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Winter Water Quality Responses of the Tarrytown Reservoir to Environmental Changes and Their Downstream Implications

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Abstract

Winter precipitation and snowmelt can alter surface-water chemistry by changing runoff, dilution, and the transport of dissolved ions, sediments, and road salts. However, relatively little is known about how these winter events affect water quality simultaneously within reservoir systems and their downstream waters. Understanding these responses is important for identifying spatial differences in winter water-quality dynamics and improving watershed monitoring and management. This study investigated winter water quality dynamics in the Tarrytown Reservoir in New York State and its downstream waters to evaluate the effects of precipitation events on aquatic conditions. Water samples were collected throughout the winter season before and after precipitation events. Multiple water quality parameters, including pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), total organic carbon (TOC), hardness, total alkalinity, sulfate, nitrate, phosphate, fluoride, and chloride, were analyzed at five sampling locations representing both reservoir and downstream rivers. The results showed that precipitation affected water quality parameters differently. Reservoir sites generally exhibited significant decreases in EC, TDS, hardness, and alkalinity following precipitation. In contrast, the downstream Saw Mill River site exhibited significant increases in EC, TDS, TOC, and NaCl. Turbidity, sulfate, phosphate, nitrate, and fluoride showed relatively limited responses to precipitation events. Principal component analysis (PCA) revealed substantial overlap between pre- and post-precipitation samples but showed greater variability among post-precipitation observations. Overall, winter precipitation influenced dissolved constituents more strongly than suspended solids and nutrient-related parameters. In addition, reservoir and downstream sites exhibited different responses to precipitation events, highlighting the importance of considering both temporal and spatial variability when evaluating winter water quality dynamics and watershed management strategies.

Keywords: Winter water quality; Tarrytown Reservoir; Precipitation; Downstream water quality; Principal component analysis

1. Introduction

The Tarrytown Reservoir is a connected reservoir system in Tarrytown, New York, with downstream waters ultimately connected to the Saw Mill River and Hudson River. The surrounding watershed includes developed areas and road networks where winter rainfall, snowfall, snowmelt, and associated runoff may transport dissolved ions, sediments, and deicing salts into nearby surface waters. Because the system includes both reservoir and downstream river environments, it provides an opportunity to examine whether winter precipitation produces different water-quality responses across connected aquatic environments. Water-quality monitoring is important because reservoirs and other surface waters support human use, aquatic ecosystems, and broader watershed functions (Vasistha & Ganguly, 2020). Surface waters such as lakes, rivers, and reservoirs provide freshwater resources for many communities, while also supporting aquatic organisms that play essential roles in ecosystem functioning. Primary producers, including algae and aquatic microorganisms, form the foundation of aquatic food webs and contribute

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substantially to global oxygen production through photosynthesis (Beesley et al., 2020). Consequently, maintaining clean water quality is critical for both human and environmental health.

Water quality varies throughout the year due to seasonal changes in temperature and precipitation (Alkhadher et al., 2025). Temperature influences many physical and chemical properties of water, affecting chemical reactions, biological activity, and the behavior of dissolved constituents within aquatic systems (Ducharne, 2008; Christmas & Bassingthwaighte, 2017). Precipitation also plays a critical role in water quality by transporting sediments, nutrients, salts, and other materials from surrounding watersheds into rivers, lakes, and reservoirs, thereby altering water chemistry and overall water quality conditions (Rostami et al., 2018; Alkhadher et al., 2025).

Winter is particularly important for water quality because snowfall, snowmelt, and road salt application can substantially influence aquatic systems (Spencer et al., 2021; Jansen et al., 2025; Pascotto, 2020). Snowmelt increases runoff and streamflow, facilitating the transport of dissolved materials and sediments from surrounding watersheds into receiving waters (Spencer et al., 2021). At the same time, road salt applied for deicing can enter nearby water bodies through runoff, increasing chloride concentrations and conductivity while altering water chemistry (Pascotto, 2020; Corsi et al., 2010). Elevated chloride concentrations can adversely affect freshwater organisms and degrade water quality, making road-salt runoff an important consideration in winter watershed management (Corsi et al., 2010).

Reservoirs are managed water bodies that provide flood control, water supply, hydropower generation, and other essential services (Mácová & Kozáková, 2023). Because reservoirs regulate water movement throughout watersheds, changes in water quality within reservoirs may also influence downstream aquatic environments. As climate change and population growth place increasing pressure on water resources, understanding seasonal water quality dynamics in reservoirs has become increasingly important for effective water resource management (Nay Myo Lin & Rutten, 2016).

