Riverkeeper Tributary Monitoring Report

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Table of Contents

Executive Summary

The Hudson River's tributaries are its lifeblood and an important recreational destination for residents and tourists. For over a decade, Riverkeeper has studied water quality in the Hudson's tributaries with a focus on whether the water is safe for swimming and other water-based activities. Our tributary monitoring program has successfully filled a data gap, raised awareness, and engaged people with advocacy related to a variety of water quality issues. A community of academic, watershed coalition, and environmental education partners has developed around the study of fecal contamination in the Hudson River Watershed driven by Riverkeeper's sustained monitoring activities.

Despite these successes, our monitoring data show that many Hudson River tributary locations remain unsafe for swimming, and conditions are not improving. Human waste is a common source of contamination, and birds, agriculture and urban runoff are also important sources. New York State must improve its implementation of the Clean Water Act by updating recreational water quality standards for freshwater rivers and streams, assessing all waters for swimming use, and reinstating fecal-indicator bacteria monitoring. It must also sustain investments in wastewater infrastructure upgrades, source water protection and watershed restoration. Local municipal governments, too, have important roles in improving water quality.

In addition to allowing for the evaluation of the suitability of water for recreation, our data can be used to develop best practices for longterm fecal indicator bacteria monitoring and better understand how to improve water quality monitoring programs. Our data show that conclusions about recreational water quality vary depending on the choice of indicator. Site-specific water quality criteria may be a viable option to protect swimmers' health in some areas, if non-human sources are prevalent. Water quality assessment plays an essential role in ensuring communities have access to state programs and resources. Community-based data should play an increased role in supporting assessment efforts.

Our data show that improperly treated sewage is one of the primary sources of water quality impairment and aging infrastructure is driving sewage pollution. Infrastructure failures triggered by rain storms are a particular problem. Despite major state funding efforts in recent years, needs are outpacing improvements. As climate change increases the likelihood of precipitation extremes and lengthens the recreational season, and infrastructure continues to age, water quality is likely to worsen unless fecal pollution is addressed. New York State must continue to fund

infrastructure upgrades, and must also explore innovative management approaches. State programs in support of asset management and resilience-based planning can aid local efforts. Watershed-scale coordination will also be needed.

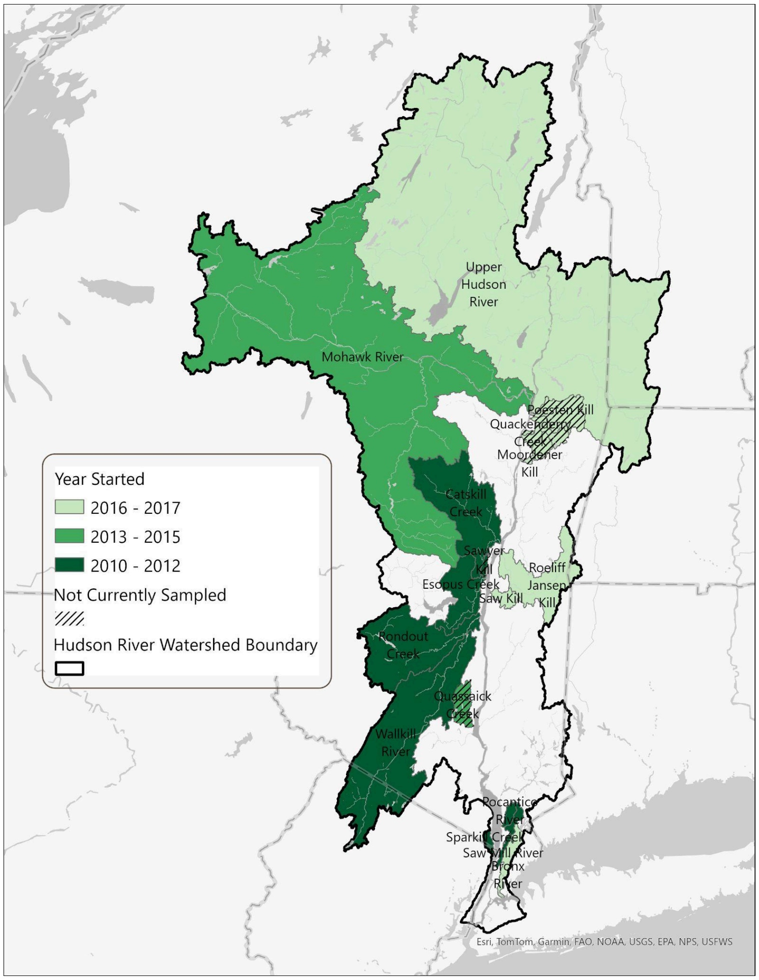
Introduction

The Hudson River is the people's beach and the ocean's nursery. People come to the Hudson to swim, paddle, and boat. Migratory fish travel up the Hudson River to reach essential spawning grounds. The Hudson's tributaries – the smaller creeks and streams that connect watershed lands to the river's main stem – are its lifeblood. Tributaries supply water, nutrients, and sediment to the Hudson River, all of which are essential to its healthy function.

As is true for the main stem of the Hudson, tributaries are recreational destinations and important wildlife habitats. Many people who live in the Hudson River Watershed connect to the river by visiting their local creeks and streams. Without healthy tributaries, the Hudson River cannot thrive.

For over a decade, Riverkeeper has studied water quality in the Hudson's tributaries (Figure 1). Our focus has been recreational water quality – measurements that tell us whether the water is safe for swimming, wading, child water play, and other activities where people are likely to ingest or become fully immersed in water – because so many people connect to the Hudson River and its tributaries through recreation. Wastewater pollution can impair recreational water quality and also affects aquatic life, drinking water quality, as well as the aesthetic value of the environment.

Figure 1: Map of Tributaries Sampled



What Do We Test For and Why?

Riverkeeper's monitoring program started in response to a question that our boat captain heard repeatedly from people while they were swimming and boating: "Is the water safe?" In 2008, when Riverkeeper began routine water quality monitoring, publicly available information about recreational water quality in the Hudson River Watershed was limited to data collected at designated swimming beaches and for state waterbody assessments. The data was not widely published, and was collected too infrequently to help people make decisions about swimming. The Clean Water Act had set the goal of making the nation's waters safe for swimming, but there was too little data available in the Hudson River watershed to assess progress toward this goal.

Sewage pollution is not just a recreational problem: fecal contamination and sewage-related contaminants can also threaten drinking water supplies and pose challenges for drinking water treatment (EPA, 2023b).

Thus, Riverkeeper began routinely testing the water in the Hudson River Estuary, and soon learned that tributaries had poorer water quality compared to other locations in the river. The original sampling plan covered the tidal portions of tributaries, or parts of the Hudson River strongly influenced by tributary discharges. People living in the tributary watersheds were curious to know about water quality further upstream, and this interest led Riverkeeper to create a volunteer-based water quality program focused on tributaries.

Riverkeeper has tested the water for *Enterococcus* since the beginning of our monitoring program, and we added *E. coli* in 2021. Entero and *E. coli* are both fecal-indicator bacteria (FIB) – bacteria that are used as surrogates for detecting the potential presence of pathogens, which are challenging to monitor directly (EPA, 2012a). FIB are present in the guts of warm-blooded animals in high abundance, but they are not harmful to human health themselves. When FIB are present in the water, they indicate the presence of waste, and, therefore, an increased likelihood that pathogens are present.

FIB tell us where and when fecal contamination is generally present. However, they don't tell the sources, timing, or entry routes of waste inputs. By law, human sewage must be treated prior to discharge, and properly treated sewage will not contribute FIB or their associated pathogens to the water. In addition to sewage that enters the water from leaky sewer pipes, overflows or incomplete treatment, potential sources may include urban runoff, septic systems, agricultural runoff, wildlife, and streambed sediments.

We compare our results with EPA's Recommended Water Quality Criteria (RWQC), issued in 2012, and we use EPA-approved methods to culture FIB, a process that takes 24 hours to obtain a result following a sample. These are the most up-to-date, science-based recommendations for recreational water quality monitoring. EPA reaffirmed them in 2017 after conducting and reviewing new research (EPA, 2018). The agency published a subsequent literature review in 2023, which encouraged the use of quantitative polymerase chain reaction (qPCR), a testing method that yields results in a few hours, and announced plans to develop additional criteria specific to viruses (EPA, 2023c). The EPA has focused on establishing criteria that protect children, due to their higher vulnerability to infection during water recreation (EPA, 2023c).

The RWQC offer two thresholds for interpreting water quality based on the concentration of FIB in multiple samples of water taken from the same location over time: the Geometric Mean (GM, expressed in cells/100 mL), and the Statistical Threshold Value (STV, expressed as a percentage of samples).[1] The GM gives information about water quality averaged over time, and the STV gives information about the frequency of pollution spikes. To be considered safe for swimming, a waterbody cannot violate either the GM nor the STV thresholds. The 2012 RWQC also included the Beach Action Value, a suggested tool for day-to-day beach management. If the Entero or *E. coli* count in a single sample exceeds the BAV, EPA recommends notifying beachgoers of poor water quality.

The RWQC were derived based on statistical relationships between FIB abundance and illness reports at ocean and Great Lakes beaches known to be impacted by human sewage. The threshold values relate to a specific rate of illness, and the EPA provided states with two sets of criteria it could apply, to be more or less protective. Riverkeeper compares results to the more protective rate of 32 illnesses per 1000 swimmers. To date, one territory and one tribe have established standards based on the more protective criteria, while all states, tribes and territories have selected criteria associated with the less-protective rate of 36 illnesses per 1,000 swimmers. The actual risk to each individual swimmer varies depending on age, immune system, exposure, and other factors.

Achievements

Our tributary monitoring program had three goals:

(1) Fill a water quality data gap;
(2) Raise awareness about sewage pollution; and
(3) Engage people about other important water issues.

With respect to these goals, the program has been a success.

[1] EPA criteria call for calculating the GM and STV based on a rolling monthly basis, with weekly sampling. Our sampling occurs monthly, but over time should reveal similar patterns.

Goal 1: Data

Today, Riverkeeper's website displays recent water quality information from 150 sampling locations in 12 tributary watersheds. Whereas we started by posting only data from our own boat-based laboratory, we now also publish information collected by a network of laboratories situated at non-profits, universities, and colleges throughout the Hudson River Watershed. In some cases, volunteers who collect data are organized by Riverkeeper directly, and in other cases by partners who provide data for Riverkeeper to interpret and display.

In addition to providing useful information on a day-to-day basis, our monitoring dataset is an asset unto itself, because it covers a long time interval and broad geographic area, has good continuity, and includes multiple FIB. Long-term microbial water quality monitoring programs such as Riverkeeper's are an important component of understanding climate change's impacts on water quality. To help more people access the data, we published our dataset in open-source format in 2022 (Riverkeeper, 2022). The data has been put to use to identify specific local infrastructure failures and prioritize local wastewater treatment investments, inform watershed planning efforts, and support lobbying efforts to increase statewide funding for water infrastructure improvements.

Goal 2: Awareness

Riverkeeper's water quality testing program sparked a regional movement of community-based sewage pollution monitoring. In 2011, we published results of our Hudson River Estuary main stem sampling program, which showed that Entero counts were higher at tributary mouths than at other sites. This was unexpected, and local advocates wanted more information. In 2012, volunteers collected land-based samples monthly over the entire recreational season in six tributary watersheds. Since then, a total of 15 tributary watersheds have been sampled routinely for at least one season, covering up to 251 sites over 595 stream miles.

People can use past sampling results to help decide where they feel it is safe to swim, or to explore patterns and trends. Since 2014, when the tributary sampling section of the Riverkeeper website launched, over 186,000 people have visited these pages. Nearly 500 volunteers have been involved in this sampling program (Riverkeeper, n.d.).

Goal 3: Engagement

This water quality monitoring work has been done through collaboration with non-profit organizations, educational institutions, Conservation Advisory Committees and Environmental Conservation Commissions, volunteer watershed groups, and other partners. In 2020, Riverkeeper and The Sanctuary for Independent Media launched the Water Justice Lab in Troy. Each summer, Youth Scientist Fellows process water samples gathered by community scientists from the Upper Hudson River, learn about Troy's drinking water and wastewater systems through field trips and water sampling, and create media about their work.

Riverkeeper's tributary monitoring program has strengthened the fabric of watershed stewardship in the Hudson River Watershed. New watershed groups have formed or been strengthened around Entero monitoring in the Mohawk, Rondout, Roeliff Jansen Kill, Sparkill and Wallkill watersheds. In addition, long-standing watershed groups have added Entero monitoring to their activities. These groups have also taken up issues connected to fecal pollution, such as riparian restoration, harmful algal blooms (HABs), and drinking water source protection.

What We Have Learned

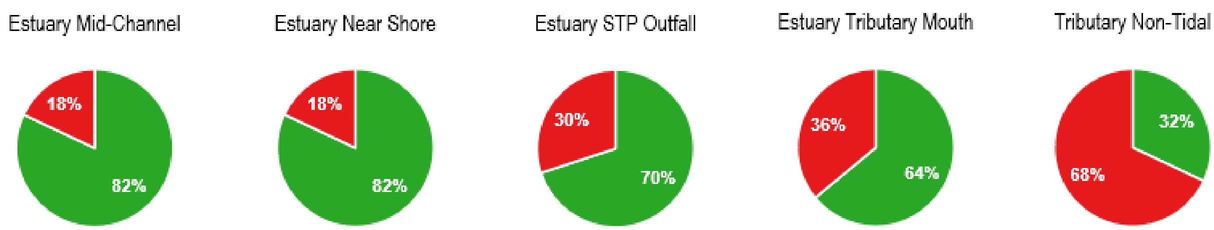
Amidst these successes, our data shows that many Hudson River tributaries still fall short of the Clean Water Act (CWA) goal of swimmable water after more than fifty years, and our source tracking work in various watersheds shows that fecal-indicator bacteria point to complex water quality problems.

How's the Water In Tributaries?

Riverkeeper's boat-based Estuary sampling program includes four site types: the mid-channel of the river, which is relatively deep and well-mixed; near shore sites, where depth is shallower; STP (sewage treatment plant) outfalls, where the water column is dominated by treated wastewater treatment plant effluent; and the tidal mouths of tributaries, where waters are a mix of tributary and estuary water.

By comparing the percentage of samples that exceed EPA's Beach Advisory Value across these different environments, we see that tributaries are a source of contamination to the Hudson River. Tributary mouth locations sampled from the boat tend to have higher Entero counts than Hudson River Estuary mid-channel or near shore sites, as indicated by a higher percentage of samples exceeding EPA's recommended BAV (Figure 2). Non-tidal tributary waters within and beyond the estuary boundaries are almost twice as likely to be unsafe for swimming.

