South Branch-Piedmont has fluctuated in proportion of impaired sites and in the longterm analyses, many sites showed significant positive trends. However, there has been a weak decline in water quality in recent years.
- Sites showing long-term and recent declines will be targeted as case studies. This includes sites along the South Branch, North Branch, Rockaway Creek, and Peapack Brook.
- RHA will utilize case studies as well as prescriptions for protection and restoration of subwatersheds described in the Watershed Conservation Plan (Strano et al. 2017).
- Sites that have shown improvement or have not changed still need protection. Sites that have declined likely require restoration.
- Maintaining forested areas, both upland and in riparian zones, are key to protecting water quality. This will require some preservation of land but also improved land use planning at the municipal level and the participation of landowners in being good stewards of forests on private land.
- Wide forested stream buffers are critical to stream health. They stabilize stream banks, shade streams and thereby decrease temperatures while increasing oxygen levels, filter nutrients and pollutants from stormwater, slow floodwaters, and provide important food resources for aquatic animals.
- For existing developed areas, stormwater must be better managed especially as New Jersey experiences increases in precipitation and extreme storms with climate change. This is a land use planning and infrastructure issue. Minimizing the amount of impervious cover in a catchement to below 10% to avoid the impacts of stormwater runoff is necessary. This may require retrofitting existing development and infrastructure. Green infrastructure such as rain gardens and bioswales are a key component to improve existing development and also incorporate into all new projects.
- The role of waste water treatment plants are a target for exploration in the watershed because they discharge nutrients, organic material and chemicals including pharmaceuticals and personal care products, and microplastics into streams and rivers

(MacDonald 2018), and potentially alter salinity, temperature, oxygen levels, and pH of receiving waters.

- River Friendly Best Management Practices (BMPs) including reducing stormwater runoff with green infrastructure, planting native species, minimizing nutrients from septic systems, animal waste and fertilizers, conserving water, planting native species, minimizing road salt and pesticide applications and other practices are a critical part that each of us can play in protecting water resources. Read more about BMPs and techniques for protecting streams and groundwater on our website www.raritanheadwaters.org. are outlined in RHA's Watershed Conservation Plan (Strano et al. 2017).

4.What are the next steps in understanding remaining questions about what is causing declines and improvements in stream health?

While this analysis provided information on benthic macroinvertebrate communities with a focus on HGMI and NJIS, the underlying metrics including increases in richness, increases in number of pollution sensitive taxa, increases in non-insect taxa, and decreases in sensitive EPT taxa need to be explored further. This study identifies specific sites and regions where water quality has declined and improved. Where there have been declines or water quality is impaired, in depth stressor analyses will be conducted and recovery plans with specific targets will be developed and shared with municipalities, landowners, and other partners. Data will be explored to better understand what stressors at local (chemical, habitat) and catchement (land use-land cover) scales have changed in a location to cause declines in water quality. Also, by exploring sites showing improving health over time, valuable lessons can be learned on what it will take to restore impaired streams. A next step is to explore which species contributed to the changes in macroinvertebrate indicators. Local and catchment-level causes of declines need to be explored in a more focused analysis. Resiliency of the community to extreme weather events including storms and droughts also needs to be better understood because the region is being heavily influenced by increased precipitation due to climate change. A question we hope to answer is what stream conditions contribute to a stable, resilient macroinvertebrate community. The results from these analyses will be published in similar RHA Working Papers in coming years.

References Cited

Allan, J.D., and L.B. Johnson, 1997. Catchment-scale analysis of aquatic ecosystems. Freshwater Biology 37:107-111.

Arguez, A., I. Durre, S. Applequist, M. Squires, R. Vose, X. Yin, and R. Bilo, 2010. NOAA's U.S. Climate Normals (1981-2010). Monthly, Seasonal, and Annual Normals. NOAA National Centers for Environmental Information. DOI:10.7289/V5PN93JP [Accessed on 02/13/2019].

Arnold, C.L., Jr, and C.J. Gibbons 1996. Impervious surface coverage: The emergence of a key environmental indicator. Journal of the American Planning Association 62:243-258.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling, 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-8-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Davies, S., and S. Jackson, 2006. The biological condition gradient: A descriptive model for interpreting change in aquatic ecosystems. Ecological Applications 16(4):1251–1266.

Dodds, W.K., and M.R. Whiles, 2004. Quality and quantity of suspended particles in rivers: continent-scale patterns in the United States. Environmental Management 33:355-367.

Dodds, W. K., C. T. Robinson, E. E. Gaiser, G. J. A. Hansen, H. Powell, J. M. Smith, N. B. Morse, S. L. Johnson, S. V. Gregory, T. Bell, T. K. Kratz, and W. H. McDowell, 2012. Surprises and insights from long-term aquatic data sets and experiments. BioScience 62:709-146.

Drake, A.A., Jr., R.A. Volkert, D.H. Monteverde, G.C. Herman, H.F. Houghton, R.A. Parker, and R.F. Dalton, 1997. Bedrock geologic map of northern New Jersey (IMAP 2540- A). https://pubs.er.usgs.gov/publication/i2540A

Dudley, N., and S. Stolton, 2003. Running pure: the importance of forest protected areas to drinking water. World Bank/WWF Alliance for Forest Conservation and Sustainable Use, Gland Switzerland. https://openknowledge.worldbank.org/handle/10986/15006

England, L.E., and A.D. Rosemond, 2004. Small reduction in forest cover weaken terrestrial-aquatic linkages in headwaters streams. Freshwater Biology 49:721-734.

Fitzhugh, T.W., and B.D. Richter, 2004. Quenching urban thirst: growing cities and their impacts on freshwater ecosystems. BioScience 54:741-754.

Gerritsen and Leppo, 2005. Biological Condition Gradient for Tiered Aquatic Life Use in New Jersey. Prepared for U.S. EPA OST, U.S. EPA Region 2, and the New Jersey Department of Environmental Protection. Prepared by Tetra Tech, Inc., Owings Mills, MD.

Giller, P.S., and B. Malmqvist, 2004. *The Biology of Streams and Rivers*. In the Biology of Habitats Series, M.J. Crawley, C. Little, T.R.E. Southwood, and S. Ulfstrand (series Editors). Oxford University Press Inc., New York, NY.

Herman et al. 1998

Hickman, R.E., and R.M. Hirsch, 2017. Trends in the quality of water in New Jersey streams, water years 1971-2011: U.S. Geological Survey Scientific Investigations Report 2016-5176, 58 p. https://doi.org/10.3133/sir20165176.

Hilsenhoff, W. L. 1987. An improved biotic index of organic stream pollution. Great Lakes Entomologist 20:31-39.

Iman, R.L., and W.J. Conover, 1983. *A Modern Approach to Statistics*. New York, Wiley & Sons. 497 p.

Jessup, B.K., 2007a. Development of New Jersey High Gradient Macroinvertebrate Index (HGMI). Prepared for USEPA and NJDEP by Tetra Tech, Inc. https://www.state.nj.us/dep/wms/bfbm/download/HGMI_report.pdf

Jessup, B.K., 2007b. South Branch Raritan River, 12-year monitoring trends in water quality using macroinvertebrate data. Prepared for U.S. Environmental Protection Agency Region 2 under contract #68-C-04-006.

Kratzer, E. B., J.K. Jackson, D.B. Arscott, A.K. Aufdenkampe, C.L. Dow, L.A. Kaplan, J.D. Newbold, and B.W. Sweeney, 2006. Macroinvertebrate distribution in relation to land use and water chemistry in New York City drinking-water-supply watersheds. Journal of the North American Benthological Society 24:954-976.

Kurtenbach, J., 1990. A method for rapid bioassessment of streams in New Jersey using benthic macroinvertebrates. Bull. N. Am. Benth. Soc. 8(1):129

MacDonald, K., Microplastic Pollution in Relation to Wastewater Treatment Plants, Land Use, Local Physical Conditions, & Biological and Chemical Measures of Water Quality: Results of a Pilot Study on the South Branch Raritan River, New Jersey (USA). Raritan Headwaters Working Paper #2 available at www.raritanheadwaters.org

McCafferty, P.W., 1983. *Aquatic Entomology: The Fishermen's and Ecologists' Illustrated Guide to Insects and Their Relatives*. Ill. A.V. Provonsha. Jones and Bartlett Publishers, Sudbury, MA.

Meador, M.R., and R.M. Goldstein, 2003. Assessing water quality at large geographic scales: relations among land use, water physiochemistry, riparian condition, and fish community structure. Environmental Management 31:504-517.

NJDEP (New Jersey Department of Environmental Protection) 2015. Visual Assessment Manual. https://www.state.nj.us/dep/wms/bears/docs/Habitat%20Manual%202015-2016.pdf

Paul, J.P., and J.L. Meyer, 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32:333-365.

Phillips, P.J., D.A. Eckhardt, D.A. Freehafer, G.R. Wall, and H.H. Ingleston 2002. Regional patterns of pesticide concentrations in surface waters of New York in 1997. Journal of the American Water Resources Association 38:731-745.