Although numerous studies have investigated seasonal water quality variation, relatively few studies have examined how winter precipitation events influence water quality in both reservoir systems and their downstream waters. Understanding these responses is important because winter environmental conditions can alter water chemistry through dilution, runoff, and the transport of dissolved materials. Monitoring water quality before and after precipitation events can therefore provide valuable information regarding the effects of winter environmental changes on aquatic systems.

In this study, winter water quality in the Tarrytown Reservoir and its downstream waters was investigated to evaluate how seasonal environmental events influence aquatic conditions. Water samples were collected throughout the winter season, including periods before and after precipitation events such as snowfall and rainfall. Multiple water quality parameters, including pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), total organic carbon (TOC), alkalinity, hardness, and major ions, were analyzed to assess temporal changes associated with precipitation and to compare water quality patterns between the reservoir and downstream sites. By examining both seasonal variation and spatial differences among sampling locations, this study aims to improve understanding of winter water quality dynamics within the reservoir system and its downstream waters and to provide information that may support future watershed and water resource management strategies.

2. Materials and methods

2.1 Sampling sites

The Tarrytown Reservoir, located in Tarrytown, New York, consists of two connected water bodies: the South Reservoir and the North Reservoir. Water within the system generally flows from the South Reservoir to the North Reservoir before exiting the reservoir system and continuing through downstream waterways toward the Saw Mill River and ultimately the Hudson River. To evaluate both spatial variation and downstream changes in water quality, five sampling sites were established along this flow path (Figure 1).

Site 2 was located near the downstream end of the South Reservoir. Site 3 was established near the upper region of the North Reservoir, immediately downstream of the South Reservoir. Site 4 was located near the outlet of the reservoir system, representing the final reservoir sampling location prior to downstream transport. Site 5 was

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established in the Saw Mill River downstream of the reservoir system, while Site 1 was located in the Hudson River.

2.2 Sample collection and Measurements

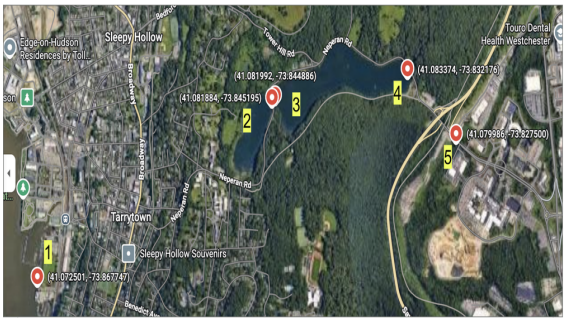


Figure 1. The map of the Tarrytown Reservoir, including locations of the sampling sites.

Water samples were collected from all five sampling sites during 10 sampling events between December 31, 2025, and March 24, 2026. Sampling was conducted on December 31, 2025; January 4, January 11, January 19, February 14, February 22, March 4, March 15, March 21, and March 24, 2026. Samples were collected at approximately 12:00 PM on each sampling date. Pre-precipitation samples were collected before winter precipitation events. Post-precipitation samples were generally collected approximately one day after precipitation events based on available field records; however, exact hour-level intervals could not be consistently reconstructed for all events. Based on this classification, December 31, January 4, February 14, March 15, and March 21 were categorized as pre-precipitation sampling events, whereas January 11, January 19, February 22, March 4, and March 24 were categorized as post-precipitation sampling events.

Detailed quantitative records of precipitation amount, snowfall accumulation, and snowmelt conditions were not available for the individual sampling events. In addition, records of road-salt application within the study area were not available. Therefore, road salt was treated as a possible but unmeasured factor when interpreting changes in conductivity, dissolved solids, and chloride-related measurements. At each sampling event, water samples were collected from the surface water at each site using clean sampling containers. To improve measurement reliability, three replicate samples were collected from each site during every sampling event. All samples were analyzed for water quality parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, total organic carbon (TOC), total alkalinity, hardness, chloride, sulfate, nitrate, phosphate, and fluoride concentrations. Sampling was conducted repeatedly throughout the winter season.