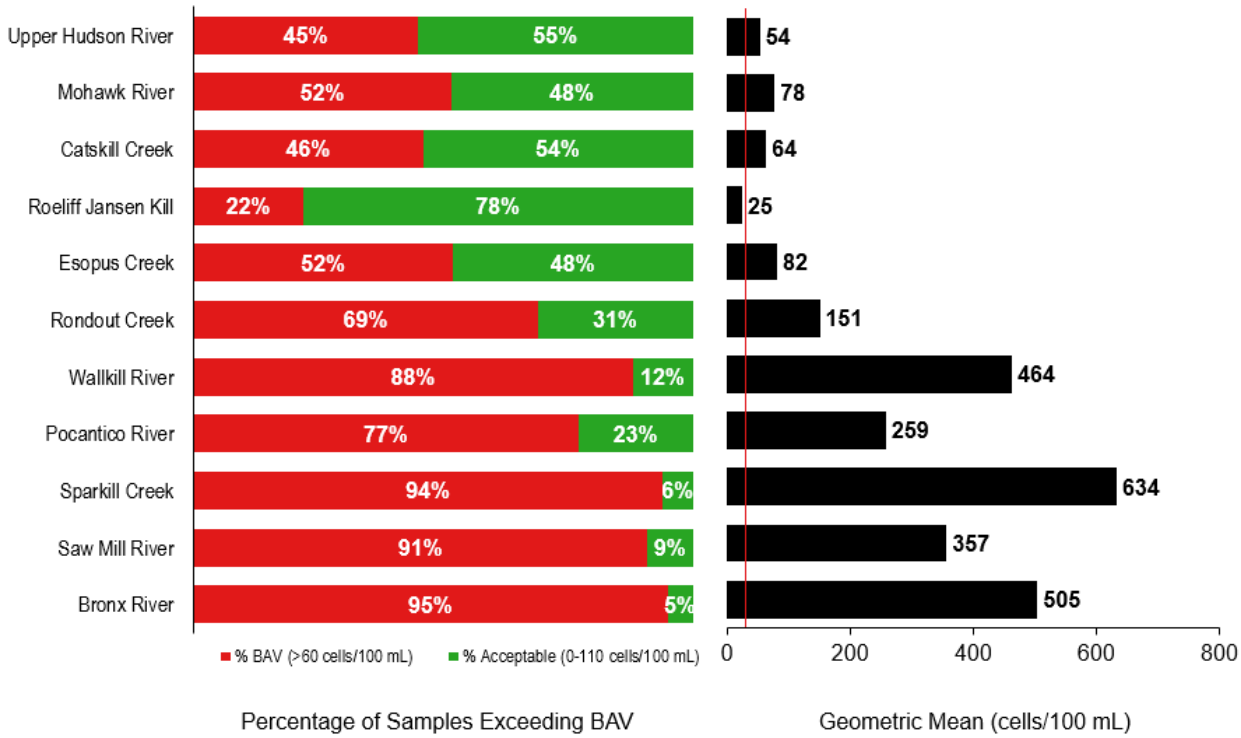
Figure 2: Hudson River Estuary and Tributary Water Quality Comparison



Our sampling has also shown that water quality varies by watershed (Figure 3). The years sampling occurred, number of sites sampled, frequency of sampling, and duration of sampling vary among the tributaries involved in this study, so comparisons among datasets are approximate (see Appendix # for detailed information about the datasets.) However, looking at samples grouped by watershed, none of the watersheds sampled fully achieves EPA's recommended recreational water quality criteria.[2]

[2] EPA criteria call for calculating the GM and STV based on a rolling monthly basis, with weekly sampling. Our sampling occurs monthly, but over time should reveal similar patterns.

Figure 3: Tributary Watershed Water Quality Comparison



Sewage pollution isn't just a Hudson Valley–or even a New York State–problem. In EPA's most recent report of nationwide water quality to Congress, pathogens were among the top three pollutants impairing streams and rivers (EPA, 2017).

Water quality also varies from location to location *within* watersheds. Watersheds with good overall water quality have pollution hotspots and, conversely, watersheds with poor overall water quality have locations with lower Entero counts.

What is the Role of Weather?

Almost everywhere we and our partners have sampled, Entero counts are higher after rain (Figure 4), a pattern that holds in communities throughout the U.S. (EPA, 2023b). The likely reasons include permitted discharges of untreated or partially treated sewage through combined sewer overflows; spills or overflows due to equipment failure or pipe breaks; leaks; stormwater runoff; and resuspension of streambed sediments. Runoff can also contribute FIB associated with wildlife, agriculture, pets and other sources.

Figure 4: Geometric Means of *Enterococcus* Counts in Wet and Dry Samples

Combined sewer systems are designed to discharge untreated wastewater during heavy rainfall or snowmelt, but these systems are only found in the Hudson River Watershed in certain communities along the Hudson River and the Mohawk River, and all around New York City. In other areas, wet-weather sewage pollution is more likely to come from unplanned leaks and spills caused by infrastructure failure. As aging pipes acquire cracks and root punctures over time, rainwater infiltration becomes a major component of wet-weather wastewater flows. These flows strain the system, triggering equipment breaks and failures. With more extreme storms due to climate change, overflows associated with old pipes overwhelmed by inflow and infiltration are likely to increase. Power outages are also a common cause of spills.

Surface runoff is also a significant wet-weather Entero source. Runoff from urban streets contains a high abundance of Entero, but the proportion of pathogenic organisms that can harm human health is low when compared to sewage (O'Mullan et al., 2018). In suburban or rural areas, runoff washes waste from wildlife, domestic or food animals into the water. The health risks of animal wastes mobilized by runoff depend on its source and age (EPA, 2010).

Sediment resuspension also contributes to wet-weather Entero counts. Entero readily attach to sediment particles and sink, making sediments a bacterial reservoir (O'Mullan et al., 2019). Other fecal bacteria may also persist in sediments, but pathogen persistence in sediments is not well understood (O'Mullan et al., 2019). When wet weather brings high flows, the sediments and associated microbes are resuspended into the water column. Turbidity can also increase the persistence of FIB and pathogens.

What Are the Sources of Fecal Contamination in Hudson River Tributaries?

In places where FIB counts are high, the next step is to search out contamination sources. Source tracking has advanced significantly during the lifespan of Riverkeeper's tributary monitoring program. Dozens of methods have been developed and tested, at various levels of technological complexity and cost (Hagedorn et al., 2011). The two main categories of source tracking markers are chemical and biological. The former group includes substances such as caffeine and sucralose, that are ubiquitous in daily life and can reasonably be expected to be present in any domestic wastewater flow (Cantwell et al., 2017). Water quality indicators such as conductivity, turbidity, and nutrients also provide useful context. Biological source tracking uses DNA markers that are highly specific to individual animal groups. EPA has verified DNA markers to reliably identify human, cow, bird, dog, and other wastes (National Institute of Standards and Technology, 2022).

No single method is infallible, and the best options are not always affordable or feasible. At the low-tech end of the spectrum, streamwalks can often be very effective for locating contamination sources, although terrain, property access, and underground infrastructure present challenges. DNA-based source tracking allows very specific sources to be targeted, but it is expensive and results can be expensive and nuanced. Care must be taken when interpreting DNA sample results because recently killed bacteria may produce positive results. This is particularly important immediately downstream of wastewater treatment plants. On the other hand, due to relatively low concentrations of bacterial DNA relative to water, the absence of evidence of a particular DNA marker in a sample is not evidence of absence of that source in watershed. For any source tracking approach, samples or observations must be timed to coincide with inputs, a non-trivial challenge when sources are unknown and likely to vary with precipitation and flow.

Source Tracking Results in Hudson River Tributaries

Riverkeeper has partnered with watershed groups, municipalities, NYS DEC, and academic researchers to complete multiple source tracking projects (Figure 5). We place our source tracking results in the context of peer-reviewed literature based on Hudson River studies. Taken as a whole, source tracking and research by Riverkeeper and partners leads to the following major conclusions about fecal contamination in Hudson River tributaries:

- Human sewage contamination is common, but not ubiquitous;
- Wastewater systems (both centralized and individual septic systems) may be important sources; and
- Birds and stormwater are important FIB sources.

Figure 5: Riverkeeper Source Tracking Summary

SOURCE TRACKING TIMELINE

2014 — Optical Brightener Testing

Catskill, Esopus, Pocantico, Rondout, Sparkill, Wallkill

- Hgh Entero counts were associated with OBs, confirming that sewage was likely a contamination source.
- This method is best used for real-time, field-based source tracking.

2015 — Seasonal Camp Investigation

Rondout

- Entero results confirmed watchdog reports of a failing septic system.
- Our report triggered DEC enforcement action.

2016 — Subwatershed Study

Rondout, Wallkill

- Subwatershed hotspots were identified by weighting Entero abundance with estimated flow.
- Dry- and wet-weather counts can be used to select next steps. For high dry-weather counts, sewage leaks are more likely. For high wet-weather counts, stormwater controls can be employed, and pipes should be checked for leaks.

2017 — DNA Marker Study

Rondout, Wallkill

- Results confirmed human contamination, and identified specific locations.
- Avian contamination was widespread and common, although to different degrees in the two watersheds.
- Site-specific water quality criteria may be appropriate for these watersheds.

DEC Pilot Study

Sparkill

- Project combined Desktop GIS Analysis and Intensive Entero Sampling.
- Entero counts were higher in areas with wastewater infrastructure, compared to forest.
- Results pointed to both wastewater infrastructure and stormwater infrastructure as Entero sources.

2018 — Stormwater Outfall Testing

Sparkill

- Multiple outfalls flowed during dry weather, and Entero counts were frequently very high.
- Results show that MS4 'sniff test' approach may not be effective.

Desktop GIS Analysis

Rondout

- Most soils in the watershed are poorly suited for septic systems, even where this type of treatment is dominant, including institutional-scale systems.
- Septic management models from elsewhere in New York State should be applied here.

2019 — Intensive Entero Sampling

Rondout

- Samples from a seasonal camp showed another instance of poor institutional septic system oversight and management, but this time our reports did not receive a strong enforcement response.
- Entero abundance was higher downstream of High Falls hamlet.
- Of all the tributaries flowing through the hamlet, the least developed had the lowest Entero counts.

Intensive Entero Sampling

Wallkill

- Entero abundances were extremely high throughout the watershed.
- Results agreed with DNA Marker Study conclusion that wildlife or stormwater runoff sources are more important Entero sources than sewage.

Sources: Wastewater Infrastructure

Source tracking studies using the EPA-approved, human-specific DNA marker HF183 have been completed in the Mohawk, Sparkill, Wallkill, Rondout Watersheds (EPA, 2023a). The areas studied in these watersheds have different types and densities of wastewater systems, and human fecal contamination was detected in all of them (Table x).

Table 1: Human-Specific DNA Marker Detection in Hudson River Tributaries

Watershed & Study Lead	Study Area	Human DNA Marker Results
Mohawk: Carolyn Rodak, SUNY Polytechnic (Lininger et al., 2019; Rodak & Endres, 2019)	Main stem and tributaries in the Utica-Rome area	Present at 9 of 10 locations; At 7 of the 9 sites where present, was detected in >40% of samples
Rondout: Riverkeeper & Ruth Richardson, Cornell University (Brooks et al., 2020)	Rosendale and Wawarsing areas	Present at 6 of 8 locations; Detected in 2/3 of samples at one location; Detected in 1/6 samples in 5 of 6 locations where present
Sparkill: Sparkill Creek Watershed Alliance & Greg O'Mullan, CUNY Queens College (Vail et al., 2020; Vail et al., 2021)	2020: Throughout watershed 2021: Residential area in upper watershed	Present at 7 of 9 locations in 2020; Present at 9 of 14 locations in 2021 (locations changed between years); Concentrations were significantly higher after rainfall
Wallkill: Riverkeeper & Ruth Richardson, Cornell University (Brooks et al., 2020)	Black Dirt, Gardiner, and New Paltz areas	Present at 14 of 16 locations; Frequency of detection varied

In the **Rondout Watershed**, human marker was uniformly present, but infrequent, everywhere except one sampling location downstream of a WWTP, where it was frequently detected. This treatment facility has well-documented upgrade needs, which are underway as part of an industrial development project. Future FIB and MST sampling should be used to study how water quality changes after plant upgrades. The diffuse signal of human waste elsewhere may be due to failing septic systems, which predominate in the Rondout Watershed despite poorly suited soils (Quinlavan, 2019).

In the **Mohawk Watershed**, the human waste marker was more frequent within the CSO area near Utica. The Long Term Control Plan required under the Clean Water Act to reduce – but not eliminate – overflows is due to be completed in 2023. Even after implementation of this multi-year plan, 40 CSOs will remain.

In **Sparkill Watershed**, the human waste marker was more frequent in an area with higher wastewater infrastructure density. Collection system repairs in these areas would improve stream water quality. Riverkeeper and Sparkill Creek Watershed Alliance, with support from the major owner of sewage infrastructure in the watershed, the Town of Orangetown, completed a DEC-funded water quality assessment of the Sparkill Creek in 2020-2021 in order to ensure that the town has access to state grant and loan programs that prioritize investments in waterways with DEC-defined impairments.

In the **Wallkill Watershed**, sites with the highest detection frequencies tended to be situated in the upper and middle watershed (south of the Town of Shawangunk). In this area, infrastructure types are mixed, with centralized treatment facilities of varying sizes serving about 57% of the properties and septic systems serving the rest (NYS Office of Information Technology Services, 2023). Sediment may play an important role in this area. Human waste was present in every sample collected from Quaker Creek, a Wallkill River tributary that receives non-disinfected effluent from the Florida Wastewater Treatment Plant. This WWTP was upgraded in 2023 with a disinfection system. Future sampling could track changes in the creek.

Sources: Stormwater Runoff

In the Sparkill Creek source tracking studies, human fecal marker was absent from street runoff samples despite high Entero abundances (Vail et al., 2021). This is consistent with previous work showing that FIB may not be coupled with pathogens in street runoff (O'Mullan et al., 2018). The Sparkill Watershed sampling did detect human fecal markers in two stormwater outfalls (Vail et al., 2020). Sewage can enter the stormwater collection system through cross-connections, resulting in discharges of human waste from stormwater outfalls. In 2018, the Town of Orangetown conducted an EPA-approved survey of all stormwater outfalls in the municipality, which contains the Sparkill Watershed, and no cross-connections were found (Town of Orangetown, 2018). Although 6 of the 16 inspected outfalls in the Sparkill Creek watershed were flowing in wet weather, no physical indicators of illicit discharges were observed, and no outfalls were sampled for water quality analysis (Town of Orangetown, 2018). Since very high levels of stormwater-related Entero are such a widespread occurrence in the watershed, the question of how much risk street runoff poses to human health is an important one for helping to prioritize Entero reductions.