Poff, N.L. 1997. Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. Journal of the North American Benthological Society 16:391-409.

Robinson, D.A., 2014. Exploring New Jersey Climate Variability and Change. Proceedings of the 2014 Geological Association of New Jersey Annual Meeting.

Rosenberg, D.M., and V.H. Resh (editors) 1993. *Freshwater Biomonitoring and Benthic Macroinvertebrates*. Chapman and Hall, New York.

Runkle, J., K. Kunkel, S. Champion, R. Frankson, B. Stewart, and W. Sweet, 2017. New Jersey State Climate Summary. NOAA Technical Report NESDIS 149-NJ. 4 pp.

Scarsbrook, M.R., I.K. Boothroyd, and J.M. Quinn, 2000. New Zealand's national river water quality network: Lon-term trends in macroinvertebrate communities. New Zealand Journal of Marine and Freshwater Research 34:289-302.

SPSS, 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.

Strano, H., K. MacDonald, and M. M. Thomas, 2018. North and South Branch Raritan Watershed Conservation Plan https://www.raritanheadwaters.org/wp-content/uploads/2018/09/WatershedConservationPlan_web.pdf

Sustainable Raritan River Initiative, 2016. State of the Raritan Report Volume 1. Available at http://raritan.rutgers.edu/wp-content/uploads/2017/01/SOR-Final-2017-01-30.pdf

Sustainable Raritan River Initiative, 2018. State of the Raritan Report Volume 2. Available at http://raritan.rutgers.edu/wp-content/uploads/2019/07/SOTR-v2-Final-2019-06-12_reduced-size.pdf

Sweeney, B.W., 1993. Effects of streamside vegetation on macroinvertebrate communities of White Clay Creek in Eastern North America. Proceedings of the Academy of Natural Sciences of Philadelphia 144:291-340.

Voshell, J.R., Jr., 2014. *A Guide to Common Freshwater Invertebrates of North America*. Ill. A.B. Wright. The McDonald and Woodward Publishing Company, Granville, OH.

Wallace, J.B., S. L. Eggert, J.L. Meyer, and J.R. Webster, 1999. Effects of resource limitations on a detrital-based ecosystem. Ecological Monographs 69:409-442.

Wang, L.H., and P. Kanehl, 2003. Influences of watershed urbanization and instream habitat on macroinvertebrates in cold water streams. Journal of the American Water Resources Association 39:1181-1196.

APPENDIX A.

NJ High Gradient Macroinvertebrate (HGMI) score (Jessup 2007a)

NJDEP developed a new tool for identifying biological degradation in the high gradient streams of New Jersey: the High Gradient Macroinvertebrate Index (HGMI). Two forms of the index were developed, one for application with genus level taxonomy and one for family level data. RHA identifies organisms to genus and species level when possible thus the HGMIgen is calculated. As part of the HGMI, seven metrics are calculated and scored for inclusion in the index: • Total number of genera • Percent of genera that are not insects • Percent of EPT individuals (excluding Hydropsychidae, including Diplectrona) • Number of scraper genera • Hilsenhoff Biotic Index • Number of attribute 2 genera (highly sensitive and uncommon taxa) • Number of attribute 3 genera (sensitive and common taxa)

A suite of commonly applied, empirically proven, and theoretically responsive metrics was calculated for possible inclusion in a multimetric index. Tolerance metrics were based on both Hilsenhoff tolerance values and Biological Condition Gradient (BCG) taxa attribute groups (Davies and Jackson 2006; Gerritsen and Leppo 2005). Hilsenhoff tolerance values are on a 0 to 10 scale (most sensitive to most tolerant). The Hilsenhoff scale was derived primarily to address taxa tolerance to organic pollutants (Hilsenhoff 1987). Attributes associated with taxa for BCG analysis range from sensitive-endemic to pollution tolerant. BCG attributes were assigned to taxa by consensus during a workshop on assessment of New Jersey's wadeable streams (Gerritsen and Leppo 2005). Several metrics describe richness and composition of Ephemeroptera, Plecoptera, and Trichoptera (EPT; mayflies, stoneflies, and caddisflies) insects. High Gradient Macroinvertebrate Index 13 Tetra Tech, Inc. All richness metrics (e.g., insect taxa and non-insect taxa) were calculated such that only unique taxa are counted. Those taxa that were identified at higher taxonomic levels because of damage or under-developed features were not counted as unique taxa if other individuals in the sample were identified to a lower taxonomic level within the same sample. Genus level taxonomy was expected to provide more responsive metrics, so all metrics were calculated at the genus level. Metrics that performed well or were previously part of the NJIS were also calculated at the family level. Metrics were not calculated at the species level because several specimens were not identified below genus. Collapsing to genus level provides greater taxonomic consistency, though species level attributes are lost. Habit metrics were calculated using insect taxa only. Habit attributes were not assigned to non-insects by NJDEP. Metrics were calculated in a relational database. Once calculated, the metrics were imported into the statistical package Statistica for further analysis.

Make this a table: Macroinvertebrate Index for High Gradient Streams (HGMI Metric)

(Highlands, Ridge and Valley, Piedmont Physiographic Provinces)

Category Metric Score Assessment

Excellent 63 - 100 Not Impaired

Good 42 - < 63 Not Impaired

Fair 21 - < 42 Impaired

Poor < 21 Impaired

New Jersey Impairment Score Calculation (Kurtenbach 1990; Poretti et al. 2007)

The benthic macroinvertebrate samples are scored using the New Jersey Impairment Scoring (NJIS) Criteria for Rapid Bioassessments. This protocol evaluates a 100 organism subsample on five criteria: Taxa Richness, EPT families, Percent Dominance, Percent EPT, and Family Biotic Index.

1. Taxa Richness refers to the total number of macroinvertebrate families found at the stream monitoring site; a more diverse sample typically indicates a healthier site.
2. "EPT Families" refers to the total combined number of organisms in the sample that belong to the Ephemeroptera (mayflies), Plecoptera (stoneflies), and Tricoptera (caddisflies) families. Generally, the presence of more EPT families indicates a healthier site.
3. Percent Dominance refers to the proportion of the total sample comprised of the dominant family; a smaller percentage of the total sample dominated by one family indicates a healthier site.
4. Percent EPT refers to the proportion of the total sample comprised of EPT organisms. A greater percentage of the total sample comprised of EPT organisms indicates a healthier site.
5. Family Biotic Index (FBI) represents the summation of the following calculation: The number of individuals within a family is multiplied by the Hilsenhoff Family Tolerance Value, and this number is then divided by the total number of organisms in the sample. A lower biotic index value indicates a healthier site.

Each of the five metrics is given a score of 0, 3, or 6 depending on where it falls on the scale, and then all are totaled for a final NJIS index score. The possible scores range from 0 – 30 where 30 indicates the high end of non-impaired, and 0 indicates a site which is severely impaired.

Index metrics	6	3	0
Taxa Richness (Total Families)	>10	10-5	4-0

E+P+T Index (EPT)	>5	5-3	2-0
Percent Dominance	<40	40-60	>60
Percent EPT	>35	35-10	<10
Modified Family Biotic Index	<5	5-7	>7

The biological conditions and their attributes are discussed below:

Non-impaired: Total Score: 24 – 30. Benthic community is comparable to other undisturbed streams within the region. A community characterized by a maximum of taxa richness, balanced taxa groups, and good representation of intolerant species.

Moderately Impaired: Total Score: 9 – 21. Macroinvertebrate richness is reduced in particular EPT taxa. Taxa composition changes result in reduced community balance and intolerant taxa become absent.

Severely Impaired: Total Score: 0 – 6. A dramatic change in the benthic community has occurred. Macroinvertebrates are dominated by a few taxa which are very abundant. Tolerant taxa are the only individuals present.

APPENDIX B.