Turbidity was quantified using optical density measurements at 860 nm (OD860), a commonly used method for assessing water clarity and suspended particulate matter (APHA, 2017). Water samples were transferred into clean cuvettes, and absorbance was measured at 860 nm using a spectrophotometer. The pH meter (VIVOSUN, Ontario, CA, USA) were used to determine pH. A DANOPLUS KIB0408 6-in-1 water quality tester (DANOPLUS, Hong Kong) was used to obtain readings for total organic carbon (TOC), chemical oxygen demand (COD), electrical conductivity (EC), UV275, total dissolved solids (TDS), and temperature. The instrument was calibrated using distilled water according to the manufacturer's instructions prior to measurement. TOC values reported in this study were the instrument-reported TOC readings. Because detailed information regarding the instrument's internal TOC estimation algorithm and TOC-specific calibration procedure is not provided by the manufacturer, these TOC measurements were interpreted as screening-level estimates rather than reference-method TOC measurements. The sensor of the device was fully submerged in the designated water sample. This procedure was repeated three times for each sample. The water sample was gently shaken prior to each measurement to ensure homogeneity. The average of the three readings was calculated to obtain an accurate and reliable result. Ion chromatography was used to determine the concentrations of chloride, phosphate, nitrate, sulfate, and fluoride in the water samples (Metrohm AG, Herisau, Switzerland).

The Water Test Strips (Varify, San Diego, CA, USA) was used to determine the Hardness and Total Alkalinity. Each test strip was fully submerged in the water sample, and then removed and allowed to react for 30 seconds. The resulting color changes on the strip were visually compared to the reference color chart provided. The process is repeated three times.

2.3 Statistical analysis

All statistical analyses were performed using R software (version 4.5.1; R Foundation for Statistical Computing,

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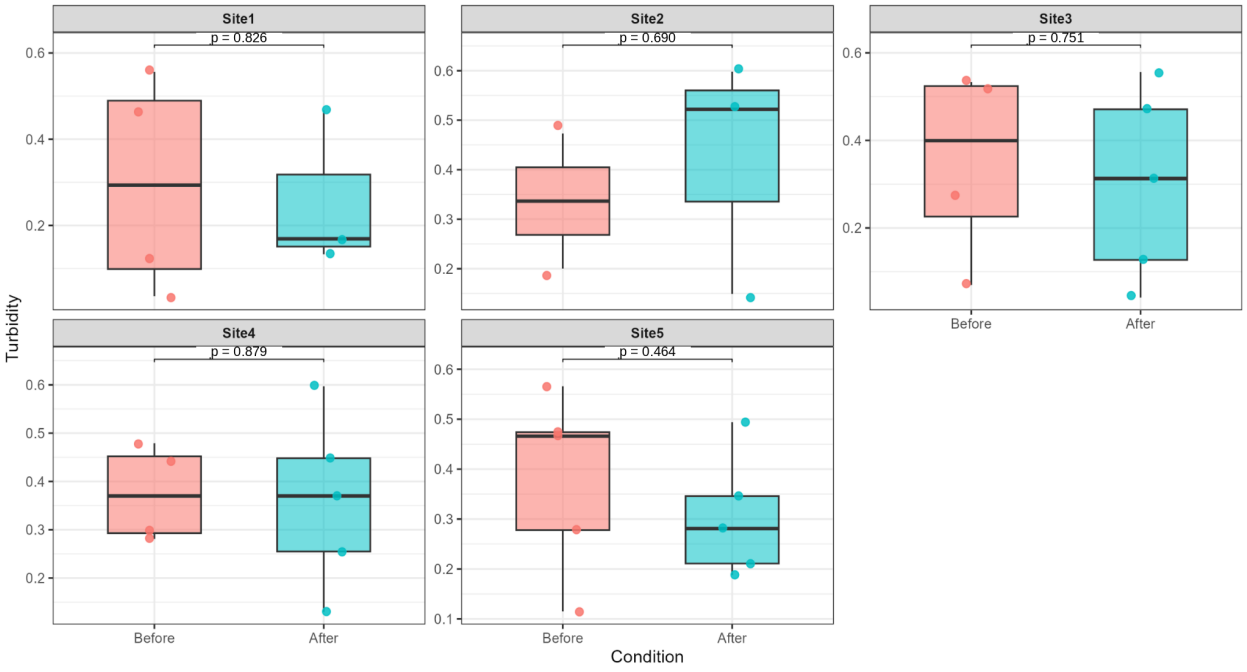
Vienna, Austria). Water quality data were grouped according to sampling site and precipitation condition (pre- and post-precipitation). Because only two conditions were compared at each sampling site, Welch's two-sample t-test was used to evaluate differences between pre- and post-precipitation conditions. Welch's t-test was selected because it does not require the assumption of equal variances between the two groups. A significance level of $p < 0.05$ was applied for all statistical tests.