Sources: Birds

The Rondout Creek and Wallkill River study included a DNA marker for bird waste. Avian fecal contamination was the most common source type in both watersheds (48% and 66% of samples, respectively). Avian sources of fecal contamination are generally considered less dangerous than human or other animal sources, but birds can transmit human pathogens and antibiotic-resistant bacteria to water (Green et al., 2012; United States Geological Survey, 2022). Recently, avian flu transmission through wild bird populations has increased, along with the potential that the virus will acquire mutations that make it more threatening to humans (Miller, 2022). In sum, avian sources should not be ignored.

How Source Tracking Protects Health

Human waste is considered to be the highest priority because it is most likely to carry human pathogens (EPA, 2009). The Rondout-Wallkill study also included direct pathogen measurements. Pathogenic organisms such as rotavirus, *Giardia*, and pathogenic *E. coli* strains were detected in samples, and some were associated with human DNA markers (Richardson, 2017).

However, risk is not simply a matter of source: studies comparing the health risks of different fecal sources in various types of waters have made it clear that risk levels vary with source, age, and path to the water (EPA, 2009; Soller et al., 2010). Water quality modeling has shown that a small amount of a very infectious fecal source may be a bigger threat than a large amount of less infectious waste, and it is possible for FIB levels to exceed EPA thresholds without a corresponding risk to swimmer health (Soller et al., 2010).

Source tracking can help improve swimming conditions in multiple ways. The most straightforward is by confirming where human waste is entering the water, so that those inputs can be eliminated. Confirming other sources is also helpful, because where non-human sources are prevalent and Entero is high without an increased health risk, site-specific water quality standards may be used to safely keep waters open for recreation (EPA, 2012a).

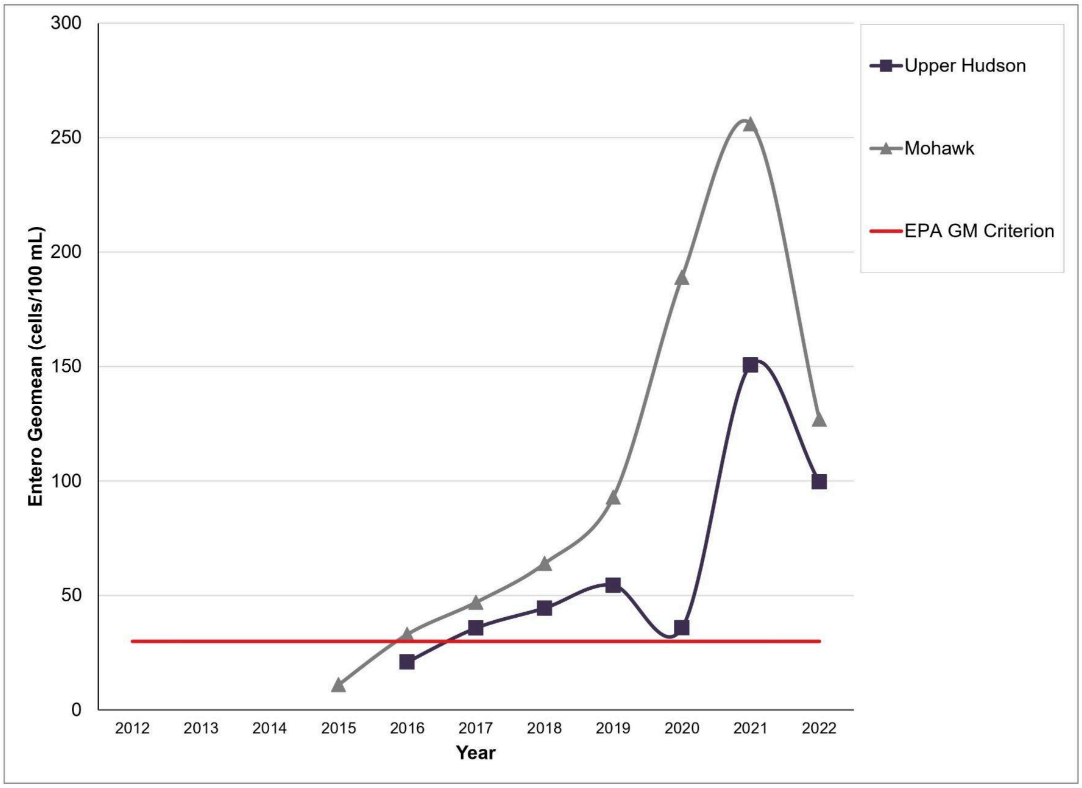
How Has Water Quality Changed Over Time?

There is no single answer to the question of how water quality (and, more specifically, Entero concentration) has changed over time. The data help us to understand the variability of Entero from year to year, the role of precipitation over longer time periods, and the importance of other environmental variables. While our monitoring program design is able to document interannual variability and trends, other study designs are needed to explore the drivers of change.

Water Quality Has Declined In the Upper Hudson and Mohawk Watersheds

Entero counts have increased in the Upper Hudson and the Mohawk Rivers since the start of sampling (2016 and 2015, respectively), although they decreased in 2022 (Figure 6). In both of these watersheds, the first year of sampling data indicated swimmable water, but none have since.

Figure 6: Watershed Geometric Means Over Time in the Upper Hudson and Mohawk Watersheds

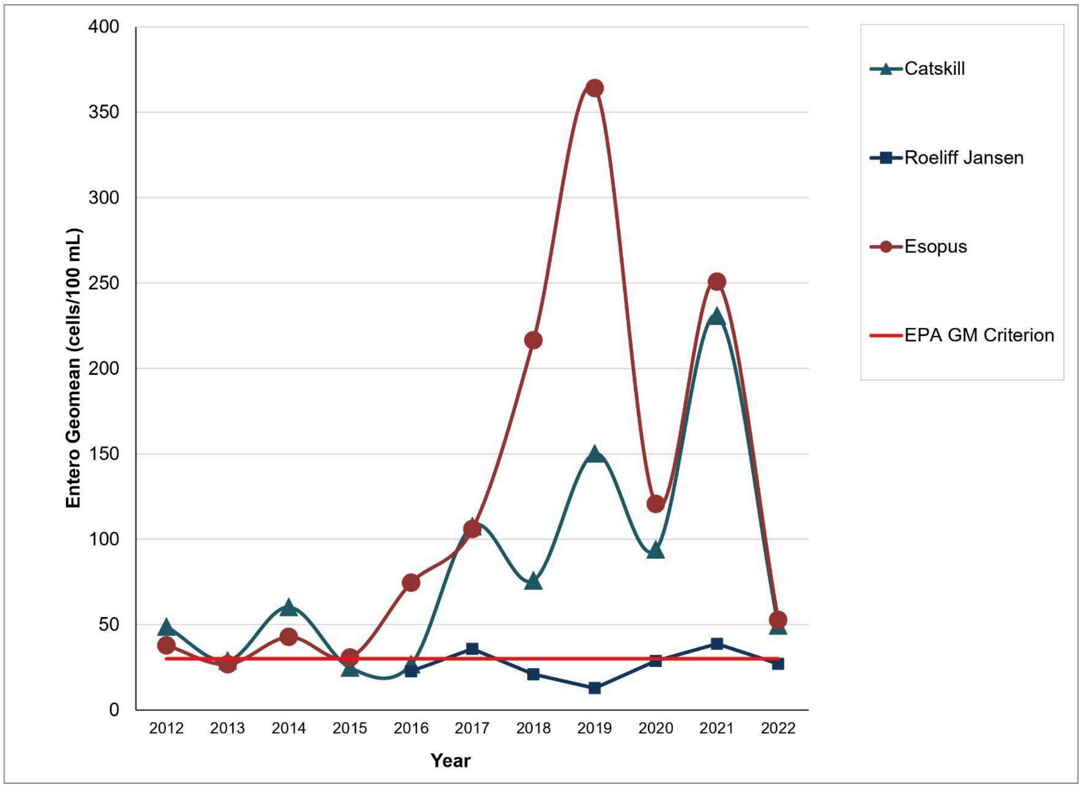


Water Quality Has Varied Without A Clear Trend In Many Tributaries

In most of the tributaries we and our partners have sampled, water quality has fluctuated up and down over time. These fluctuations have different impacts on how we interpret water quality, depending on the magnitude of change and the range of Entero values observed.

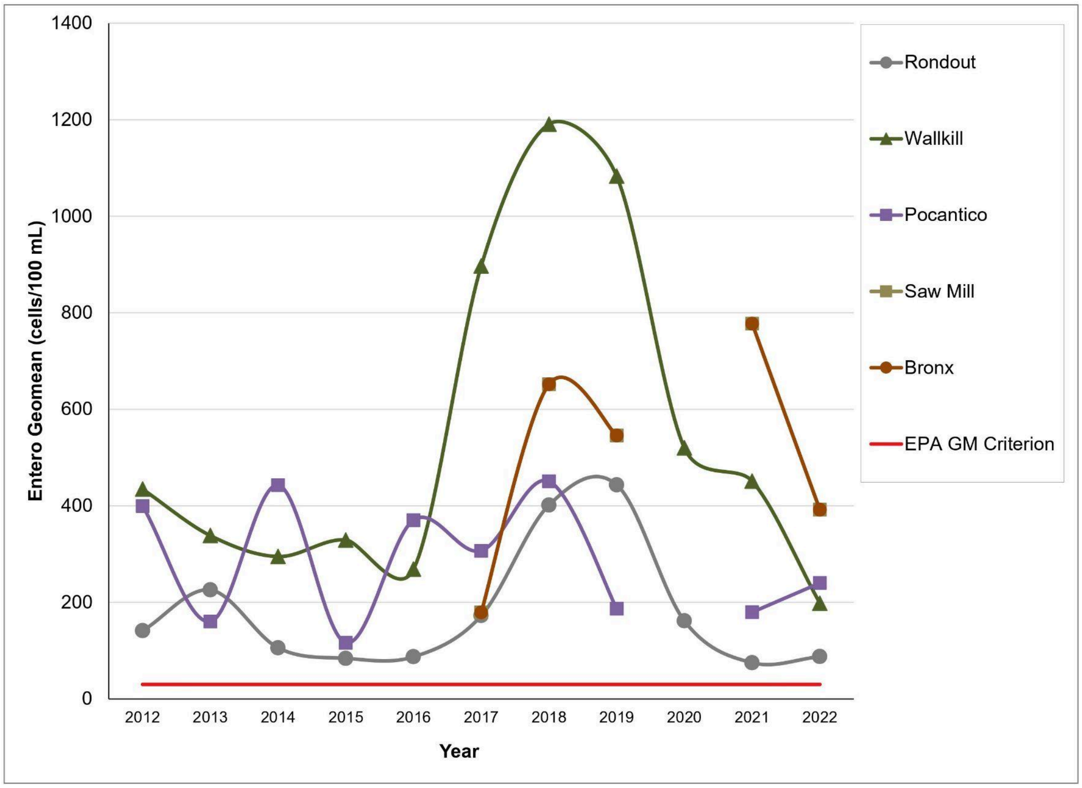
In the Roeliff Jansen Kill, average water quality has alternated between meeting and exceeding EPA-recommended criteria, while water quality has generally not met EPA-recommended criteria in the Catskill and Esopus Creeks (Figure 7).

Figure 7: Watershed Geometric Means Over Time in the Catskill, Roeliff Jansen, and Esopus Watersheds



Water quality has also varied in the **Rondout, Wallkill, Pocantico, Saw Mill and Bronx Watersheds** (Figure 8), but in these waterways, Entero abundances have never fallen below the EPA-recommended BAV.

Figure 8: Watershed Geometric Means Over Time in the Rondout, Wallkill, Pocantico, and Saw Mill Watersheds

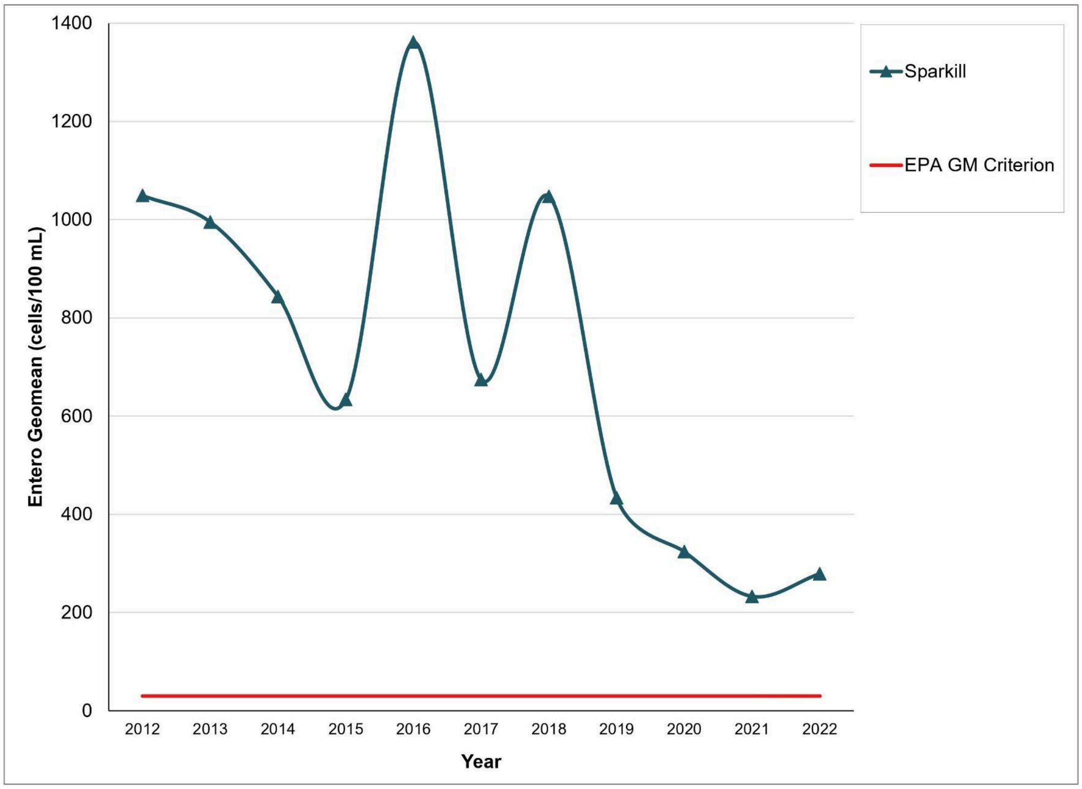


These watersheds show that longterm monitoring reveals variation that could easily be misinterpreted as trends if only shorter time scales are observed. Care should be taken in drawing conclusions from less frequent water quality testing, as results will be highly dependent on the timing and duration of sampling. These results also show that in order to determine what remediation actions are needed to improve water quality, it is necessary to monitor over a long duration and in a variety of environmental conditions to truly understand trends and pollution source variability.