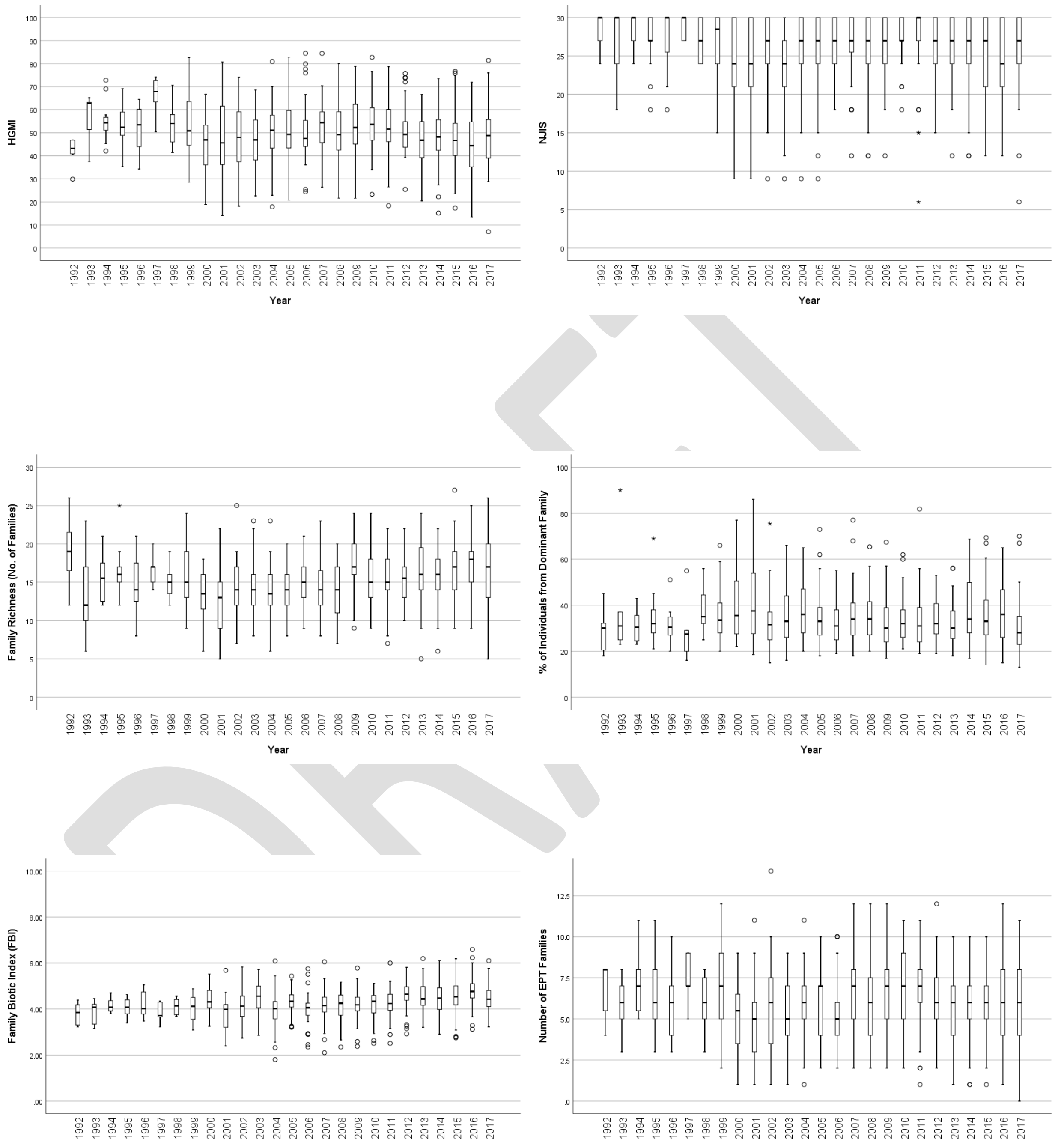
Descriptive Statistics By Branch-Region North Branch, South Branch; Highlands (Hi), Piedmont (Pi), Border (Bo)

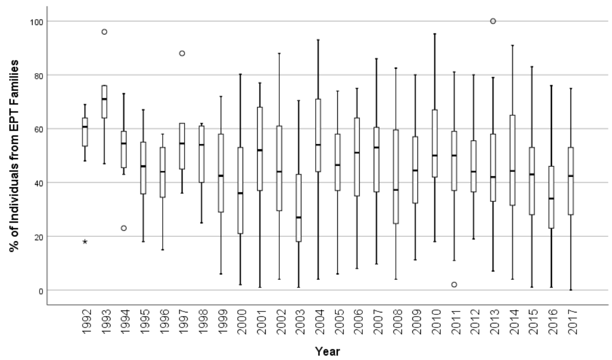
Benthic Macroinvertebrate Metric	Branch_Region	Mean	Std. Deviation (+/-)	N
HGMI	North_Bo	58.2543	15.92631	42
	North_Hi	54.4448	11.99913	244
	North_Pi	42.4083	10.63772	41
	South_Bo	48.8041	6.77078	32
	South_Hi	50.7454	9.41089	89
	South_Pi	46.5529	9.77475	167
	Total	50.9306	11.87478	615
TotalBugsGen	North_Bo	95.05	14.680	42
	North_Hi	94.99	14.136	244
	North_Pi	99.78	.909	41
	South_Bo	99.66	1.004	32
	South_Hi	98.57	3.367	89
	South_Pi	98.32	7.313	167
	Total	96.98	10.642	615
DomGenPerc	North_Bo	26.47	12.523	42
	North_Hi	25.89	11.402	244
	North_Pi	28.24	10.095	41
	South_Bo	28.51	8.873	32
	South_Hi	21.83	8.535	89
	South_Pi	27.33	9.994	167
	Total	26.03	10.661	615
HBIGen	North_Bo	4.369536	.8910796	42
	North_Hi	4.598122	.8226633	244
	North_Pi	4.907422	.3223042	41
	South_Bo	4.795635	.3722803	32
	South_Hi	4.954718	.6342581	89
	South_Pi	5.016256	.5543824	167
	Total	4.778555	.7216298	615
HSensEPT	North_Bo	37.02	19.709	42

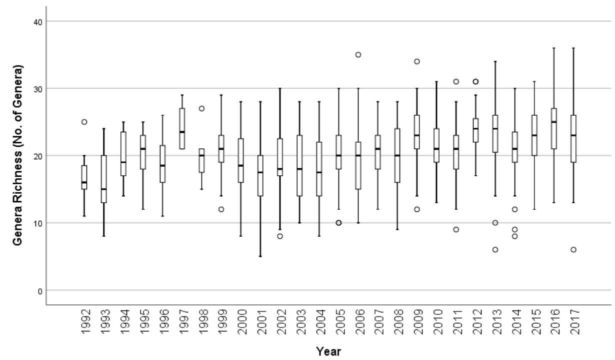
	North_Hi	31.87	16.601	244
	North_Pi	15.48	9.941	41
	South_Bo	18.30	7.899	32
	South_Hi	19.76	8.500	89
	South_Pi	22.59	14.366	167
	Total	26.15	15.875	615
HNonInsect	North_Bo	13.93	9.335	42
	North_Hi	12.91	7.403	244
	North_Pi	18.35	11.197	41
	South_Bo	16.81	8.878	32
	South_Hi	16.64	7.607	89
	South_Pi	17.11	8.751	167
	Total	15.23	8.540	615
H#Scrapers	North_Bo	3.62	1.912	42
	North_Hi	3.30	1.557	244
	North_Pi	2.83	1.482	41
	South_Bo	3.84	1.439	32
	South_Hi	3.62	1.386	89
	South_Pi	4.14	1.534	167
	Total	3.59	1.588	615
H2Genera	North_Bo	2.93	1.800	42
	North_Hi	3.09	1.963	244
	North_Pi	.85	.882	41
	South_Bo	1.66	1.035	32
	South_Hi	2.39	1.520	89
	South_Pi	1.07	1.015	167
	Total	2.21	1.816	615
H3Genera	North_Bo	5.60	2.509	42
	North_Hi	4.16	1.971	244
	North_Pi	3.44	2.025	41
	South_Bo	3.66	1.310	32
	South_Hi	4.07	1.870	89
	South_Pi	3.23	1.543	167
	Total	3.92	1.955	615

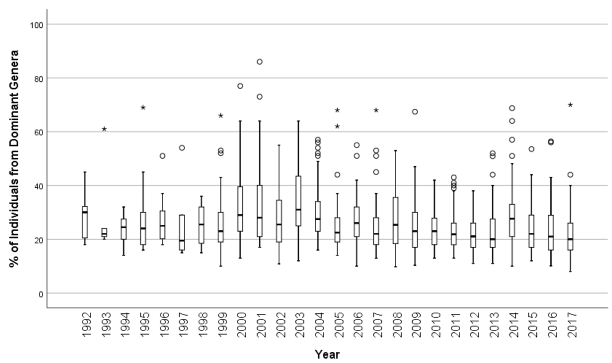
APPENDIX C.

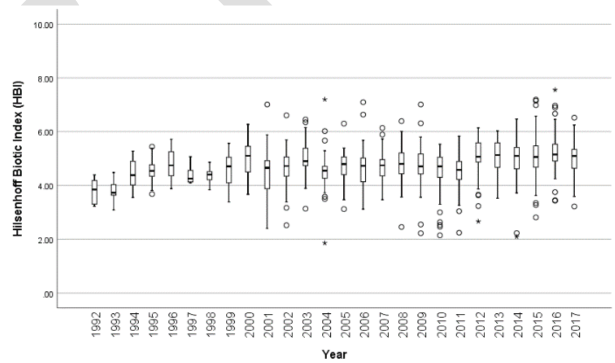
Figures 10.