Descriptive statistics, including median values and data distributions, were visualized using boxplots with individual data points overlaid. Principal Component Analysis (PCA) was performed to examine overall patterns of variation in water quality and to identify the parameters contributing most strongly to differences among samples. Samples were grouped according to environmental conditions (before precipitation and after precipitation) to evaluate multivariate responses to winter environmental events.

3. Results

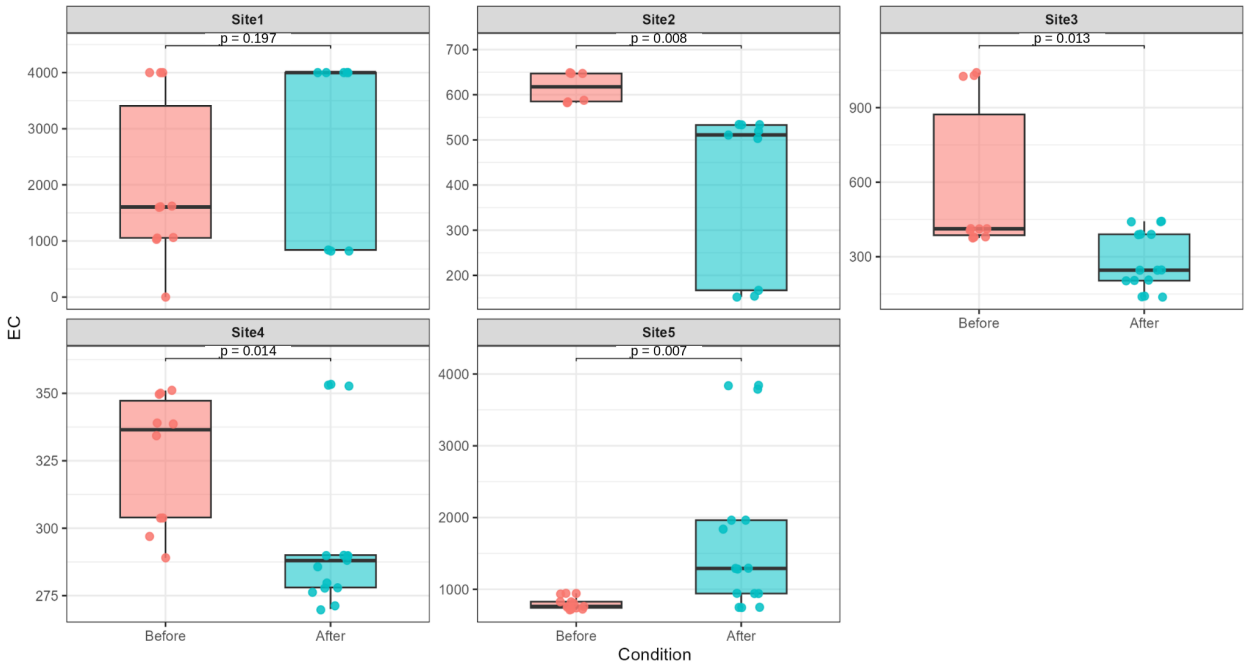
3.1 Physical Water Quality Parameters

Turbidity, electrical conductivity (EC), and pH showed different responses to precipitation across the five sampling locations (Figure 2). Turbidity remained relatively stable at all sites, with no statistically significant differences between pre- and post-precipitation conditions (Site 1: $p = 0.826$; Site 2: $p = 0.690$; Site 3: $p = 0.751$; Site 4: $p = 0.879$; Site 5: $p = 0.464$) (Figure 2A). In contrast, EC showed clear spatial differences in response to precipitation (Figure 2B). Significant decreases were observed at all reservoir sites (Site 2: $p = 0.008$; Site 3: $p = 0.013$; Site 4: $p = 0.014$), whereas EC increased at the downstream sites. The increase was significant at Site 5 ($p = 0.007$) but not at Site 1 ($p = 0.197$). pH responses were more variable among locations (Figure 2C). Site 2 showed a significant decrease following precipitation ($p < 0.001$), whereas the increase observed at Site 4 was not statistically significant ($p = 0.051$). No significant differences were observed at Site 3 ($p = 0.123$), Site 5 ($p = 0.092$), or Site 1 ($p = 0.151$). Overall, precipitation had little effect on turbidity, produced more pronounced and spatially contrasting changes in EC, and resulted in site-specific but generally limited changes in pH.