Water Quality Has Improved In the Sparkill Watershed

Sparkill Creek is the only stream sampled where average Entero counts have decreased (Figure 9).

Figure 9: Watershed Geometric Mean Over Time In the Sparkill Creek Watershed



Even though the stream is still far from safe swimming conditions, the trend toward better water quality is something to celebrate. We are currently investigating what may be responsible for the change.

Entero Over Time And the Role Of Weather

Entero counts tend to be greater after rain, so it is important to look at whether variation is due to interannual variability in precipitation. We calculated total precipitation during the recreational season (May - October) as well as total annual precipitation (January - December), and examined whether precipitation accounts for the observed Entero fluctuations.[3] The relationships between weather and Entero also depend on where you look.

[3] We have used two weather data sources for these analyses. We have classified individual samples as wet or dry based on data from local weather stations. We have calculated annual and seasonal precipitation totals based on a smaller number of regional weather stations. Statistical significance was tested using simple regression with $\alpha = 0.05$.

In the Catskill, Esopus, Rondout, and Wallkill Watersheds, total annual precipitation was a statistically significant predictor of annual Entero counts. About 40% of the variation in Entero was caused by variation in annual precipitation. Recreational season precipitation was not a statistically significant predictor of Entero counts.

In the Upper Hudson, Mohawk, and Sparkill Watersheds, year sampled was the statistically significant predictor of Entero counts. Change over time accounted for about 50-70% of the variation in annual Entero GMs. Precipitation still played a role in these watersheds, but a different one in each place. In the Upper Hudson and Mohawk Watersheds, annual Entero geometric means increased from the start of sampling (2015 in the Mohawk Watershed, 2016 in the Upper Hudson Watershed) through 2021 (Figure 6). In 2022, the geometric means decreased substantially, but not to 2015-2016 levels. In the Sparkill Watershed, Entero counts decreased overall between 2012 and 2022, with large fluctuations in the intervening years (Figure 9).

In the Roeliff Jansen, Saw Mill, and Bronx Watersheds, neither annual precipitation, recreational season precipitation, nor time was a statistically significant predictor of Entero. All three watersheds have relatively short sampling durations, and larger datasets may be needed to resolve these trends.

These analyses show that precipitation plays a role in interannual variability, but not the same role everywhere. Recreational season and annual precipitation totals had different relationships with Entero counts depending on the watershed. This suggests that seasonal factors are at play, potentially including changes in wastewater flows and treatment, bacterial ecology and survival, or other aspects of the river ecosystem. In some watersheds, other types of changes may be more important than precipitation, such as air or water temperature, land use, or infrastructure performance. Future analyses should consider multiple variables simultaneously.

Change Over Time and Water Quality Management

Our data show that Entero counts may alternate between meeting and exceeding EPA water quality thresholds from year to year. The magnitude of change can be quite significant; in some cases, Entero counts have varied by orders of magnitude during our monitoring. These changes may not be simply due to precipitation, the most obvious short-term driver of Entero counts. Antecedent weather conditions could play a role in determining instream Entero counts after rainfall events. It is also possible that these changes reflect differences in infrastructure operation not accounted for in our analysis. Any interannual variation in climate or streamflow may also affect the stream ecosystem, and therefore the abundance and persistence of Entero in the water.

NYS regulations require two consecutive years of FIB data as the basis for water quality assessments (NYS DEC, 2021a). In many tributaries, FIB abundances are so high that any 2-year snapshot would yield the same conclusion: swimming poses unacceptable risk. In other locations, different 2-year snapshots may lead to different conclusions. To best protect public health as Earth's climate changes, water quality assessments should be repeated frequently, and high-frequency monitoring should be used at swimming access points. The data also show us that water quality needs to be monitored for several years following water quality improvement projects to reliably assess impact.

Where Should We Expect Future Improvements?

Regional efforts to improve water quality are underway in a few areas of the Hudson River Watershed. In each of these cases, different circumstances are driving watershed planning, illustrating the diversity of ways that sewage pollution impacts water quality.

Mohawk River: Drinking Water Source Protection

The Mohawk River Basin Program's 2021-2026 Action Agenda proposes multiple strategies focused on reducing sewage overflows and stormwater pollution, both of which are likely sources of Entero in the Mohawk River, and protecting drinking water (NYS DEC, 2021b). One of the plan's goals is for all WWTPs to meet state and federal regulations, as well as disinfect effluent at least seasonally, by 2031. Development of a Total Maximum Daily Load (TMDL, or "pollution diet") for the Mohawk River is also underway. Although the TMDL will focus on phosphorus reductions, wastewater treatment plant upgrades will be part of the solution, and these projects are an opportunity to improve treatment and reduce FIB discharges.

Upper Hudson River: Reducing Combined Sewer Overflows

Portions of the Upper Hudson River drainage basin include combined sewer areas that discharge into the Albany Pool. This region is actively implementing projects to reduce CSOs under its Long-Term Control Plan (LTCP). The plan includes water quality improvements in certain tributaries, primarily by eliminating stormwater system cross-connections, repairing collection system pipes, and replacing failing septic systems (Albany Pool Joint Venture Team, 2011).

Wallkill River: Preventing Harmful Algal Blooms

After a HAB impacted up to 30 miles of the Wallkill River over 60 days in 2016, NYS DEC began developing a TMDL for the river (Dunne, 2019). As in the Mohawk River, the TMDL will focus on phosphorus reduction, but WWTP improvements will likely be required to achieve the TMDL goals. These upgrades will provide a major opportunity to simultaneously improve overall WWTP function, reducing pathogen and FIB discharges. Separate sewer overflows in Middletown have been reduced through infrastructure investments, and an overflow in Walden is scheduled for improvement.

What Do We Learn By Comparing Different Indicator Bacteria?

EPA's RWQC recommends either *Enterococci* or *E. coli* as a sewage pollution indicator in fresh waters. *E. coli* survival is inhibited by salt water, so only Entero is recommended in brackish and saline waters. NYS has adopted criteria consistent with EPA's 2012 RWQC and its 2022 approach to setting secondary contact criteria for fresh waters of the Great Lakes, where E. coli criteria apply, and New York State's saline waters, including the Hudson River up to the Bear Mountain Bridge, where Entero criteria apply. But standards for recreational activities in NYS freshwater streams and rivers have not been updated, leaving swimmer health protections and wastewater pollution management in these areas subject to outdated water quality indicators.

Entero and E. coli belong to different bacterial families and have different environmental tolerances. Both bacterial groups are correlated with swimmer illnesses. When used as indicators, we expect broad agreement between the two, even though some variation is also expected. To better understand how New York's selection of Entero or E. coli as FIB might impact water quality management, we began collecting paired Entero and E. coli samples in multiple tributary watersheds in 2021. (Routine paired testing has occurred in the Mohawk River Watershed since 2016.) Our Entero-E. coli comparison dataset consists of 1,752 samples from 6 watersheds. By looking exclusively at paired samples, we can directly and reliably compare the two indicators.

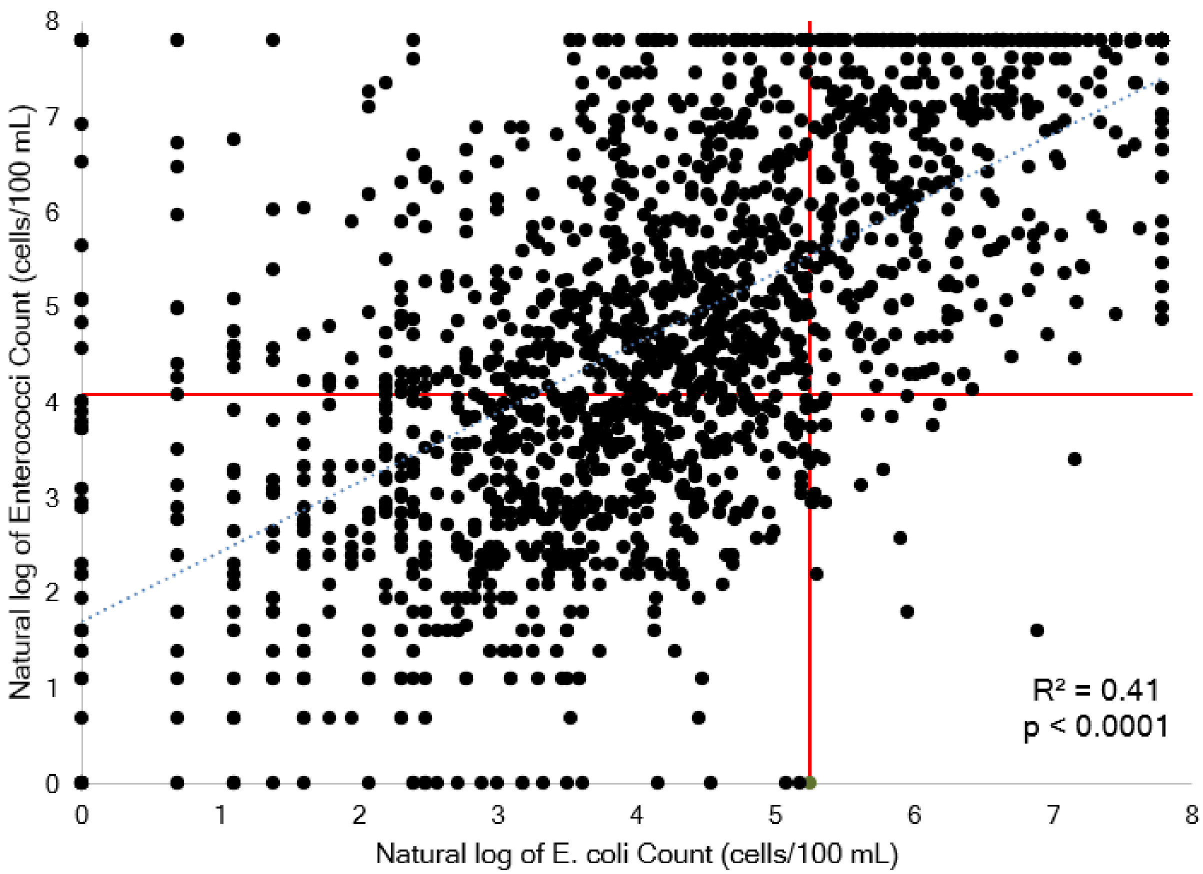
Paired Entero-E. coli Sample Results

A simple regression test showed that Entero and E. coli counts were correlated (Figure 10).[4] A considerable proportion of the variation was unexplained by the regression

[4] Correlation between Entero and E. coli counts was testing using simple regression on ln-transformed FIB counts, with $\alpha = 0.05$.

model (R^2 = 0.41). This may be related to age, type, and other characteristics of the fecal inputs, characteristics of the receiving waters (e.g., turbidity, depth, flow, temperature), relative persistence of the FIB, or other variables (Epstein et al., 2018). Long-term GMs also tracked, in that extreme high and low sites tended to be consistent between indicators.

Figure 10: Entero and E. coli Abundances in Paired Samples with EPA-Recommended BAV Thresholds

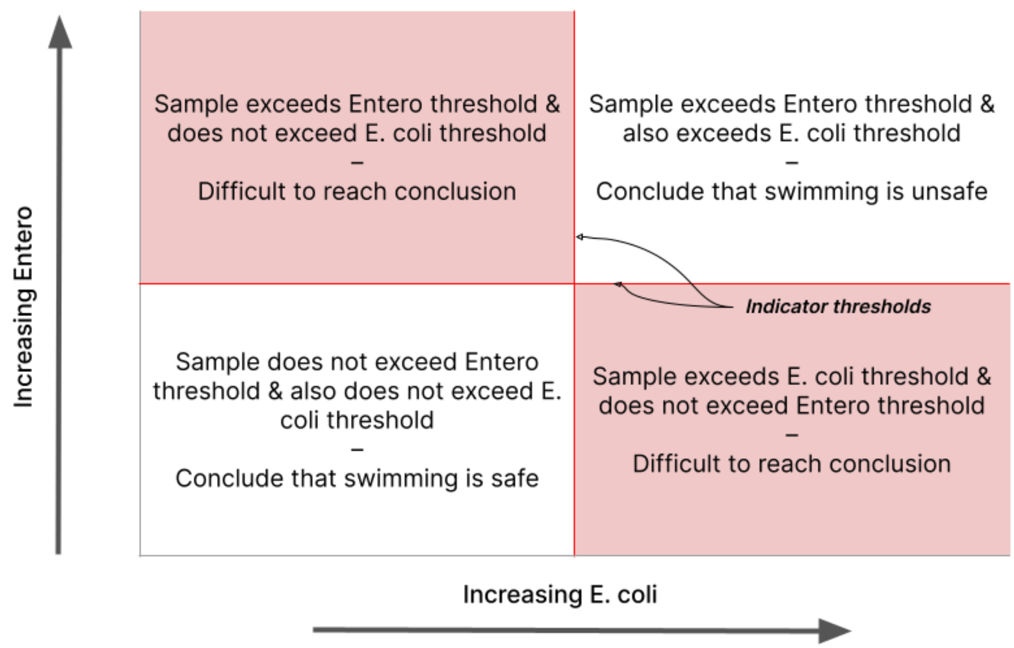


As indicators of recreational water quality, interpretation of Entero and E. coli abundances must include comparisons against EPA's recommended water quality criteria. When both indicators are measured in a single sample, there are four possible outcomes (Figure 11):

1. Both indicators fall below their thresholds: we confidently conclude that swimming is safe;
2. Both indicators exceed their thresholds: we confidently conclude that swimming is unsafe;

3. Entero falls below its threshold, and E. coli exceeds its threshold: a conclusion is more difficult to reach; and
4. E. coli falls below its threshold, and Entero exceeds its threshold: a conclusion is more difficult to reach.