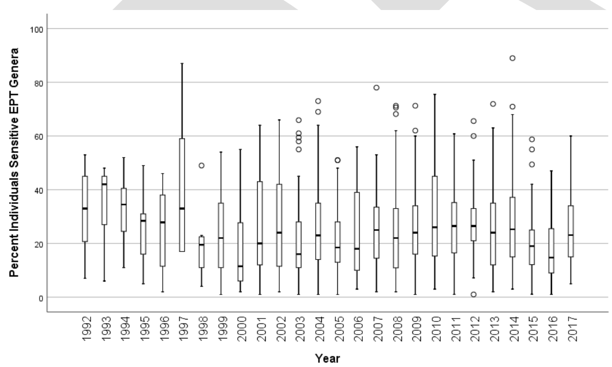


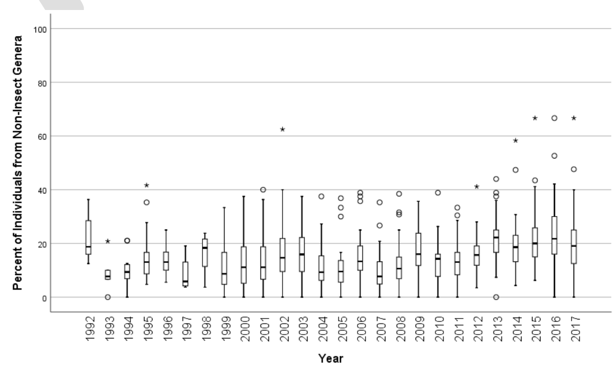

% of Individuals from EPT Families
0
20
40
60
80
100
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year

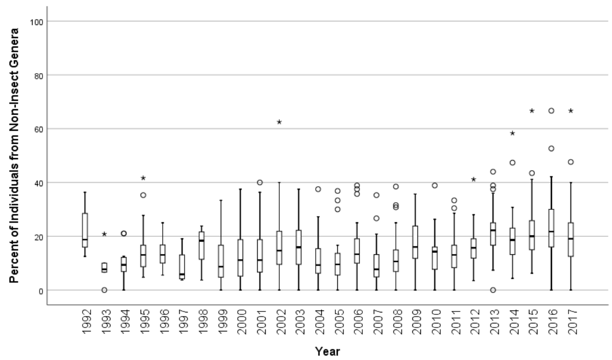

Genera Richness (No. of Genera)
0
10
20
30
40
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year

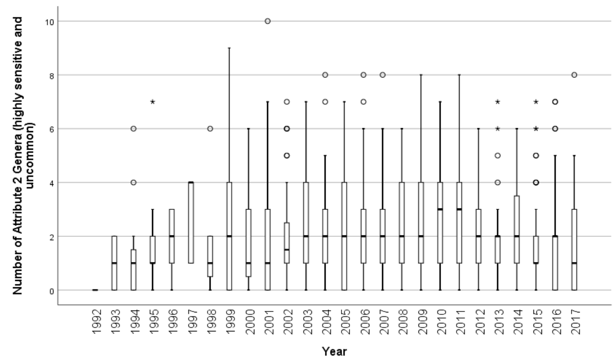

% of Individuals from Dominant Genera
0
20
40
60
80
100
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year

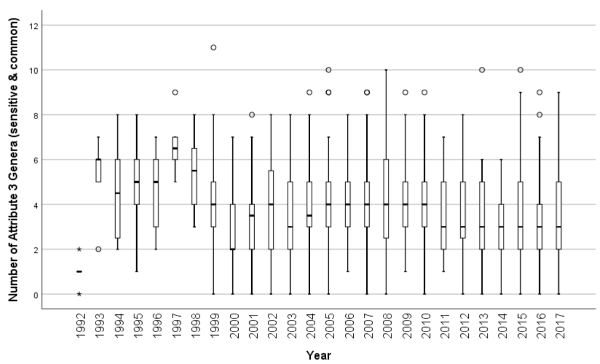

Hilsenhoff Biotic Index (HBI)
.00
2.00
4.00
6.00
8.00
10.00
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year


Percent Individuals Sensitive EPT Genera
0
20
40
60
80
100
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year


Percent of Individuals from Non-Insect Genera
0
20
40
60
80
100
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
Year

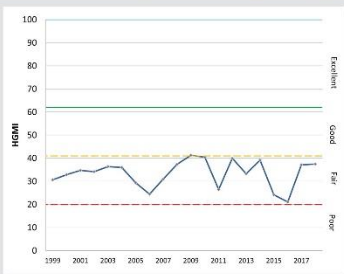

Percent of Individuals from Non-Insect Genera
Year


Number of Attribute 2 Genera (highly sensitive and uncommon)
Year


Number of Attribute 3 Genera (sensitive & common)
Year

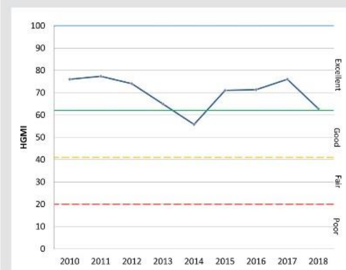
APPENDIX D.

Back Brook Site 18 (BB18)

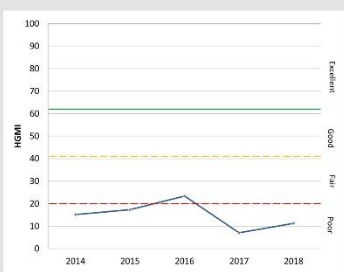


Beaver Brook Site 1 (BE01)

Black River Site 3 (BR03)



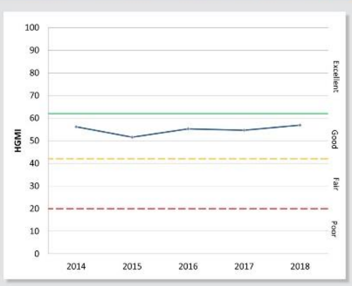
Black River site 4 (BR04)



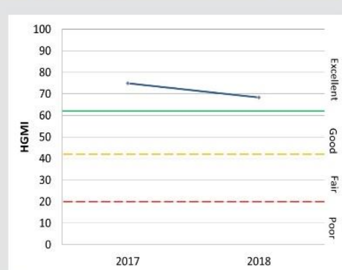
Black River Site 5 (BR05)

Black River Site 6 (BR06)

Burnett Brook Site 1 (BU01)

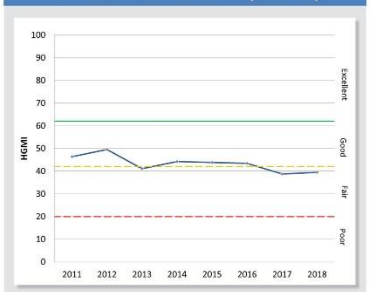


Capoolong Creek Site 1 (CC01)



Cold Brook Site 1 (CB01)

Cold Brook Site 3 (CB03)

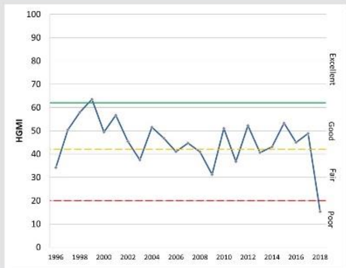


Chambers Brook Site 2 (CH02)

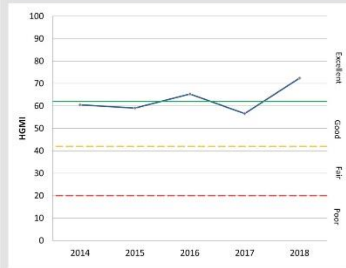
Drakes Brook Site 1 (DB01)

Raritan Headwaters
Your water is our mission.

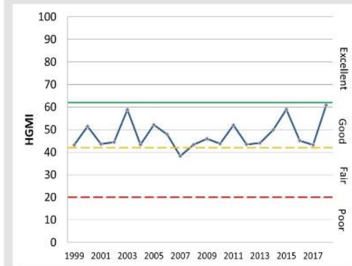
Drakes Brook Site 12 (DB12)



Herzog Brook Site 1 (HE01)

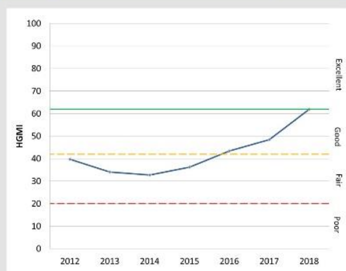


Holland Brook Site 17 (HB17)

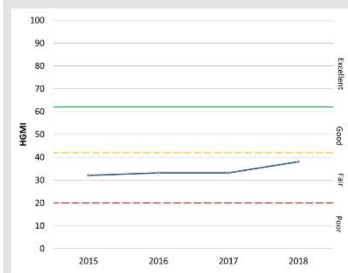


Hollow Brook Site 1 (HL01)

Ledgewood Brook Site 1 (LB01)

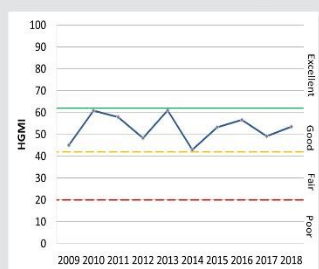


Middle Brook Site 1 (MD01)

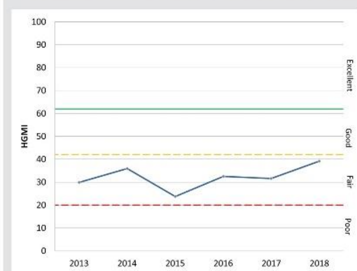


Mine Brook Site 1 (MN01)