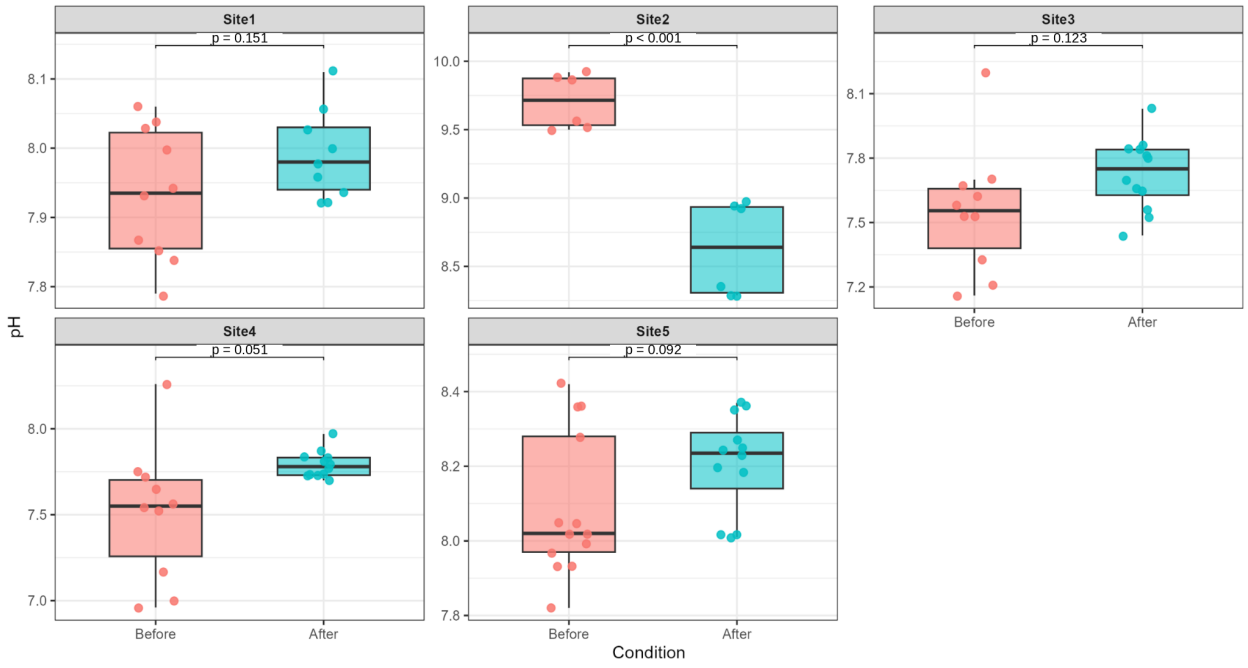


(A)

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(B)



(C)

Figure 2. Physical water quality parameters before and after precipitation events at five sampling locations within the Tarrytown Reservoir system and downstream waters. (A) Turbidity (OD860); (B) Electrical conductivity (EC, us/cm); (C) pH

3.2. Chemical Water Quality Parameters

Hardness

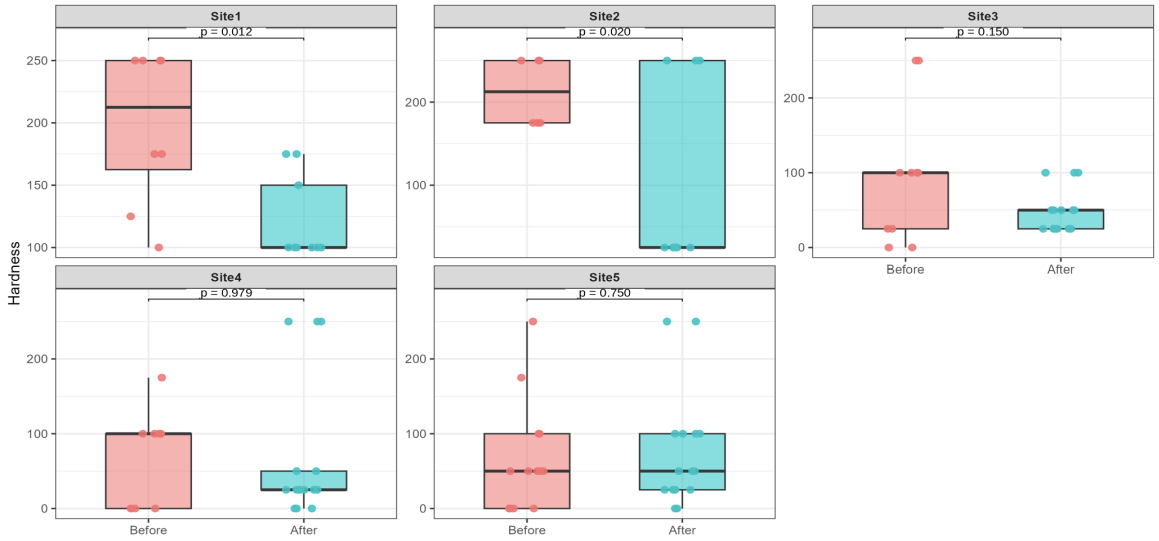
Changes in hardness varied among sampling locations following precipitation events (Figure 3A). Within the reservoir system, hardness decreased at all three sites; however, only Site 2 exhibited a statistically significant reduction ($p = 0.020$), while Sites 3 and 4 did not ($p = 0.150$ and $p = 0.979$, respectively). At downstream locations,