Figure 11: Implications of Indicator Selection for Water Quality Management Decisions



The paired sample results underscore that fecal contamination is a widespread problem in our region's streams. Over one quarter of samples and nearly one half of sites exceeded the EPA-recommended thresholds for both Entero and E. coli. Very few locations have unambiguously good water quality: only 8% of site GMs fell below the threshold for both indicators.

Some portion of samples will lead to uncertainty about water quality simply because environmental variability and normal measurement error are an inherent part of FIB science. As long as these cases occur relatively infrequently, and at about the same rate for both FIBs, they are not cause for concern. However, in about 35% of our paired samples, Entero exceeded the BAV while E. coli did not, while only 1% of samples had E. coli above the BAV and Entero below it. This imbalance means that Entero is a more conservative indicator, a pattern that has been observed in other regions (Kinzelman et al., 2003; Peed et al., 2011). The proportion of high Entero/low E. coli samples varied by watershed, from 12% to 42% of samples. Long-term average results (GMs) tell a similar story. At 45% of the sampling locations, Entero GMs exceeded EPA's threshold while E. coli did not. Conversely, no site exceeded the E. coli threshold without also exceeding the Entero threshold.

The differences between Entero and E. coli, and the variation among watersheds, may be partly influenced by contamination sources. When researchers have further analyzed samples that exceed only one of the FIB thresholds, the contamination sources have differed depending on whether Entero or E. coli exceeded its threshold (Li et al., 2021).

Freshwater salinization may need to be considered when selecting FIB. Winter road salt application has increased the salinity of streams and rivers throughout the U.S. One experimental study has shown that E. coli survival may be enhanced by freshwater salinization within a certain range and to differing degrees depending on salt type (DeVilbiss et al., 2021). The effect range corresponds to the salinity level observed in an urbanized Mohawk River tributary (J. Garver, personal communication, May 23, 2023). As with other research topics, a key question is whether and how this phenomenon impacts pathogens.

The Hudson River is an estuary, with a wide range of salinity values, so only Entero allows us to directly compare conditions throughout the entire Hudson River Watershed. This makes it a logical indicator choice for the estuary, but we must weigh indicator performance against the value of a uniform indicator throughout the watershed.

Sewage Pollution Causes & Solutions

The regulatory structures and funding sources of the 1972 CWA provided for significant improvements in wastewater treatment standards and water quality. Now, fifty years later, many communities are struggling with the financial burden of maintaining their infrastructure, and New York is not applying its CWA tools effectively. These factors are undermining water quality. Our monitoring data underscore the importance of managing water quality impacts of rain events, and the central role of local land and infrastructure managers in doing so.

Cause 1: Infrastructure

The 1972 CWA created a minimum wastewater treatment standard and established the NPDES (National Pollutant Discharge Elimination System) permitting program to control pollutant discharges (40 C.F.R. § 125; 40 C.F.R. § 133). These actions led to major decreases in FIB abundance in the Hudson River (Brosnan et al., 2006). The CWA's early success was largely due to federal grant funding that allowed local communities to build infrastructure that they could not otherwise afford. The first decade of CWA appropriations were the largest public works expenditure since the Interstate Highway System, and covered 50%-75% of project costs (Copeland, 2016; Ramseur, 2018).

During the 1980s and 1990s, the CWA funding streams were converted from grants to loans, and local municipalities became directly responsible for nearly 100% of project costs (Ramseur, 2018). Small communities have struggled to qualify for these loans and pay off the debts (Ramseur, 2018). At the same time, federal wastewater infrastructure appropriations have steadily declined to a fraction of needs (Ramseur, 2018).

Wastewater infrastructure requires ongoing maintenance and periodic upgrades to prevent water quality from backsliding, and Hudson River Watershed communities have not been able to keep up with the work. Sewer pipes in systems serving Hudson River Estuary tributaries are 40-65 years old, according to data from the Hudson River Estuary Program (Table x) (Hudson River Estuary Program, 2017). Some of these systems lack disinfection or operate wet-weather bypasses that discharge raw sewage during rain. Many others experience chronic failures or frequent wet-weather breakdowns. Often, Hudson River Watershed municipalities struggle even to maintain accurate inventories of infrastructure needs because the system demands have overwhelmed available resources.

Table 2: Inventory of Wastewater Discharges to Hudson River Tributaries

Watershed	Number of Municipal WWTPs (NYS DEC, 2023)	Average Volume Treated by Municipal WWTPs (mgd)	Total Miles of Sewer Pipe (Hudson River Estuary Program, 2017)	Average Age Of Sewer Pipe (Hudson River Estuary Program, 2017)	Class 2 "Package Plants" (NYS DEC, 2014)	Septic Systems per mi^2.
Bronx	3	N.D.	N.D.	N.D.	N.D.	1
Hudson-Hoosic	11	N.D.	N.D.	N.D.	N.D.	27
Hudson-Wappinger	41	2.6	155	49	74	81
Lower Hudson	26	2.5	126	54	54	56
Middle Hudson	47	4.5	391	43	135	39
Mohawk	28	N.D.	N.D.	N.D.	N.D.	26
Rondout	27	14.6	382	65	79	41
Sacandaga	4	N.D.	N.D.	N.D.	N.D.	14
Schoharie	15	N.D.	N.D.	N.D.	N.D.	20
Upper Hudson	5	N.D.	N.D.	N.D.	N.D.	9

About one-third of NY's wastewater treatment plants are located in the Hudson River Watershed, and it accounts for about 40% of New York State's documented infrastructure needs (Table x). From 2015-2021, New York State has allocated $3 billion for drinking and wastewater infrastructure projects under the Water Infrastructure Improvement Act (Environmental Advocates NY, 2023). As these funds have been released, application volume has increased, and new drinking water regulations for emerging contaminants have come into effect, increasing demand for the allocated funds (Environmental Advocates NY, 2023).

Table 3: Wastewater Infrastructure Project Funding Needs

	Amount (in millions) (NYS Environmental Facilities Corporation, 2022)	**% of NYS Total**
All NYS	$5,737	n/a
Hudson Watershed	$2,262	39.4%
Estuary Main Stem	$370	6.4%
Upper Hudson	$218	3.8%
Mohawk	$349	6.1%
Estuary Tributaries	$141	2.5%
New York City (within HRW)	$1,184	20.6%

Although wastewater, storm water, and drinking water are delivered and regulated as separate entities in our society, this is not the most efficient or sustainable way to provide the water we need to live. The traditional wastewater treatment model disrupts natural hydrological cycles, consumes fossil fuels, and reduces downstream water quality, at great financial cost. As NYS invests in conventional approaches for urgent repairs, it must also move toward watershed-based management and resource recovery by prioritizing One Water solutions that integrate drinking water, wastewater, and stormwater management; utilizing nature-based solutions that align human and environmental benefits; and accounting for the heat, nutrients, and gas in wastewater streams as resources (American Society of Civil Engineers, 2021).

Infrastructure Solutions

- U.S. Congressional representatives should increase the availability of funding for projects in New York State, through both new legislation such as the NY-NJ Watershed Protection Act, and through appropriations and authorizations to support existing programs, including the Bipartisan Infrastructure Law, Clean Water State Revolving Fund, NY-NJ Harbor and Estuary Program and Water Resources Development Act.

- New York State budgets should continue to allocate funding for wastewater infrastructure projects. New York should restore the cuts to the Clean Water Infrastructure Act proposed by Gov. Hochul and make a new five-year commitment totaling $4 billion to account for increases in project costs and growing needs to address emerging pollution issues. Further, a portion of infrastructure planning and implementation funding should be allocated directly to the NY SWIMS initiative, so that water quality improvements can be achieved at site-level scales where new beaches or river pools are proposed.
- New York State Legislature should develop consistent predictable funding for operations and management (O&M) for drinking water, stormwater and sewage infrastructure similar to the current Consolidated Local Street and Highway Improvement Program (CHIPS) program.
- New York State should increase staffing at DEC to reduce the permitting backlog, enforce existing pollution permit limits, increase the pace of water quality assessments and clean water plan development and implementation, update relevant water quality standards, and address other priorities listed here.
- New York State DEC should develop routine and integrated watershed-based permitting, assessment, reclassification, and enforcement efforts to maximize water quality benefits in waterways. SPDES permitting should include provisions to ensure that flood-vulnerable infrastructure is protected or moved.
- To meet the PlaNYC goal of eliminating sewer overflows by 2060, New York City should conduct integrated watershed planning, comply with Sewage Pollution Right to Know requirements, and commit to the infrastructure investments that go far above those documented in CSO Long Term Control Plans, including increased green infrastructure installation and maintenance through an integrated citywide approach. New York State and the EPA should use every tool in federal and state law to ensure compliance with water quality standards to deliver the swimmable water quality New Yorkers deserve.
- Westchester County should proceed with the consolidation of municipal sewer systems and invest in sewer system maintenance and repair to eliminate leaks, infiltration and inflow in the county's vast sewer system.
- Local governments in the Hudson Valley that maintain combined sewer systems should follow models such as Kingston, NY, and invest in sewer separation, green infrastructure and other strategies that exceed the requirements of CSO Long Term Control Plans; communities such as Catskill,

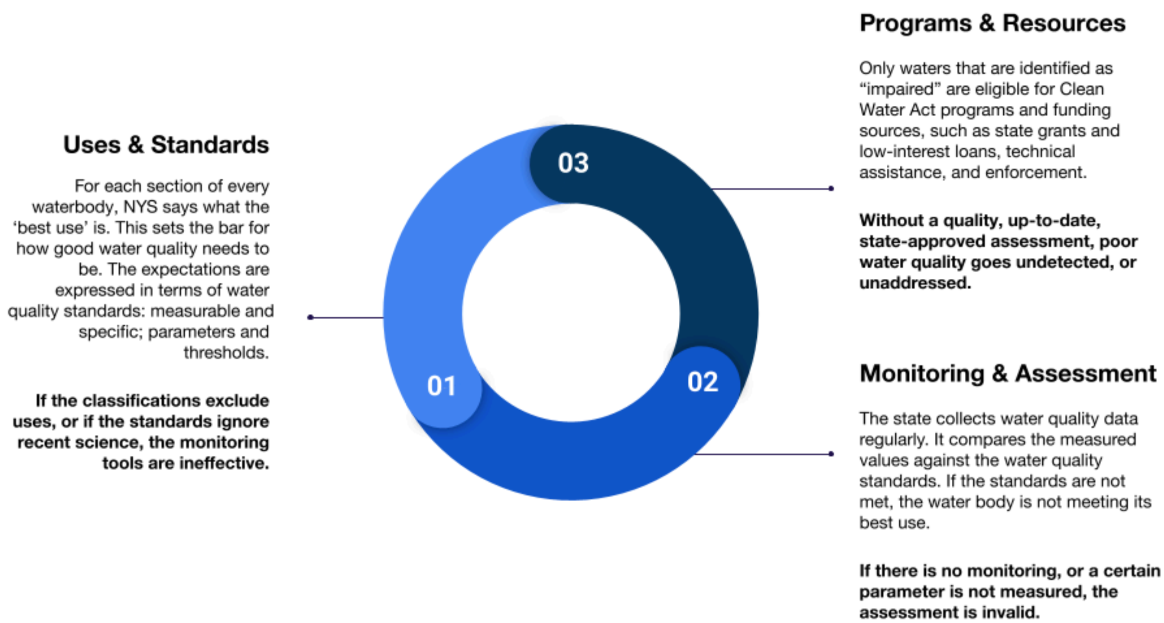
NY, that have committed to eliminating combined sewer overflows; and communities such as the six Capital District communities that are collaborating to address the most significant overflows affecting their shared reach of the Hudson as the highest priorities.

- Local governments in the Hudson Valley that maintain sewer infrastructure should aggressively seek Engineering and Planning Grants to define inflow and infiltration reduction strategies, and then apply for state and federal funding to implement those projects. This is particularly important in the coming years, when historic levels of federal and state funding will still be available.
- Municipalities should utilize NYS DEC's Asset Management for Publicly Owned Treatment Works program to proactively manage climate change impacts.
- NYS DEC should complete and implement the Total Maximum Daily Load (TMDL) clean water plans for phosphorus in the Mohawk River and Wallkill River watersheds, establish numeric nutrient criteria for flowing waters, and develop plans for other waterways with nutrient impairments.
- Local governments and non-governmental organizations involved in 9-element, Drinking Water Source Protection, Harmful Algal Bloom or other DEC-approved watershed planning should identify sewage and stormwater infrastructure needs, including green infrastructure, to ensure eligibility for grant funding.
- NYS DEC should support wastewater treatment innovation through permitting, design specifications, and pilot project grants.
- NYS DEC should routinely monitor waters for all applicable uses to ensure that communities can qualify for state programs and fairly compete for funds.
- NYS Legislature should develop and invest in programs to recruit and train drinking water and wastewater operators, particularly in the face of the water industry's widespread shortages of qualified workers.
- NYS Legislature should pass legislation to ensure that stormwater fees can be assessed separately from drinking water or sewer fees, to ensure equitable allocation of costs to address stormwater-associated pollution.

Cause 2: Poor Clean Water Act Implementation

The CWA uses designated uses, water quality standards, and water quality assessment to protect water quality (Figure 12). Swimming and other designated uses are the basis of water quality goals. Water quality standards are sets of parameters, measurement requirements, and threshold values that are designed to ensure the conditions required to support a designated waterbody use. Water quality assessment is a foundational part of the CWA, and is a key to unlocking programs and resources for water quality protection. Water quality assessments determine whether waters meet their designated uses by comparing water quality data to the applicable standards. Assessments are use-specific, so water quality monitoring plans must include all parameters mentioned in the applicable water quality standards in order to obtain a comprehensive assessment.

Figure 12: Water Quality Protection Under the Clean Water Act



Swimming is a designated use in almost 5,000 miles of Hudson River Watershed streams. Riverkeeper's tributary monitoring work has exposed gaps in water quality management as envisioned by the CWA and enacted by New York State.

Recreational Water Quality Standards Standards Are Outdated

EPA issued ready-to-adopt bacterial indicator recommendations for all waterbody types in 2012 (EPA, 2012a). NYS has adopted these recommendations in saline waters, including the Hudson River up to the Bear Mountain Bridge, as well as freshwater areas of the Great Lakes. However, standards for the majority of the state's flowing freshwaters, including all of the Hudson River Watershed, continue to be based on EPA's previous recommendations, issued in 1986.