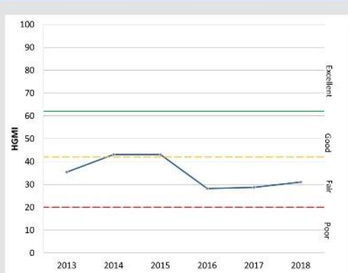
Mulhockaway Creek Site 20 (MC20)



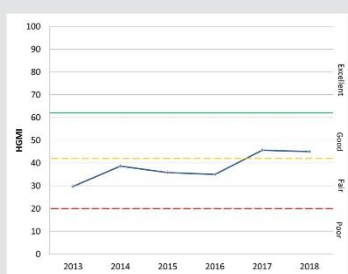
Neshanic River Site 1 (NR01)



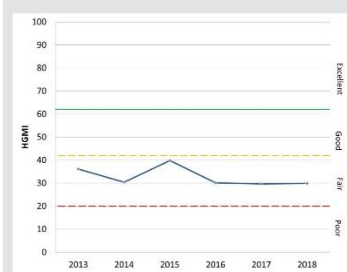
Neshanic River Site 2 (NR02)



Neshanic River Site 3 (NR03)

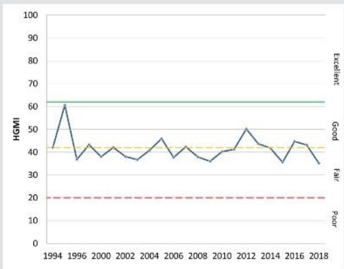


Neshanic River Site 5 (NR05)

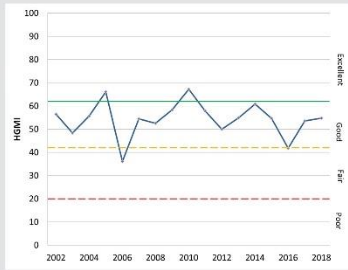


Raritan Headwaters
Your water is our mission.

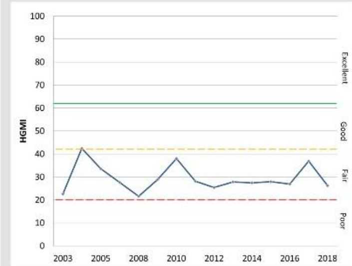
Neshanic River Site 10 (NR10)



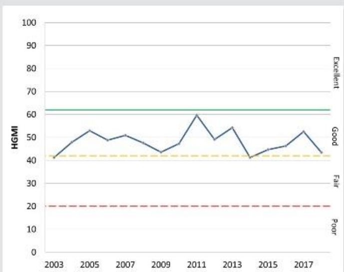
North Branch Site 3 (NB03)



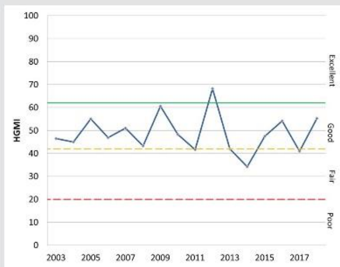
North Branch Site 6 (NB06)



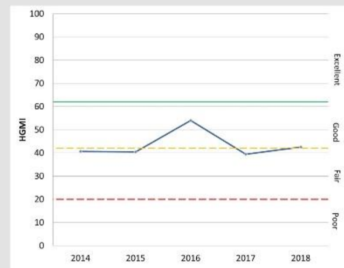
North Branch Site 10 (NB10)



North Branch Site 14 (NB14)



North Branch Site 15 (NB15)

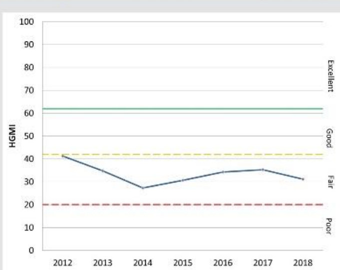


North Branch Site 16 (NB16)

North Branch Site 17 (NB17)

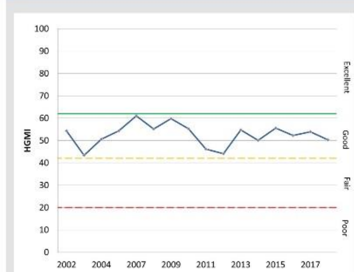
North Branch Site 18 (NB18)

Peapack Brook Site 1 (PB01)



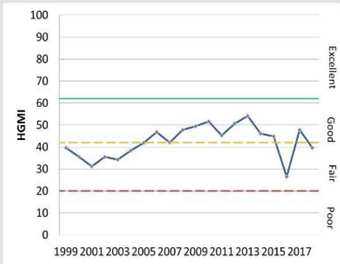
Peapack Brook Site 6 (PB06)

Peapack Brook Site 8 (PB08)

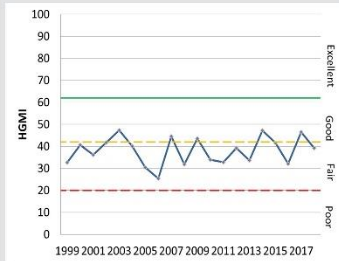


Raritan Headwaters
Your water is our mission.

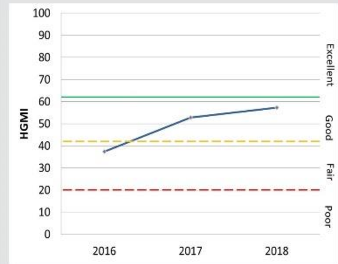
Pleasant Run Site 15 (PR15)



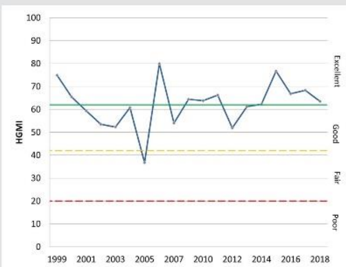
Pleasant Run Site 16 (PR16)



Prescott Brook Site 1 (PS01)

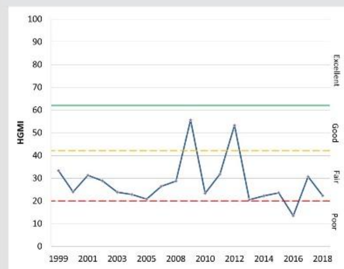


Rockaway Creek Site 4 (RC04)

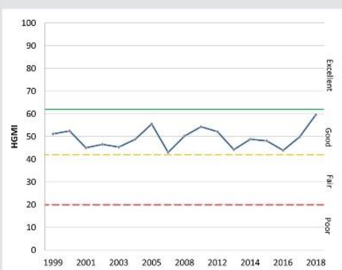


Rockaway Creek Site 6 (RC06)

Rockaway Creek Site 15 (RC15



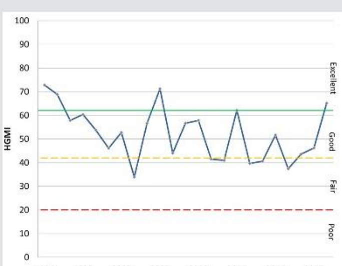
Rockaway Creek Site 16 (RC16)



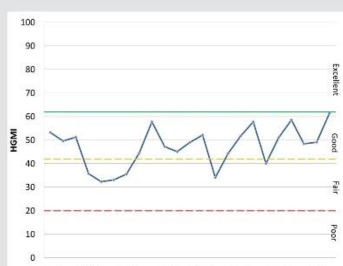
Rocky Run Site 1 (RK01)

South Branch Site 1 (SB01)

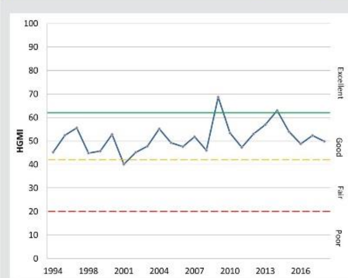
South Branch Site 2 (SB02)



South Branch Site 3 (SB03)

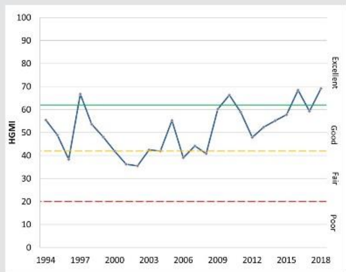


South Branch Site 4 (SB04)

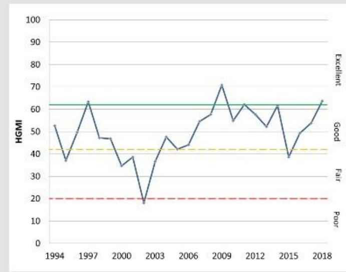


Raritan Headwaters
Your water is our mission.