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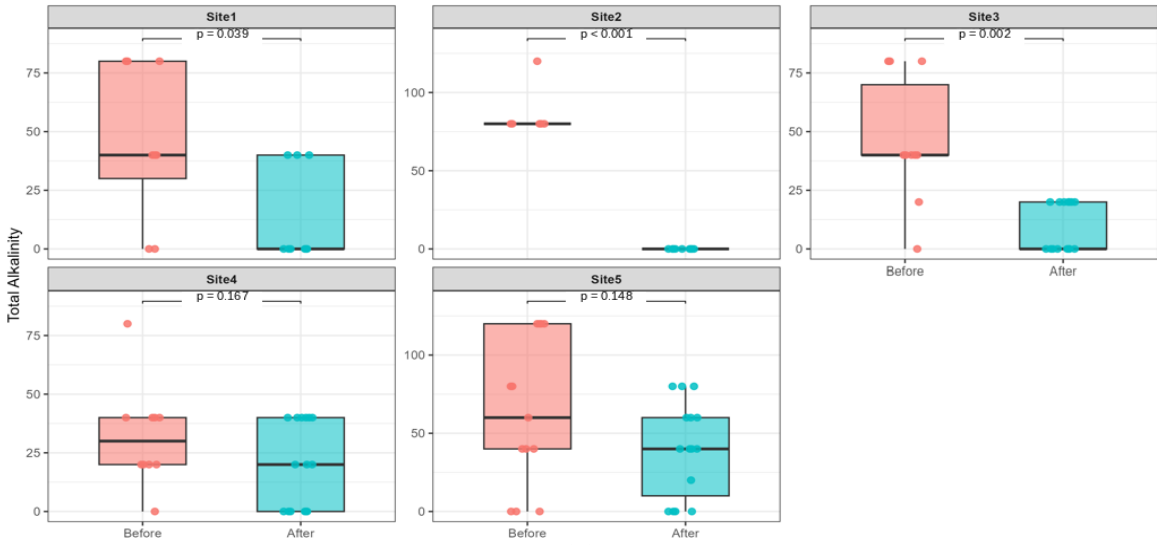
Site 1 showed a significant decrease following precipitation ($p = 0.012$), whereas Site 5 exhibited little difference between conditions ($p = 0.750$). Hardness values after precipitation were generally lower than pre-precipitation values at most sites.

Total Alkalinity

Total alkalinity decreased following precipitation at several sampling locations (Figure 3B). Within the reservoir system, significant decreases were observed at Sites 2 and 3 ($p < 0.001$ and $p = 0.002$, respectively), while Site 4 showed a smaller, non-significant decrease ($p = 0.167$). Among downstream locations, Site 1 exhibited a significant decrease in alkalinity ($p = 0.039$), whereas Site 5 showed no statistically significant change ($p = 0.148$). Lower alkalinity values following precipitation were observed throughout much of the sites.