New York's Water Quality Monitoring Is Inadequate

NYS DEC removed sewage indicators from its Rotating Integrated Basin Studies (the program that provides data for CWA assessment) in 2012 (NYS DEC, 2013). In 2021, DEC also stopped using Department of Health beach monitoring data and NYS DEC-confirmed HAB reports as evidence of recreational water quality impairment (NYS DEC, 2021a). The current assessment policy also excludes evaluation of swimming use in Class C waters (NYS DEC, 2021a). The total effect of these policies is that NYS DEC no longer routinely assesses baseline recreational water quality in Hudson River tributaries.

Infrastructure funding and technical assistance programs rely on NYS DEC's Waterbody Inventory/Priority Waterbody List (WI/PWL) to qualify and prioritize potential recipients. Documentation of a waterbody impairment on the WI/PWL is a major scoring factor in applications for multiple state and federal loan and grant programs. This lack of monitoring directly disadvantages communities that need funding and programmatic support for water quality improvements.

Community Science Data Is Underutilized

Forty percent of NY streams are unassessed as of 2018 (NYS DEC, 2018). The CWA requires states to use "all existing and readily available data and information" to assess water quality, and specifically identifies the need for such data in areas where "members of the public" have reported water quality problems (40 C.F.R. § 130.7). Despite this, NYS DEC policy precludes all but a small fraction of available information from being used. Riverkeeper has collected more than 10,000 FIB samples in Hudson River tributaries, but this data has been underused by DEC due to stringent, one-size-fits-all data quality requirements.

It is important for NYS to establish data quality assurance standards for its regulatory processes. However, NYS DEC's data use policy requires *all* data to meet conditions appropriate for full regulatory data use, such as 303(d) list determinations (NYS DEC, n.d.-a). These requirements are prohibitive for many volunteer groups. To facilitate broader use of community science data, DEC should differentiate quality assurance standards according to intended data uses. For example, some community-based data could be accepted under less stringent quality control guidelines, and be used to identify hotspots that need professional monitoring. This is similar to the approach used by NYS DEC's volunteer-based Water Assessments by Volunteer Evaluators (WAVE) program.

For community groups that want to take sampling a step further, NYS DEC should establish a program to support volunteer stream monitoring. New York State Conservation Law currently includes a volunteer water quality monitoring program with a long track record of success: the Citizens' Statewide Lakes Assessment Program (CSLAP). CSLAP has been active for nearly four decades, and data from the program has been used for impaired waterbody listings and other assessments, developing state water quality criteria, permitting, and invasive species control programs (NYS DEC, n.d.-b). However, CSLAP is only for lakes. NYS needs a CSLAP-type program for rivers and streams. The program should involve robust outreach and support to communities that are experiencing environmental injustice.

Under NYS law, data to be used in regulatory programs must be analyzed at laboratories that have received Environmental Laboratory Approval Program (ELAP) certification. Watershed groups often partner with colleges and universities to conduct water quality monitoring and research. Unfortunately, some ELAP staffing and reporting requirements are challenging for academic institutions to meet, and reduce opportunities for student participation in laboratory activities (NYS Department of Health, n.d.). Therefore, academic laboratories are rarely ELAP-certified.

The ELAP program could be adapted to provide a project-based certification for academic or non-profit institutions. Quality control, staffing, and other measures would be developed on a time-bound, project-specific basis. This type of approval is compatible with the existing ELAP model, certifies facilities for specific combinations of method, parameter, and matrix (e.g., air, soil, water). Project-based ELAP approval would benefit multiple stakeholders. NYS would gain useable data; academic institutions would provide student experiences with real-world implications; and stewardship groups could increase the reach of their work.

Clean Water Act Implementation Solutions

The following actions apply to NYS DEC. The New York State Legislature should provide the funding to DEC needed to implement these recommendations.

- Add fecal-indicator bacteria monitoring to the Rotating Integrated Basin Study and other water quality assessment programs, including the Hudson River Estuary Program's effort to monitor unassessed stream segments.

- Update freshwater fecal indicator bacteria water quality standards to align with EPA criteria, including use of E. coli or Entero to assess waters and recognition that Class C waters should achieve "swimmable" quality.
- Develop methods to identify likely septic system influence on water quality as part of water quality assessments, and develop methods to facilitate – or bypass – impaired waterway designations in order to facilitate community access to the existing Septic Repair and Replacement Program.
- Explore the suitability of site-specific recreational water quality standards in some tributaries, for example by studying whether birds or contaminated sediments are a significant contributor to measured FIB in the Rondout Creek and Wallkill River, and assessing the relative influence of different sources of FIB in the Esopus Creek.
- Work with partners to conduct high-frequency monitoring for public notification at swimming access points, including existing and potential new public beaches or river pools, as well as areas frequented by the public that are not officially sanctioned swimming areas.
- Facilitate broader use of community science data by expanding data uses and differentiating quality assurance standards.
- Create a CSLAP-type program for rivers and streams.
- Work with DOH to adapt and provide project-based ELAP certification for academic or non-profit institutions.

Cause 3: Poor Septic System Management

Properly designed and well-functioning septic systems can effectively treat waste. However, many septic systems in our local communities were constructed before modern standards were in place, and operate with no regulatory oversight. Septic systems can be expensive to repair or replace, especially if routine maintenance has lapsed. Municipalities, regional entities, and New York State have used diverse strategies to improve septic system management.

In 2019, the towns of Bolton and Queensbury (both in the Lake George region), enacted laws requiring septic system inspection before a property's sale (Craig, 2019; Moore, 2019). This ensures that systems receive at least occasional attention. In the Finger Lakes region, eight municipalities formed the Keuka Watershed Improvement Cooperative in 1994 to limit negative impacts from septic systems (EPA, 2012b). The cooperative enables the municipalities to routinely inspect about 3,000 septic systems through shared ordinances, funding, and inspection team staffing.

At the state level, the NYS Septic Repair and Replacement Program was established in 2017 under the Clean Water Infrastructure Act (NYS DEC, 2021c). Homeowners may be reimbursed for up to 50% (with a maximum of $10,000) of the cost to repair or replace eligible septic systems. Participation is limited to certain geographic areas, and is based on information in the WI/PWL. In this way, the lack of state-approved bacterial monitoring in the Hudson River Watershed precludes tributaries from qualifying for this program. The second round of program funding, announced in July 2022, provided $30 million for septic replacements. There are no Hudson River Watershed rivers or streams involved in the program.

Septic System Management Solutions

- Municipalities should implement local ordinances requiring routine septic system maintenance and inspection, either individually or as part of cooperatives. Models elsewhere in the state, such as in the Lake George Watershed and in Cayuga County, should be implemented in the Hudson River watershed.
- Municipalities should seek opportunities to form watershed-based cooperatives to share the financial and staffing burdens of septic system management.
- NYS should continue to increase funding for the Septic Repair and Replacement Program, and New York State should expand access to the program, given current gaps in the water quality assessments and impairment listings currently necessary for eligibility. Program accessibility could be expanded based on GIS analysis of septic system age and density, proximity to waterways and soil suitability, for instance.
- In areas with chronic septic system failures and poor suitability for septic replacement and repair, sewers should be developed or extended, or innovative site-specific solutions should be developed. Technical assistance and funding programs should be streamlined and coordinated to support funding for these types of complex projects.

Cause 4: Climate Change

NYS has already experienced increases in total annual precipitation and frequency, as well as increasing intensity of extreme events (Frankson et al., 2022; NYS DEC, 2021d). These increases are predicted to continue, even as precipitation becomes more variable. As summer temperatures increase with climate change, the recreational season will lengthen. About one in four wastewater treatment plants in the Hudson River Watershed are already at risk from flooding at current sea level (Partners Restoring the Hudson, 2018). New York State's official sea level rise projections, developed under the Community Risk and Resiliency Act, anticipate that the Hudson will rise 1-6 feet higher by the end of the century (NYS DEC, n.d.-c).

Climate change will affect water quality and quantity, pathogen and FIB survival, and operation and efficiency of wastewater treatment systems (US EPA, 2023b). The U.S. Climate and Health Assessment predicts that climate change will cause increased recreational use of waters, and increased impacts to recreational water quality (Trtanj et al., 2016). However, future recreational water quality is difficult to predict because there are multiple sources of uncertainty, and multiple ways that we can alter the direction and magnitude of trends (US EPA, 2023b). Local land use and infrastructure management decisions will heavily influence the severity of climate change impacts (US EPA, 2023b).

Our Entero monitoring results show us that controlling wet-weather sources of fecal contamination is important for achieving swimmable water quality. As precipitation increases with climate change, sewage pollution is likely to worsen unless wastewater collection pipes are repaired to prevent infiltration, treatment plants are moved out of floodplains, and wet-weather bypasses are eliminated.

As the climate changes, Earth is also experiencing a biodiversity crisis, caused largely by land use change, habitat destruction, changing climate, and pollution. As we attempt to remediate water pollution, we should look for solutions with multiple benefits. Urban runoff and agricultural runoff are significant sources of Entero and other pollutants, and methods for reducing these pollutants can also address flooding and species declines.

One multiple-benefit strategy is riparian corridor restoration, which can slow stormwater runoff, mitigate flooding, create wildlife habitat, and provide agricultural products. Riverkeeper is working to restore free-flowing streams through dam removal, which helps aquatic ecosystems become more resilient to climate change by restoring habitat, connectivity, and riparian processes. Riverkeeper advocates for drinking water source protection through a watershed management approach. Protecting water quality at the source means a lighter burden on water treatment plants. The watershed approach maintains high source water quality by preserving the forests, riparian zones, and wetlands that connect to rivers and streams.

In urban areas, green infrastructure provides similar benefits while also reducing flows through stormwater and wastewater collection systems. In Westchester County, the condition of wastewater collection infrastructure varies across municipalities. Riverkeeper supports sewer system consolidation to bring all municipal infrastructure into good repair and eliminate the stormwater infiltration that causes overflows and spills. Riverkeeper is also working to reduce CSO overflows in Yonkers.

Climate Change Adaptation Solutions

- U.S. EPA should finalize its Water Quality Climate Change Literature Review and related resources.
- EPA and New York State should ensure that predicted precipitation volumes and extremes influence current permitting for a range of relevant programs, including municipal separate storm sewer (MS4), SPDES and CSO Long Term Control Plans; as well as for TMDLs and other clean water plans.
- NYS Legislature should fund the Environmental Protection Fund at $400 million, to support a range of programs, including $7.5 million for the Hudson River Estuary Program.
- New York's updated wetlands regulations should protect as many wetlands as possible.
- New York State and communities should utilize existing programs to develop and implement watershed management strategies to preserve or restore forested stream buffers; protect and re-connect floodplains; protect steep slopes; protect wetlands as well as small, intermittent and ephemeral streams and their buffers; implement agricultural best management practices; manage stormwater; and restore damaged streambanks and channels. Communities engaged in these typically complex initiatives should benefit from greater scores in the Climate Smart Communities Program.
- Communities with land use authorities should update planning and zoning rules to restrict building in flood plains, streams and wetlands and their buffers, preserve steep slopes and implement other best practices for watershed management. Upstream municipalities should be particularly mindful of the impacts of their responsibility to protect downstream neighbors. Communities should utilize the training and resources available via the Pace University Land Use Leadership Alliance (LULA).
- DEC's Resilient New York planning program should be continued and expanded to address water quality and quantity issues.

- New York State should utilize the new Climate Impacts Assessment to communicate clearly the risk of precipitation extremes to local and regional communities, and watershed planning and stormwater management should be adapted to account for the likelihood of both extreme rainfall and drought.
- Municipalities should join information-sharing forums like the Flood Resilience Network convened by Hudson River Watershed Alliance and NY SeaGrant; and access support for programs such as the Climate Smart Communities Program from the Hudson River Estuary Program and Partners for Climate Action's Local Champions program.
- Municipalities and non-governmental organizations should work with the Hudson River Watershed Alliance, the Hudson River Estuary Program and regional watershed groups to identify and implement priorities for watershed planning and management. Water quality impacts from climate change should be a focus of local and regional planning for drinking water source protection and climate adaptation.
- Lower Hudson Watershed stakeholders should utilize the NY-NJ Harbor and Estuary Program, and the Hudson River Estuary Program to bring watershed-scale coordination and funding for monitoring and restoration projects.
- Longterm water quality monitoring programs should be fully supported and expanded, with the spatial and temporal coverage required to interpret current conditions and develop predictions.

Research Agenda

The depth and breadth of our dataset, especially when combined with data collected by partners, provide a foundational understanding of fecal-indicator bacteria in the Hudson River Watershed. However, additional studies are needed to fully understand the impacts of wastewater discharges in the Hudson River Watershed. Some important research topics are outlined below.

Fecal Contamination Sources

- What are specific causes of elevated FIB concentrations at public access points where communities want to sustain or expand access to swimming, such as Marbletown's Esopus Creek beach at Tongore Park?

- Do FIB abundance or variability decrease after different types of water quality improvement projects, and on what timescales?
- What sources of fecal contamination are present in Hudson River tributaries that haven't yet been studied?
- How do occurrences of human, stormwater, agricultural and avian sources vary throughout the Hudson River's subwatersheds? What other sources are important?
- What land use or infrastructure-related variables are correlated with various fecal sources?
- What health risks do the different sources pose, and what factors affect health risk?
- What are differential health risks posed by varying levels of fecal contamination in waterways of different depths and uses?
- How abundant are each of the sources? How does the volume of inputs influence the level of risk? How do abundance and relative risk vary around the watershed? What variables are they correlated with?
- Can we develop cost-effective and easy-to-use source tracking tools and models?
- Where and when are site-specific water quality standards appropriate?

Fecal-Indicator Bacteria Persistence in Sediment

- How long do FIB persist in tributary sediments? How long do pathogens persist in the same or similar environments?
- How do FIB move through tributary environments? Where and when are sediments deposited? When and where are sediments resuspended?
- What are sediment FIB and pathogen abundances in tributaries that receive regular inputs of non-disinfected or untreated sewage, such as Quaker Creek and Tin Brook, in the Wallkill River Watershed? How do these environments compare with areas that have chronically failing septic systems, or other FIB sources?
- Can fresh and resuspended FIB be differentiated during rain events?

Fecal-Indicator Bacteria Selection

- How should Entero and E. coli monitoring be used in the Hudson River Watershed system?
- In cases where Entero exceeds EPA's RWQC threshold and E. coli does not, what is the actual human health risk? What are the Entero and E. coli sources?
- How is freshwater salinization affecting salinity levels in the watershed's streams, and how does this influence FIB choice?
- How is pathogen survival affected by freshwater salinization?
- Which Hudson River tributaries are most susceptible to the combined impacts of freshwater salinization and fecal contamination?