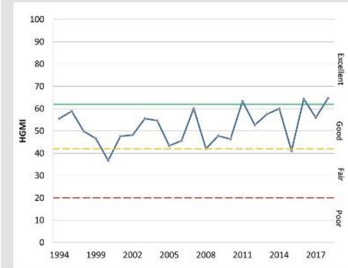
South Branch Site 5 (SB05)



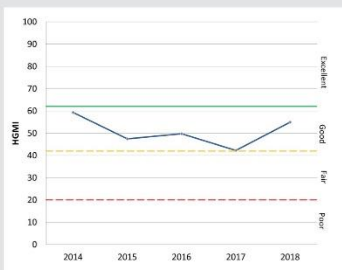
South Branch Site 6 (SB06)



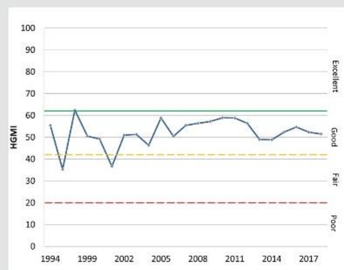
South Branch Site 7 (SB07)



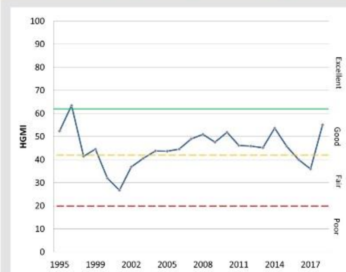
South Branch Site 8 (SB08)



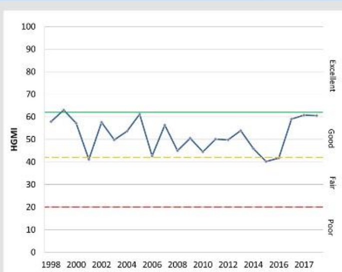
South Branch Site 9 (SB09)



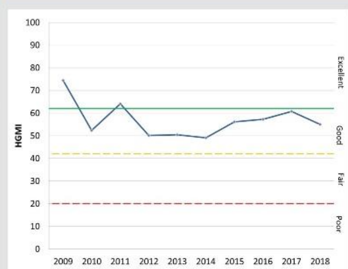
South Branch Site 11 (SB11)



South Branch Site 13 (SB13)



South Branch Site 19 (SB19)



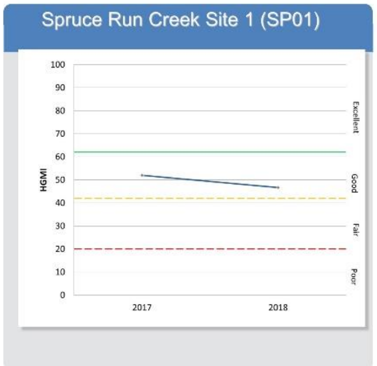
South Branch Site 21 (SB21)

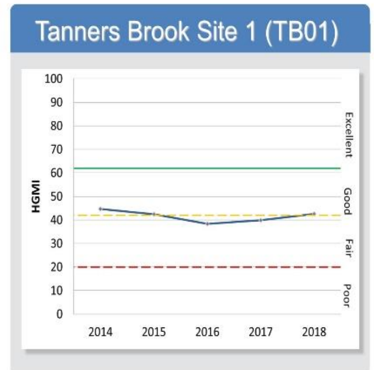
South Branch Site 22 (SB22)

South Branch Site 24 (SB24)

South Branch Site 25 (SB25)

Raritan Headwaters
Your water is our mission.

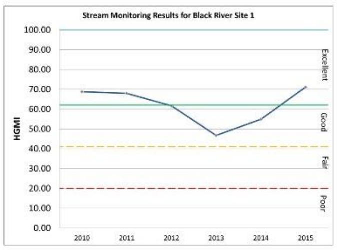




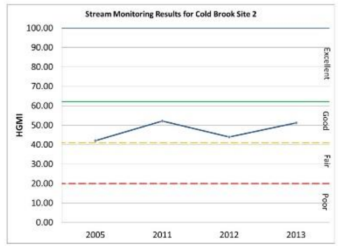
Raritan Headwaters
Your water is our mission.

Retired Sites Stream Monitoring Results

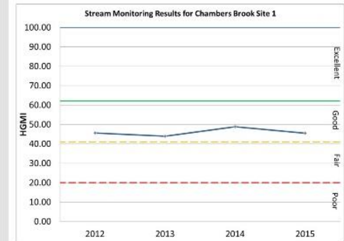
Black River Site 1 (BR01)



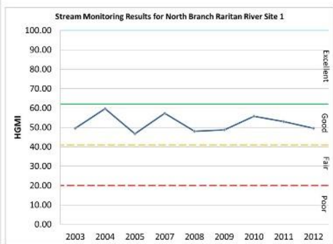
Cold Brook Site 2 (CB02)



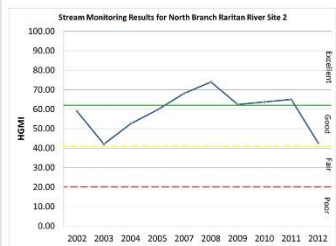
Chambers Brook Site 1 (CH01)



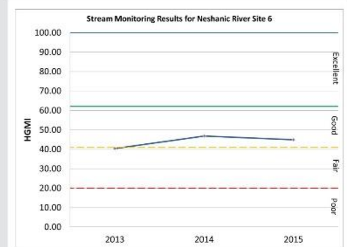
North Branch Raritan River Site 1 (NB01)



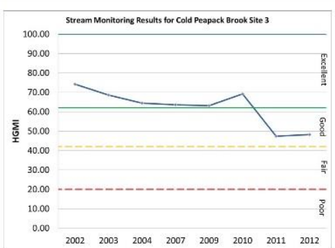
North Branch Raritan River Site 2 (NB02)



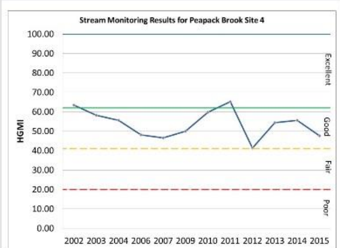
Neshanic River Site 6 (NR06)



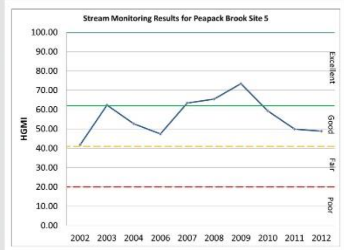
Peapack Brook Site 3 (PB03)



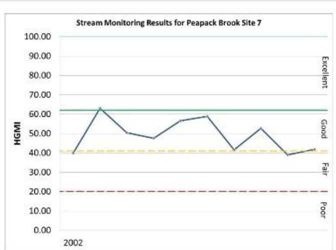
Peapack Brook Site 4 (PB04)



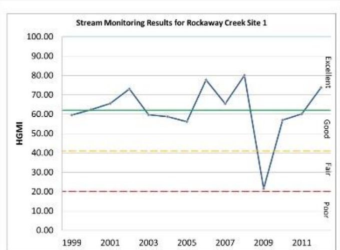
Peapack Brook Site 5 (PB05)



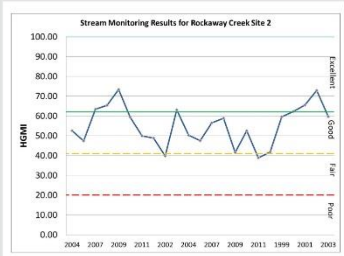
Peapack Brook Site 7 (PB07)



Rockaway Creek Site 1 (RC01)



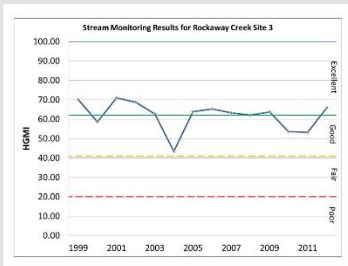
Rockaway Creek Site 2 (RC02)



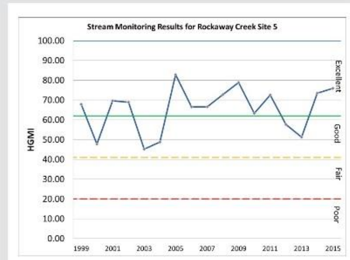
Raritan Headwaters
Your water is our mission.