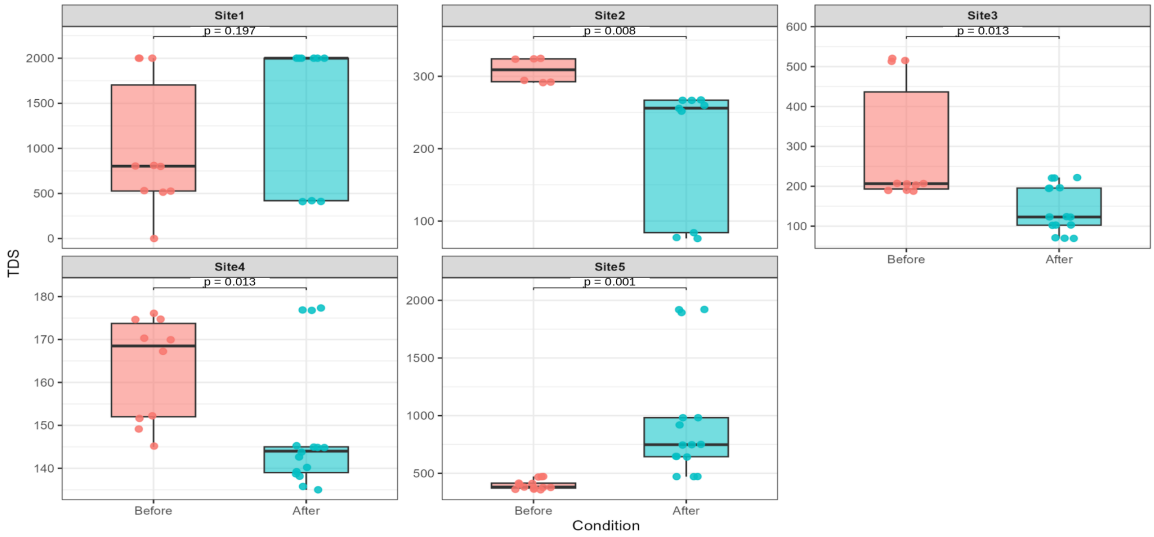


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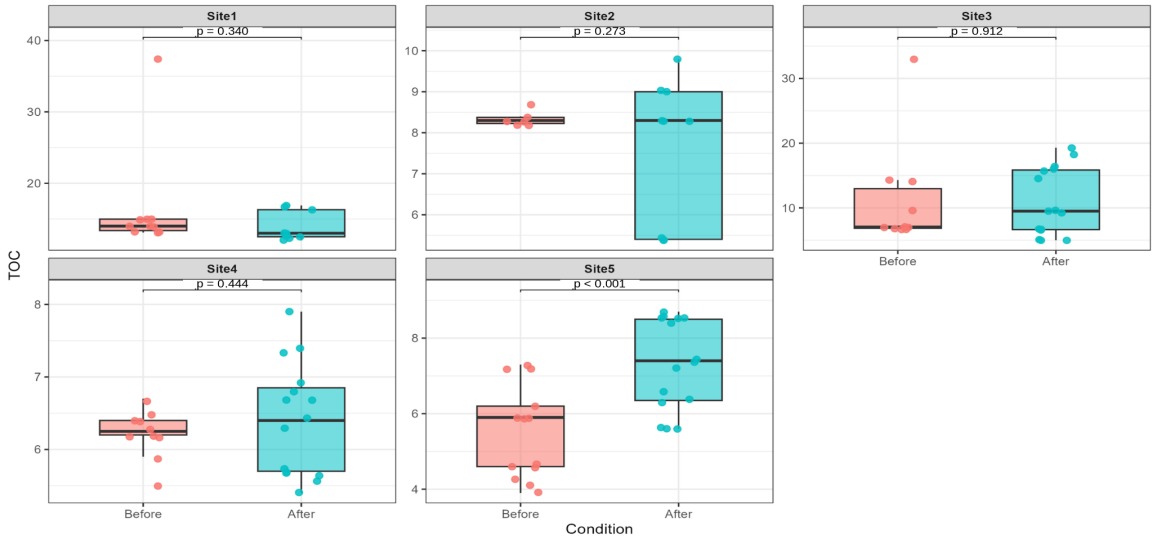


(B)

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(C)



(D)

Figure 3. General chemical water quality parameters before and after precipitation events at five sampling locations within the Tarrytown Reservoir system and downstream waters. (A) hardness; (B) total alkalinity; (C) total dissolved solids (TDS); and (D) total organic carbon (TOC).

Total Dissolved Solids

TDS exhibited a pattern similar to that observed for EC (Figure 3C). Significant decreases in TDS were observed at all reservoir sites following precipitation (Site 2: $p = 0.008$; Site 3: $p = 0.013$; Site 4: $p = 0.013$). At downstream locations, Site 5 exhibited a significant increase in TDS following precipitation ($p = 0.001$), whereas Site 1 showed a non-significant increase ($p = 0.197$). Reservoir sites therefore exhibited lower TDS values after precipitation, while Site 5 exhibited higher values.