Climate Change and Sewage Pollution

- How do other environmental variables interact with precipitation and time as drivers of interannual FIB variability?
- How will rising air and water temperatures affect FIB & pathogen survival?
- How will changing precipitation patterns alter FIB inputs, streamflow, and sediment dynamics?
- How will future stormwater flows impact the frequency of wastewater infrastructure failures and CSOs?
- What wastewater system upgrades and repairs will be most effective at reducing future sewage leaks and spills?
- What innovations should be prioritized to reduce GHG emissions and other environmental impacts of wastewater treatment?

Conclusion

Swimming is a designated use in almost 5,000 miles of Hudson River Watershed streams. Despite the popularity of water-based recreation in the region, data collected by Riverkeeper and partners suggest that our tributaries don't meet the criteria suggested by EPA to protect swimmer health. State water quality management policies partly explain this. Riverkeeper's analysis of 11 years of tributary monitoring data exposes gaps in water quality management as envisioned by the CWA and enacted by New York State. Fifty years after the passage of the CWA, water quality in the Hudson River Watershed is at risk of managed decline. Community-based science has untapped potential to help set water quality on the right track.

Evidence of human waste as a contamination source is common in the Hudson River Watershed, although it is by no means present at all places and times. Both septic and centralized wastewater systems are probable contributors. Many communities are struggling with the financial burden of maintaining their wastewater infrastructure, but a lack of state-approved water quality data prevents them from accessing the funding and programmatic support that they need to improve water quality. The dataset that Riverkeeper and our partners have created—and continue to grow—can be used to infer where such data is most urgently needed.

The impacts of climate change will change every piece of the recreational water quality puzzle, including changes in recreational water use, water quality and flow, microbiological survival, and wastewater system operations. In the face of this, our network's FIB dataset provides critical information about the geographic and temporal variability of Entero, the relationship between Entero and E. coli, and the sources of Entero. This information should guide DEC's water quality management policy and research agenda.

Sewage pollution is not just a recreational issue: fecal contamination and other wastewater-associated pollutants also threaten drinking water sources. Due to these connections, water quality improvements can proceed along multiple approaches, but NYS DEC must use all its available tools by updating recreational water quality standards; reinstating routine FIB monitoring; monitoring the impacts of water quality improvement projects; and collaborating on research into the variables that influence water quality. Simultaneously, New York State budgets must continue to fund wastewater infrastructure projects.

References

Albany Pool Joint Venture Team. (2011.) *Albany Pool CSO long term control plan.* https://www.albanypoolcso.org/wp-content/uploads/2019/05/LTCP-Final.pdf

American Society of Civil Engineers. (2021). 2021 report card for America's infrastructure. https://infrastructurereportcard.org

Brooks, Y. M., Spirito, C. M., Bae, J. S., Hong, A., Mosier, E. M., Sausele, D. J., Fernandez-Baca, C. P., Epstein, J. L., Shapley, D. J., Goodman, L. B., Anderson, R. R., Glaser, A. L., & Richardson, R. E. (2020). Fecal indicator bacteria, fecal source tracking markers, and

pathogens detected in two Hudson River tributaries. Water Research, 171, 115342. https://doi.org/10.1016/j.watres.2019.115342
Brosnan, T. M., Stoddard, A., & Hetling, L. J. (2006). Hudson River sewage inputs and impacts: past and present. In J. S. Levinton & J. R. Waldman (Eds.), The Hudson River Estuary (335-348). Cambridge.
Cantwell, M. G., Katz, D. R., Sullivan, J. C., Shapley, D., Lipscomb, J., Epstein, J., Juhl, A. R., Knudson, C., & O'Mullan, G. D. (2017). Spatial patterns of pharmaceuticals and wastewater tracers in the Hudson River Estuary. Water Research, 137, 335-343. https://doi.org/10.1016/j.watres.2017.12.044
Copeland, C. (2016). Water infrastructure financing: history of EPA appropriations. Congressional Research Service. https://castor.house.gov/uploadedfiles/water_infrastructure_finance_report.pdf
Craig, G. (2019, May 8). Bolton passess septic system inspection law. The Post Star. https://poststar.com/news/local/bolton-passes-septic-system-inspection-law/article_2dffeae0-5be1-5c88-b3a4-610bc3c8ca40.html
DeVilbiss, S. E., Steele, M. K., Krometis, L-A. H., & Badgley, B. D. (2021). Freshwater salinization increases survival of Esherichia coli and risk of bacterial impairment. Water Research 191, 116812. https://doi.org/10.1016/j.watres.2021.116812
Dunne, A. (2019, May 16). Wallkill River Summit: NYS DEC to begin clean water plan [Radio broadcast]. WAMC. https://www.wamc.org/hudson-valley-news/2019-05-16/wallkill-river-summit-nys-dec-to-begin-clean-water-plan
Environmental Advocates NY. (2023). Untapped potential: a new era for New York's water infrastructure. https://eany.org/wp-content/uploads/2023/02/EANY-Untapped-Potential_FINAL.pdf
Epstein, J., Brabetz, B., Dueker, E., Juhl, A.R., Knudson, C., Law, N., Lipscomb, J., O'Mullan, G.O., Rodak, C., & Shapley, D. (2018, May 2). *Comparison of Two Commonly Used Fecal Indicator Bacteria in Waterways of the Hudson River Watershed* [Poster]. Hudson River Environmental Society Hudson River Symposium, New Paltz, NY, USA.
Frankson, R., Kunkel, K. E., Champion, S. M., Stewart, B. C., Sweet, W., DeGaetano, A. T., & Spaccio, J. (2022). New York State Climate Summary 2022. NOAA/NESDIS. https://statesummaries.ncics.org/chapter/ny
Green, H. C., Dick, L. K., Gilpin, B., Samadpour, M., & Field, K. G. (2012). Genetic markers for rapid PCR-based identification of gull, Canada goose, duck, and chicken fecal contamination in water. Applied and Environmental Microbiology, 78(2), 503-510. https://doi.org/doi:10.1128/AEM.05734-11
Hagedorn, C., Harwood, V. J., & Blanch, A. R. (2011). Overview. In C. Hagedorn, A. R. Blanch & V. J. Harwood (Eds.), Microbial source tracking: Methods, applications, and case studies. Springer. https://doi.org/10.1007/978-1-4419-9386-1
Hudson River Estuary Program. (2017). Hudson River SPDES data [Data file]. Obtained via FOIL request.
Kinzelman, J., Ng, C., Jackson, E., Gradus, S., & Bagley, R. (2003). Enterococci as Indicators of Lake Michigan Recreational Water Quality: Comparison of Two Methodologies and Their Impacts on Public Health Regulatory Events. Applied and Environmental Microbiology, 69(1), 92-96. https://doi.org/10.1128/AEM.69.1.92-96.2003
Li, X., Kelty, C. A., Sivaganesan, M., & Shanks, O. C. (2021). Variable fecal source prioritization in recreational waters routinely monitored with viral and bacterial gene indicators. Water Research, 192, 116845. https://doi.org/10.1016/j.watres.2021.116845
Lininger, K. J., Ormanoski, M., & Rodak, C. M. (2019). Observations and correlations from a 3-year study of fecal indicator bacteria in the Mohawk River in upstate NY. Water, 14, 2137. https://doi.org/10.3390/w14132137

Miller, B. J. (2022). Unprecedented bird flu outbreaks concern scientists. Nature, 606, 18.
Moore, K. (2019, March 20). Septic systems getting fixed as new Queensbury law kicks in. The Post Star. https://poststar.com/news/local/septic-systems-getting-fixed-as-new-queensbury-law-kicks-in/article_F29947fd-d926-5372-b485-e325609af8b8.html
National Institute of Standards and Technology. (2022, April 12). NIST collaborates with EPA to develop a standard to improve fecal pollution measurements in recreational waters. https://www.nist.gov/news-events/news/2022/04/nist-collaborates-epa-develop-standard-improve-fecal-pollution-measurements
NYS DEC. (2023). Wastewater facility [GIS resource]. Retrieved from https://data.gis.ny.gov/datasets/1b6e74e884f34b1ca720887b55c6937a_0/explore
NYS DEC. (2021a). Consolidated assessment and listing methodology. https://www.dec.ny.gov/docs/water_pdf/calmmay2021.pdf
NYS DEC. (2021b). Mohawk River Basin action agenda: 2021-2026. https://www.dec.ny.gov/docs/water_pdf/mohawkrbaa2021.pdf
NYS DEC. (2021c). State septic system replacement fund program outline. https://nysefc.app.box.com/s/vrodsipyy7vxn4bzq60qmthzrra0wk6z
NYS DEC. (2021d). Observed and projected climate change in New York State: an overview. https://www.dec.ny.gov/docs/administration_pdf/ccnys2021.pdf
NYS DEC. (2018). New York State Section 305(b) Narrative Report.
NYS DEC. (2014). Hudson River Estuary SPDES data [Data file]. Obtained via FOIL request.
NYS DEC. (2013, June 19). NYSDEC DOW water quality monitoring and assessment programs [Presentation]. On file with author.
NYS DEC. (n.d.-a). Water quality assurance. Retrieved June 14, 2023, from https://www.dec.ny.gov/chemical/23850.html
NYS DEC. (n.d.-b). CSLAP Sampling Activities. Retrieved June 14, 2023, from https://www.dec.ny.gov/chemical/81616.html
NYS DEC. (n.d.-c). Community Risk And Resiliency Act (CRRA). Retrieved December 17, 2023, from https://dec.ny.gov/environmental-protection/climate-change/new-york-response/crra-0
NYS Department of Health. (n.d.). Requirements for laboratory certification/certification manual. https://www.wadsworth.org/regulatory/elap/requirements-for-laboratory-certification-certification
NYS Environmental Facilities Corporation. (2022). Final intended use plan: Clean Water State Revolving Fund, federal fiscal year 2023. https://efc.ny.gov/system/files/documents/2022/10/2023-iup-final-a.pdf
NYS Office of Information Technology Services. (2023). NYS tax parcel centroid points [GIS resource]. Retrieved from https://data.gis.ny.gov/datasets/nys-tax-parcel-centroid-points/explore
O'Mullan, G. D., Juhl, A., Reichert, R., Schneider, E., & Martinez, N. (2019). Patterns of sediment-associated fecal indicator bacteria in an urban estuary: benthic-pelagic coupling and implications for shoreline water quality. Science of the Total Environment, 656, 1168-1177. https://doi.org/10.1016/j.scitotenv.2018.11.405
O'Mullan, G. D., Montero, A., Reichert, R., Keller, J., Blanford, W., & Engel. R. (2018, June 10-15). *The urban street surface as a source of fecal bacteria to coastal waterways: dry weather persistence, indicator diversity, and a novel management solution* [Poster]. Association for the Sciences of Limnology and Oceanography Summer Meeting, Victoria, BC, Canada. https://www.aslo.org/wp-content/uploads/OSM-2018-Program-Book.pdf

Partners Restoring the Hudson. (2018). Full TEC narrative: storm and wastewater. http://thehudsonweshare.org/wp-content/uploads/2018/08/Storm-and-WasteWater.pdf
Peed, L. A., Nietch, C. T., Kelty, C. A., Meckes, M., Mooney, T., Sivaganesan, M., & Shanks, O. C. (2011). Combining land use information and small stream sampling with PCR-based methods for better characterization of diffuse sources of human fecal pollution. Environmental Science & Technology, 45, 5652-5659. https://doi.org/10.1021/es2003167
Quinlivan, J. (2019). Rondout sub-basin: watershed analysis and Enterococci investigation.
Ramseur, J. L. (2018). Wastewater infrastructure: overview, funding, and legislative developments. Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R44963/6
Richardson, R. (n.d.). Waterborne pathogens and sources of pollution in a feces-contaminated Hudson River tributary.
Riverkeeper, Bronx River Alliance, Quassaick Creek Watershed Alliance, Sarah Lawrence College Center for the Urban River at Beczak. (2022). Riverkeeper Hudson River Tributary Community Science Fecal Indicator Bacteria Dataset (v2) [Data file]. http://www.hydroshare.org/resource/e22138bd77914201af48fce5bfc458f4
Riverkeeper. (n.d.). Community science volunteer attribution. Retrieved December 13, 2023, from https://www.riverkeeper.org/water-quality/tools-databases/tribdata/communityattribution
Rodak, C. M., & Endres, L. (2019). Validation and application of qPCR-MST of fecal contamination in the Mohawk River Watershed.
Soller, J. A., Schoen, M. E., Bartrand, T., Ravenscroft, J. E., & Ashbolt, N. J. (2010). Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. Water Research 44, 4674-4691. http://dx.doi.org/10.1016/j.watres.2010.06.049
Town of Orangetown. (2018). Outfall reconnaissance inventory sample collection field sheets. On file with author.
Trtanj, J., Jantarasami, L., Brunkard, J., Collier, T., Jacobs, J., Lipp, E., McLellan, S., Moore, S., Paerl, H., Ravenscroft, J., Sengco, M., & Thurston, J. (2016). Climate impacts on water-related illness. In Crimmins, A., Balbus, J., Gamble, J. L., Beard, C, B., Bell, J. E., Dodgen, D., Eisen, R. J., Fann, N., Hawkins, M. D., Herring, S. C., Jantarasami, L., Mills, D. M., Saha, S., Sarofim, M. C., Trtanj, J., & Ziska, L. (Eds.), The impacts of climate change on human health in the United States: A scientific assessment (pp. 157–188). U.S. Global Change Research Program, Washington, DC. http://dx.doi.org/10.7930/J03F4MH4
US EPA. (2023a, January 6). Clean Water Act analytical methods. https://www.epa.gov/cwa-methods/other-clean-water-act-test-methods-microbiological
US EPA. (2023b, June 5). *Water quality topics: pathogens*. EPA Water quality and climate literature review. https://www.epa.gov/wqclr/water-quality-topics-pathogens
US EPA. (2023c). *Report on the 2nd five-year review of EPA's recreational water quality criteria*. https://www.epa.gov/system/files/documents/2023-05/2023-5year-review-rwqc-report.pdf
US EPA. (2012a). Recreational Water Quality Criteria. https://www.epa.gov/sites/default/files/2015-10/documents/rwqc2012.pdf
US EPA. (2012a). Case studies of individual and clustered (decentralized) wastewater management programs.

https://www.epa.gov/sites/production/files/2015-06/documents/decentralized-case-studies-2012.pdf
US EPA. (2017). National water quality inventory: report to Congress. https://www.epa.gov/sites/default/files/2017-12/documents/305brtc_finalowow_08302017.pdf
US EPA. (2018). 2017 Five-Year review of the 2012 recreational water quality criteria. https://www.epa.gov/sites/default/files/2018-05/documents/2017-5year-review-rwqc.pdf
US EPA. (2010). Quantitative microbial risk assessment to estimate illness in freshwater impacted by agricultural animal sources of fecal contamination. https://www.epa.gov/sites/default/files/2015-11/documents/quantitiave-microbial-risk-fecal.pdf
US EPA. (2009). Review of published studies to characterize relative risks from different sources of fecal contamination in recreational water. https://www.epa.gov/sites/default/files/2019-03/documents/review-published-studies-relative-risks-rec-water.pdf
United States Geological Survey. (2022, August 18). Antibiotic resistant bacteria acquired by wild birds in urban settings and dispersed via migration. Environmental Health Program. https://www.usgs.gov/programs/environmental-health-program/science/antibiotic-resistant-bacteria-acquired-wild-birds
Vail, L., Elling, J., & O'Mullan, G. (2020). Microbial source tracking survey of Sparkill Creek: confirmation of methods and initial evidence supporting widespread human sewage contamination following rainfall.
Vail, L., Elling, J., & O'Mullan, G. (2021). Microbial source tracking in Sparkill Creek: increasing evidence supporting contributions of human sewage contamination beyond background levels of fecal indicators in Sparkill Creek.