Retired Sites Stream Monitoring Results

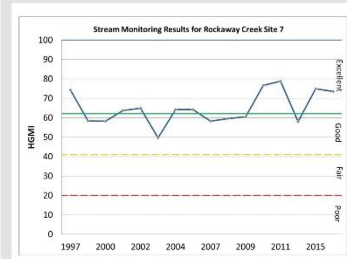
Rockaway Creek Site 3 (RC03)



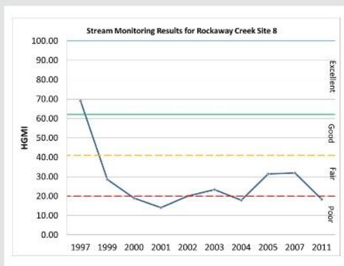
Rockaway Creek Site 5 (RC05)



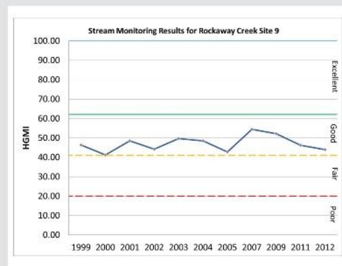
Rockaway Creek Site 7 (RC07)



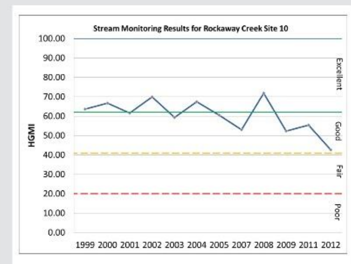
Rockaway Creek Site 8 (RC08)



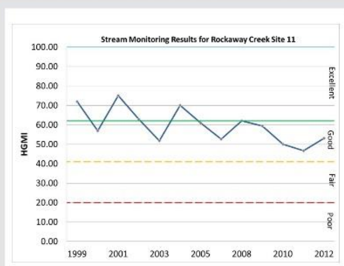
Rockaway Creek Site 9 (RC09)



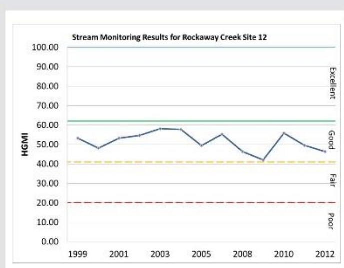
Rockaway Creek Site 10 (RC10)



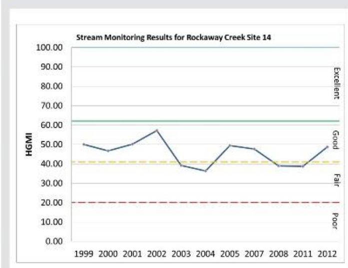
Rockaway Creek Site 11 (RC11)



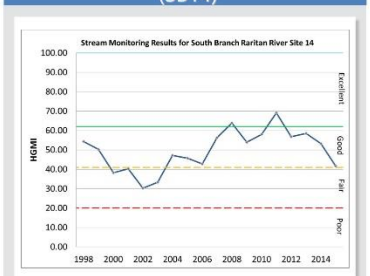
Rockaway Creek Site 12 (RC12)



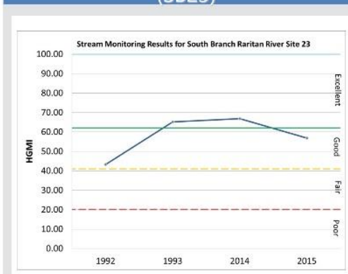
Rockaway Creek Site 14 (RC14)



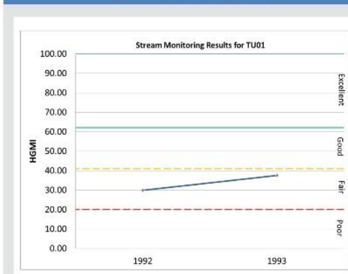
South Branch Raritan River Site 14 (SB14)



South Branch Raritan River Site 23 (SB23)



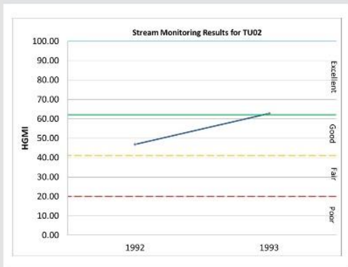
TU Site 1 (TU01)



Raritan Headwaters
Your water is our mission.

Retired Sites Stream Monitoring Results

TU Site 2 (TU02)



WB Site 1 (WB01)

Raritan Headwaters
Your water is our mission.

APPENDIX E. Raritan Headwaters Stream Monitoring Site Locations including active and retired as of 2017 (need to revise list to include retired sites)

Site ID	Status	Water_Body	Details of site	Latitude	Longitude	County	Municipality	drsqkmcalc
BB18	Active	Back Brook	Back Brook upstream of the bridge on Van Lieu's Road	40.452	-74.81585	Hunterdon	East Amwell Township	28.632
BE01	Active	Beaver Brook	Upstream of the Leigh Street bridge, adjacent to the municipal building parking lot	40.636804	-74.908726	Hunterdon	Clinton Town	17.77882241
BR01	Active	Black River	0.6 miles north on Black River Rd from County Road 512, the site is upstream of the Fish & Game Club picnic area	40.724117	-74.727818	Morris	Chester Township	80.521813
BR03	Active	Black River	1.4 miles north on Black River Rd from County Road 512, the site is upstream past the pond at the Fish & Game Club picnic area	40.736053	-74.728057	Morris	Chester Township	77.090793
BR04	Active	Black River	Upstream of the Ironia Road bridge	40.835183	-74.64467	Morris	Randolph Township	28.9686221
BR05	Active	Black River	Off of the Lake Shore Road side street	40.873266	-74.618933	Morris	Mine Hill Township	1.609757832
BR06	Active	Black River	On the Lamington River at Cowperthwaite Road	40.63341	-74.687603	Somerset	Bedminster Township	258.481
BU01	Active	Burnett Brook	Upstream of the Old Mill Road bridge near the intersection with	40.782611	-74.645214	Morris	Mendham Township	17.03014753

			Forest View Drive					
CB01	**Active**	**Cold Brook**	**Cold Brook tributary downstream of the Flint Hill Road Bridge**	**40.698093**	**-74.743278**	**Hunterdon**	**Tewksbury Township**	**1.602088877**
CB03	**Active**	**Cold Brook**	**Main stem of Cold Brook upstream of the Vleittown Road Bridge**	**40.67495**	**-74.737822**	**Hunterdon**	**Tewksbury Township**	**14.12732264**
CH01	**Active**	**Chambers Brook**	**Upstream of the bridge on County Line Road at a preserved farm**	**40.595804**	**-74.72275**	**Hunterdon**	**Readington Township**	**12.077256**
DB01	**Active**	**Drakes Brook**	**Downstream of the bridge on St. Elizabeth's driveway**	**40.840821**	**-74.694386**	**Morris**	**Mount Olive Township**	**25.61696784**
DB12	**Active**	**Drakes Brook**	**Drakes Brook just upstream of the Bartley Road bridge**	**40.81205**	**-74.72922**	**Morris**	**Mount Olive Township**	**42.91419234**
FB01	**Active**	**Flanders Brook**	**Near the intersection of Patricia Drive and Route 206, towards bottom of Mooney Road**	**40.866996**	**-74.694972**	**Morris**	**Roxbury Township**	**1.3747475**
HB17	**Active**	**Holland Brook**	**Holland Brook downstream of the Hillcrest Road bridge**	**40.56792**	**-74.73618**	**Hunterdon**	**Readington Township**	**20.7325017**
HE01	**Active**	**Herzog Brook**	**Downstream of the Black River Road bridge, south of the intersection with Southfield Drive**	**40.706759**	**-74.716547**	**Somerset**	**Bedminster Township**	**12.34430239**
LB01	**Active**	**Ledgewood Brook**	**About 270 feet upstream of Ledgewood Pond bordering Morris Canal Park**	**40.881**	**-74.6598**	**Morris**	**Roxbury Township**	**1.638012011**

LB02	**Active**	**Ledgewood Brook**	**Upstream of Ledgewood Brook Site 1, neighboring landfill**	**40.880833**	**-74.666111**	**Morris**	**Roxbury Township**	**0.492**
MC20	**Active**	**Mulhockaway Creek**	**Downstream of the County Road 635 bridge south of the intersection with Van Syckles Road**	**40.647665**	**-74.967786**	**Hunterdon**	**Union Township**	**30.29000031**
MD01	**Active**	**Middle Brook**	**On the Middle Brook, upstream of the River Road bridge**	**40.647655**	**-74.680441**	**Somerset**	**Bedminster Township**	**17.301**
MN01	**Active**	**Mine Brook**	**On the Mine Brook, downstream of the driveway bridge into Moorland Farm**	**40.682476**	**-74.635643**	**Somerset**	**Far Hills Borough**	**20.072**
NB03	**Active**	**North Branch Raritan River**	**Downstream of the schoolhouse at the intersection of Mosle Road and Union Schoolhouse roads**	**40.748819**	**-74.632835**	**Morris**	**Mendham Township**	**54.65664626**
NB06	**Active**	**North Branch Raritan River**	**.25 mile downstream of Ravine Lake on Lake Road and upstream from the carriage road**	**40.70774**	**-74.636822**	**Somerset**	**Far Hills Borough**	**68.86151315**
NB10	**Active**	**North Branch Raritan River**	**At the northwestern corner of Far Hills Fairgrounds on Peakpack Road and adjacent to a wooded preserve**	**40.68451**	**-74.64286**	**Somerset**	**Far Hills Borough**	**105.4980356**
NB14	**Active**	**North Branch Raritan River**	**East of the ball fields and downstream**	**40.674326**	**-74.638964**	**Somerset**	**Bedminster Township**	**127.591172**

			from the recreational facility					
NB15	**Active**	**North Branch Raritan River**	**Upstream of the Ironia Road bridge near the intersection with Roxiticus Road**	**40.777917**	**-74.621629**	**Morris**	**Mendham Township**	**17.79702225**
NB16	**Active**	**North Branch Raritan River**	**On the North Branch Raritan River, downstream of the River Road bridge**	**40.646823**	**-74.681046**	**Somerset**	**Bedminster Township**	**162.651**
NB17	**Active**	**North Branch Raritan River**	**On the North Branch Raritan River, at North Branch Reserve Park off of Route 28**	**40.599981**	**-74.674304**	**Somerset**	**Branchburg Township**	**448.068**
NB18	**Active**	**North Branch Raritan River**	**On the North Branch Raritan River, upstream of the Route 202 bridge**	**40.56978**	**-74.67811**	**Somerset**	**Branchburg Township**	**486.918**
NR01	**Active**	**First Neshanic River**	**Off of Kuhl Road, upstream of the confluence with the Second Neshanic River**	**40.48051**	**-74.85811**	**Hunterdon**	**Raritan Township**	**13.4460004**
NR02	**Active**	**Second Neshanic River**	**Off of Kuhl Road, upstream of the confluence with the First Neshanic River**	**40.48001**	**-74.85941**	**Hunterdon**	**Raritan Township**	**15.9953748**
NR03	**Active**	**Third Neshanic River**	**Off of the unlabeled Heron Glen Golf Course Access Road**	**40.47471**	**-74.86069**	**Hunterdon**	**Raritan Township**	**26.85117741**
NR04	**Active**	**Third Neshanic River**	**A tributary of the Third Neshanic River downstream of the County Road 579 bridge**	**40.44785**	**-74.87326**	**Hunterdon**	**Raritan Township**	**13.95871961**

NR05	**Active**	**Neshanic River**	**Neshanic River at Reaville Road near Old York Road**	**40.47086**	**-74.8267**	**Hunterdon**	**Raritan Township**	**66.18626533**
NR06	**Active**	**Neshanic River**	**Neshanic River downstream of Amwell Road, near Black Point Road**	**40.49418**	**-74.753267**	**Somerset**	**Hillsborough Township**	**138.2852764**
NR10	**Active**	**Neshanic River**	**Neshanic River below Rainbow Hill Bridge**	**40.47015**	**-74.77817**	**Hunterdon**	**East Amwell Township**	**125.7867662**
PB01	**Active**	**Peapack Brook**	**Upstream of the first bridge on Cooper Lane from Route 206**	**40.773206**	**-74.689897**	**Morris**	**Chester Township**	**1.199742011**
PB04	**Active**	**Peapack Brook**	**Peapack Brook downstream of the St. Bernard's Road Bridge**	**40.734035**	**-74.669491**	**Somerset**	**Peapack-Gladstone Borough**	**10.92584625**
PB06	**Active**	**Peapack Brook**	**Peapack Brook upstream of Jackson Avenue Bridge**	**40.72519**	**-74.668252**	**Somerset**	**Peapack-Gladstone Borough**	**17.73214823**
PB08	**Active**	**Peapack Brook**	**Peapack Brook upstream of Old Dutch Road Bridge**	**40.691898**	**-74.648924**	**Somerset**	**Bedminster Township**	**30.12580025**
PR15	**Active**	**Pleasant Run**	**Pleasant Run at a pull off near the intersection of Pleasant Run Road and Craig Road**	**40.54207**	**-74.75997**	**Hunterdon**	**Flemington Borough**	**19.22807091**
PR16	**Active**	**Pleasant Run**	**Pleasant Run north of the intersection at Renda Drive and Pleasant Run Road**	**40.5292**	**-74.74033**	**Somerset**	**Branchburg Township**	**25.34404786**
RC04	**Active**	**Rockaway Creek**	**Adjacent to Rockaway Road at the headwaters of the North Branch of Rockaway Creek**	**40.688928**	**-74.81152**	**Hunterdon**	**Tewksbury Township**	**29.82731708**

RC05	**Active**	**Rockaway Creek**	**Downstream of the intersection of Rockaway Road and Bissell Road**	**40.668786**	**-74.779311**	**Hunterdon**	**Tewksbury Township**	**39.76234788**
RC06	**Active**	**Rockaway Creek**	**North Branch Rockaway Creek along the "Rolling River Trail" downstream of mining facility**	**40.654105**	**-74.763241**	**Hunterdon**	**Tewksbury Township**	**45.29966971**
RC07	**Active**	**Rockaway Creek**	**North Branch Rockaway Creek upstream of County Road 523 bridge (Block 46.01, Lot 12)**	**40.643405**	**-74.76011**	**Hunterdon**	**Readington Township**	**47.61549712**
RC13	**Active**	**Rockaway Creek**	**South Branch Rockaway Creek off the trail at the yellow gate on Kullman Industries Drive**	**40.640076**	**-74.822362**	**Hunterdon**	**Lebanon Borough**	**19.17984016**
RC15	**Active**	**Rockaway Creek**	**South Branch Rockaway Creek at the NJDEP property west of Nelson Street (Block 21.12, Lot 46.01)**	**40.620459**	**-74.772287**	**Hunterdon**	**Readington Township**	**35.75607415**
RC16	**Active**	**Rockaway Creek**	**Main Stem Rockaway Creek along a trail at the recreational fields (Block 13, Lot 31)**	**40.624005**	**-74.750858**	**Hunterdon**	**Readington Township**	**95.56259817**
SB01	**Active**	**South Branch Raritan River**	**Downstream from Stephens Mill Road, below confluence with Turkey Brook**	**40.837475**	**-74.7434014**	**Morris**	**Mount Olive Township**	**28.312679**
SB02	**Active**	**South Branch Raritan River**	**Claremont Stretch along the main stem of the South Branch Raritan**	**40.79498**	**-74.76682**	**Morris**	**Washington Township**	**97.42074362**

			River on the Columbia Trail					
SB03	**Active**	**South Branch Raritan River**	**Main stem of the South Branch Raritan River 1/8 mile downstream of Vernoy Bridge**	**40.74127**	**-74.82482**	**Hunterdon**	**Tewksbury Township**	**144.4560912**
SB04	**Active**	**South Branch Raritan River**	**Main stem of the South Branch Raritan River downstream of Melick's Bridge on Hamden Road**	**40.611986**	**-74.908764**	**Hunterdon**	**Clinton Township**	**367.702614**
SB05	**Active**	**South Branch Raritan River**	**South Branch Raritan River just below Packers Island**	**40.55178**	**-74.85363**	**Hunterdon**	**Raritan Township**	**420.350911**
SB06	**Active**	**South Branch Raritan River**	**Main stem of the South Branch Raritan River at Darts Mill Campground**	**40.53797**	**-74.83388**	**Hunterdon**	**Raritan Township**	**435.2306174**
SB07	**Active**	**South Branch Raritan River**	**South Branch Raritan River downstream of the Higginsville Road Bridge**	**40.50948**	**-74.785**	**Hunterdon**	**Readington Township**	**473.6833378**
SB08	**Active**	**South Branch Raritan River**	**Main stem of the South Branch Raritan River downstream of the Black Point Road Bridge**	**40.502243**	**-74.738854**	**Somerset**	**Branchburg Township**	**637.137**
SB09	**Active**	**South Branch Raritan River**	**South Branch Raritan River upstream of the Orchard Drive and River Road intersection**	**40.54393**	**-74.6977**	**Somerset**	**Hillsborough Township**	**686.1206079**
SB11	**Active**	**South Branch Raritan River**	**South Branch Raritan River 300 yards downstream of**	**40.62482**	**-74.90935**	**Hunterdon**	**Clinton Township**	**312.3461478**

			Clinton Sewage Treatment Plant					
SB13	**Active**	**South Branch Raritan River**	**South Branch Raritan River 30 yards upstream of the County Highway 517 bridge**	**40.78507**	**-74.77945**	**Morris**	**Washington Township**	**112.2293911**
SB14	**Active**	**South Branch Raritan River**	**South Branch Raritan River at a pull off on Route 31 South in Rowland Mills**	**40.56297**	**-74.85612**	**Hunterdon**	**Readington Township**	**416.369856**
SB19	**Active**	**South Branch Raritan River**	**Upstream of the West Main Street and Arch Street intersection in the South Branch Reservation**	**40.664031**	**-74.89685**	**Hunterdon**	**High Bridge Borough**	**177.9079411**
SB21	**Active**	**South Branch Raritan River**	**Southwest of the dead end at Vasa Lane along the South Branch Preserve.**	**40.851167**	**-74.763557**	**Morris**	**Mount Olive Township**	**16.98339824**
SB22	**Active**	**South Branch Raritan River**	**Upstream of Califon Island Park**	**40.724366**	**-74.834403**	**Hunterdon**	**Califon Borough**	**146.5878922**
SB23	**Active**	**South Branch Raritan River**	**At River Road near the intersection with Railroad Avenue, adjecent to the Nellie Hoffman preserved property**	**40.716739**	**-74.844436**	**Hunterdon**	**Califon Borough**	**152.1714764**
TB01	**Active**	**Tanners Brook**	**Upstream of Tanners Brook Road Bridge**	**40.788083**	**-74.726466**	**Morris**	**Chester Township**	**7.108483655**