Appendix: Enterococcus Sampling Results by Location

Location	BAV	GM
Upper Hudson River		
Sampled June, August and October 2016, and monthly 2017-2022. Not sampled July 2020. Upper Hudson River samples were collected by volunteers and processed by the Water Justice Lab at Media Sanctuary in Troy (2021-2022), or by Riverkeeper (2016-2022). Special thanks to Jarrett Engineers and Doug Reed for sampling and lab support.		
Newcomb- Tahawus Road Bridge	24%	12
Newcomb- Route 28N Bridge whitewater access point	25%	16
Johnsburg- Warren County canoe access	23%	21
Warrensburg- Warren County Fish Hatchery boat launch	27%	20
Warrensburg- Schroon River at Paper Mill Park boat launch	15%	13
Lake Luzerne- Hudson above Lower Sacandaga River confluence	49%	63
Hadley- Lower Sacandaga River at whitewater recreation area	39%	36
Corinth Beach	26%	27
Moreau Lake State Park boat launch	14%	12
Glens Falls- Haviland Cove Beach	18%	28
Moreau informal access point	57%	51
Fort Edward- Bradley Beach kayak launch	62%	81
Fort Edward- Champlain Canal at East Street	26%	25
Moreau- DEC Roger's Island Pool launch site	68%	82
Saratoga- Hudson Crossing Park	41%	45
Greenwich- Batten Kill at informal access point	63%	145

Location	BAV	GM
Schuylerville municipal boat launch	43%	70
Schuylerville- Fish Creek at Schuyler's Canal Park	72%	178
Saratoga informal boat launch	33%	65
Stillwater- Riverfront Park kayak launch	44%	59
Schaghticoke- Lock 4 State Canal Park	59%	118
Schaghticoke- Hoosic River before Hudson confluence	85%	252
Mechanicville municipal canoe and kayak launch	61%	104
Halfmoon- Lighthouse Park kayak launch	43%	65
Schaghticoke municipal boat launch	78%	317
Troy- Hudson above Mohawk River	42%	47
Troy- 123rd Street boat launch	82%	577
Mohawk River		
Sampled monthly 2015-2022. Not sampled May 2020. Mohawk River samples were collected by SUNY Cobleskill and SUNY Poly students and volunteers, and processed by SUNY Cobleskill, SUNY Poly, and Riverkeeper.		
Rome- Delta Lake outlet	5%	14
Rome- Barge Canal at city boat ramp	35%	20
Rome- Bellamy Harbor Park	42%	52
Whitestown- Route 32 Bridge	52%	72
Oriskany- Oriskany Creek tributary	59%	127
Utica- Barge Canal at Historic Utica Marina	27%	30
Utica- Park & Ride fishing access	74%	178
Frankfort- Dyke Road Bridge	75%	299

Location	BAV	GM
Schuyler- Frankfort Harbor	66%	135
Ilion boat launch	63%	136
Herkimer- Gems Along the Mohawk kayak launch	68%	123
Herkimer- I-90 bridge	69%	149
Herkimer- Fishing access at STP	75%	214
Herkimer- West Canada Creek at East German St. Ext	63%	92
German Flatts- Barge Canal at Lock 18	39%	31
Little Falls- Canal Harbor boat launch at Rotary Park	49%	54
Manheim- East Canada Creek at Route 5 Bridge	60%	116
Minden- Barge Canal at Lock 16	25%	13
Fort Plain- Lock 15 kayak launch	56%	91
Canajoharie- DEC boat launch at Route 10	55%	71
Glen- Riverside Drive kayak access	61%	108
Charleston- Schoharie Creek at Burtonsville fishing access	50%	77
Glen- Schoharie Creek at Mohawk Crossing boat launch	47%	54
Florida- Old Erie Lock 28 kayak launch	66%	144
Amsterdam- North Chuctanunda Creek at Forest Ave.	91%	659
Amsterdam- North Chuctanunda Creek at Shuttleworth Park	94%	439
Amsterdam- Public dock at Riverlink Park	64%	127
Florida- Lock 10 boat launch	38%	65

Location	BAV	GM
Glenville- Lock 9 boat launch	44%	58
Rotterdam- Lock 8	33%	33
Schenectady- Union College rowing docks	60%	180
Schenectady- Rivers Casino and Resort	50%	36
Niskayuna- Aqueduct Park rowing docks	48%	40
Niskayuna- Lock 7 boat launch	37%	43
Halfmoon- I-87 crossing	44%	78
Waterford- Flightlocks Road boat launch	44%	47
Cohoes- Kayak launch at New Courtland Street	83%	323
Waterford- Tail Race fishing area	76%	162
Cohoes- Van Schaick Island at Heartt Ave informal access	90%	358
Cohoes- Van Schaick Island at Mohawk-Hudson bike/hike trail	87%	305
Green Island- Silhouette Boathouse	89%	385
Waterford Harbor	85%	530
Catskill Creek		
Sampled monthly 2012-2022. Not sampled May 2020. Mohawk River samples were collected by volunteers and processed by Riverkeeper.		
Middleburgh- The Vlaie fishing & boating access	52%	75
Oak Hill- Brandow Memorial Park boating access	49%	75
South Cairo Bridge	49%	77
Leeds- Fire Department intake	53%	73

Location	BAV	GM
Jefferson Heights- West Main Street	36%	46
Roeliff Jansen Kill		
Sampled monthly 2017-2022. Not sampled May, June 2020. Roeliff Jansen Kill samples were collected by the Roe Jan Watershed Community (https://www.roejanwatershed.org/) and processed by Bard Water Lab.		
Hillsdale- Collins Street Extension	29%	27
Copake- Roeliff Jansen Park stream access	29%	41
Copake- Robinson Pond outlet	18%	21
Copake- Noster Kill tributary at Route 7A	32%	41
Ancram- Wiltsie Road Bridge fishing access	26%	34
Ancram- Hall Hill Road Bridge	24%	30
Gallatin- Gallatin Conservation Area	34%	30
Milan- Academy Hill Road fishing access	26%	30
Clermont/Livingston- Kerley Corners Rd. Bridge	24%	22
Livingston- Below Bingham Mills Dam	8%	14
Germantown- Sportsmen's Club	18%	21
Livingston- RoeJan Creek Boat Club	21%	16
Germantown- Lasher Memorial Park floating docks	10%	9
Germantown- Cheviot Park floating docks	8%	11
Esopus Creek		
Sampled monthly 2012-2022. Not sampled May 2020. Esopus Creek samples were collected by volunteers and processed by Riverkeeper.		
Marbletown-Tongore Park swimming beach	55%	74
Hurley- Wyncoop Rd Bridge Fire Dept intake	59%	105

Location	BAV	GM
Kingston- Washington Avenue Bridge boat launch	43%	70
Lincoln Park- Orlando Park	61%	107
Lake Katrine- Sawkill Creek tributary	74%	171
Lake Katrine- Leggs Mill Bridge	62%	112
Mt Marion- USGS Streamgage	54%	101
Saugerties Village Beach	32%	37
Saugerties- Cantines Island Beach	69%	131
Saw Kill		
Sampled monthly 2016-2022. Saw Kill samples were collected by Saw Kill Watershed Community (https://sawkillwatershed.org/) and processed by Bard Water Lab. Sites Sampled (Data not available at time of analysis): • Milan (T)- Rock City • Red Hook (T)- Near golf club • Red Hook (T)- Route 199 • Red Hook (T)- Turkey Hill Road below SPDES outfall • Red Hook (T)- Lakes Kill tributary at Trees for Tribs site • Rhinebeck (T)- Below old landfill • Red Hook (T)- Near Recreation Park • Red Hook (T)- Below Red Hook Commons • Red Hook (T)- Aspinwall Road near Linden Acres • Red Hook (T)- Below Montgomery Place dam		
Rondout Creek		
Sampled monthly 2012-2022. Not sampled May 2020. Rondout Creek samples were collected by volunteers including the Wawarsing, Rochester, and Marbletown Environmental Conservation Commissions, and processed by Riverkeeper.		
Wawarsing- Below Rondout Res fishing access	20%	25
Napanoch- Route 209	72%	175
Ellenville- Sandburg Creek tributary	85%	259
Ellenville- Beer Kill tributary	77%	238
Wawarsing- Port Ben Road	84%	267

Location	BAV	GM
Wawarsing- Foordemore Road Bridge	86%	244
Kerhonkson- 42nd Street Bridge	84%	227
High Falls- Near D&H Canal	72%	175
Rosendale Trestle	78%	206
Tillson- Wallkill River below Sturgeon Pool	48%	90
Eddyville- Creek Locks fishing access	60%	122
Wallkill River		
Wallkill River samples were collected by volunteers and processed by Riverkeeper.		
Sussex, NJ- Nat'l Wildlife Refuge south end canoe access	95%	675
Unionville- Nat'l Wildlife Refuge boat & fishing	86%	413
Wawayanda- Pellets Island Bridge	98%	950
Goshen- Echo Lake Road	97%	612
Middletown public access boat launch	100%	1007
Montgomery- I-84 Crossing	98%	852
Shawangunk- Orange/Ulster Line fishing access	85%	312
Gardiner- Shawangunk Kill tributary	89%	405
Gardiner- USGS Streamgage	92%	474
New Paltz- Gardens for Nutrition	92%	529
Tillson- Rt 32 Bridge fishing access	78%	319
Tillson- Coutant Rd below Sturgeon Pool	48%	90
Pocantico River		

Location	BAV	GM
Sampled monthly 2012-2022. Not sampled 2020. Pocantico River samples were collected by volunteers and processed by the Sarah Lawrence Center for the Urban River at Beczak (2016-2022) Riverkeeper (2012-2015).		
New Castle- Below Echo Lake	60%	114
Briarcliff Manor- Long Hill Road	84%	364
Briarcliff Manor- Caney Brook tributary	90%	604
Briarcliff Manor- Below Pocantico Lake	76%	262
Sleepy Hollow- Rockefeller Brook tributary	77%	283
Sleepy Hollow- Gory Brook tributary	82%	354
Sleepy Hollow Cemetery	88%	411
Sparkill Creek		
Sampled monthly 2012-2022. Not sampled May, June 2020. Sparkill Creek samples were collected by the Sparkill Creek Watershed Alliance (http://www.sparkillcreek.org/), and processed by Lamont-Doherty Earth Observatory (2019-2022), the Sarah Lawrence Center for the Urban River at Beczak (2015-2018) Riverkeeper (2012-2014).		
Blauvelt- Marsico Court	85%	415
Blauvelt- Clausland Arm	97%	557
Tappan- Route 303	97%	705
Tappan- Moturis	98%	982
Piermont- Skating Pond	99%	1108
Saw Mill River		
Sampled every 2 weeks 2015-2022. Not sampled 2020. Additional sampling at tidal sites available at https://www.nycwatertrail.org/. Saw Mill River samples were collected by volunteers and processed by the Sarah Lawrence Center for the Urban River at Beczak.		
New Castle- Duck Pond spillway	64%	78
New Castle- Tertia Brook tributary	95%	483

Location	BAV	GM
Pleasantville- Pleasantville Road	100%	668
Mount Pleasant- Nannyhagen Brook tributary	94%	460
Mount Pleasant- Saw Mill River Road	97%	439
Elmsford- Above Mine Brook	93%	544
Elmsford- Mine Brook tributary	92%	335
Greenburgh- Rum Brook Park ballfields	97%	507
Greenburgh- Rum Brook tributary	97%	563
Ardsley- V. E. Macy Park ballfields	86%	245
Hastings- South County Trail boat access at Farragut Avenue	96%	292
Yonkers- Hearst Street	92%	259
Yonkers- Torre Place	99%	555
Yonkers- Walsh Road	99%	736
Yonkers- Van Der Donck Park	84%	271
Yonkers Paddling and Rowing Club	49%	52
Yonkers- JFK Marina boat launch	38%	30
Bronx River		
Sampled monthly 2017-2022. Not sampled 2020. Additional sampling at tidal sites available at https://www.nycwatertrail.org/. Bronx River samples were collected by volunteers and processed by the Bronx River Alliance (2017-2022), the Sarah Lawrence Center for the Urban River at Beczak (2017-2021) and Rocking the Boat (2017).		
Mount Pleasant- Highclere Lane	96%	354
Mount Pleasant- S Kensico Ave at Pat Henry Field	98%	810

Location	BAV	GM
White Plains- Westchester County Center	100%	775
Greenburgh- Greenacres Avenue	100%	670
Eastchester- Bronx River Parkway at Leewood Drive	100%	550
Bronxville- Grassy Sprain Brook	100%	951
Bronxville- Below Grassy Sprain Brook confluence	90%	429
Yonkers- Bronx R Pkwy between McLean & Wakefield Aves	97%	507
Bronx- Burke Avenue Bridge	97%	416
Bronx- River Park at 180th Street	96%	273
Starlight Park North dock	96%	405
Hunts Point Riverside Park beach & dock	79%	173
Soundview Park- Mouth of river	78%	234