Total Organic Carbon

Most sampling locations exhibited relatively small changes in TOC following precipitation events (Figure 3D). Within the reservoir system, Sites 3 and 4 showed slight increases in TOC, whereas Site 2 showed a slight decrease. None of these changes were statistically significant (Site 2: $p = 0.273$; Site 3: $p = 0.912$; Site 4: $p = 0.444$). Unlike the reservoir sites, Site 5 exhibited a significant increase in TOC following precipitation ($p < 0.001$). Site 1 showed a slight decrease, although the difference was not statistically significant ($p = 0.340$).

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3.3 Ion or nutrient-related parameters

Chloride

Chloride concentrations increased at selected sampling locations following precipitation events (Figure 4A). Within the reservoir system, Site 2 exhibited a significant increase in chloride concentration ($p = 0.004$), whereas Sites 3 and 4 showed no statistically significant changes ($p = 0.627$ and $p = 0.726$, respectively). At downstream locations, Site 5 also showed a significant increase following precipitation ($p = 0.009$), while Site 1 exhibited a non-significant increase ($p = 0.380$). The largest changes in chloride concentration were observed at Sites 2 and 5.

Sulfate

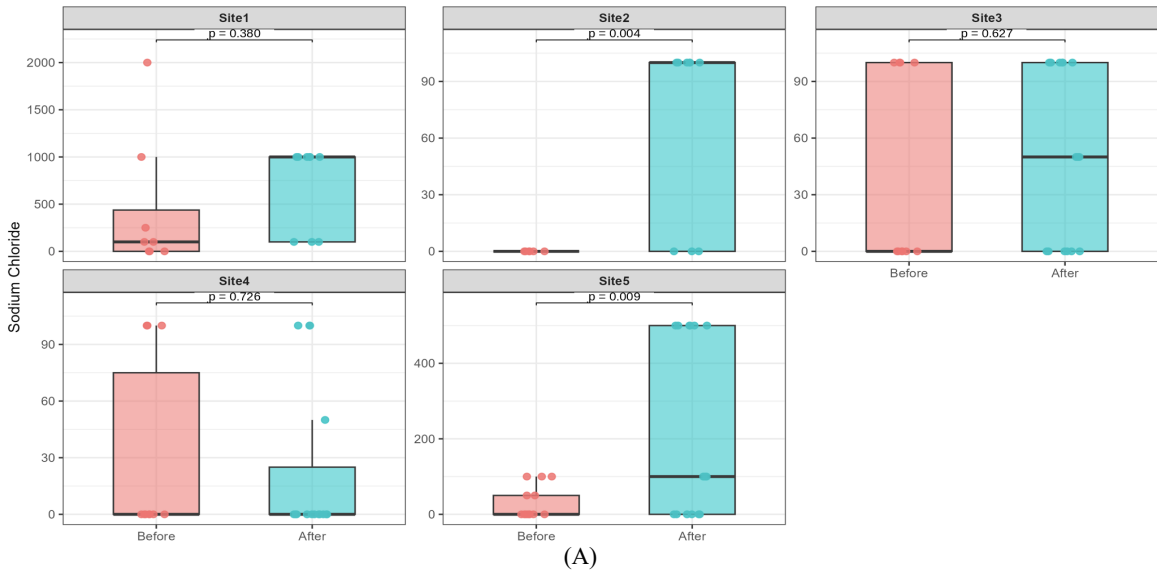
Sulfate concentrations remained relatively consistent before and after precipitation events across the study area (Figure 4B). Within the reservoir system, sulfate concentrations showed only minor fluctuations, and none of the observed differences were statistically significant (Site 2: $p = 0.211$; Site 3: $p = 0.990$; Site 4: $p = 0.683$). Similarly, downstream sites exhibited little change following precipitation (Site 5: $p = 0.581$; Site 1: $p = 0.082$). Sulfate concentrations remained within comparable ranges across all sampling sites.

Nitrate

Nitrate concentrations remained relatively stable throughout the sites following precipitation events (Figure 4C). Within the reservoir system, nitrate concentrations decreased slightly at all three sites; however, none of the observed changes were statistically significant (Site 2: $p = 0.081$; Site 3: $p = 0.083$; Site 4: $p = 0.085$). At downstream locations, Site 1 exhibited a significant decrease in nitrate concentration following precipitation ($p = 0.048$), whereas Site 5 showed no statistically significant difference ($p = 0.082$).

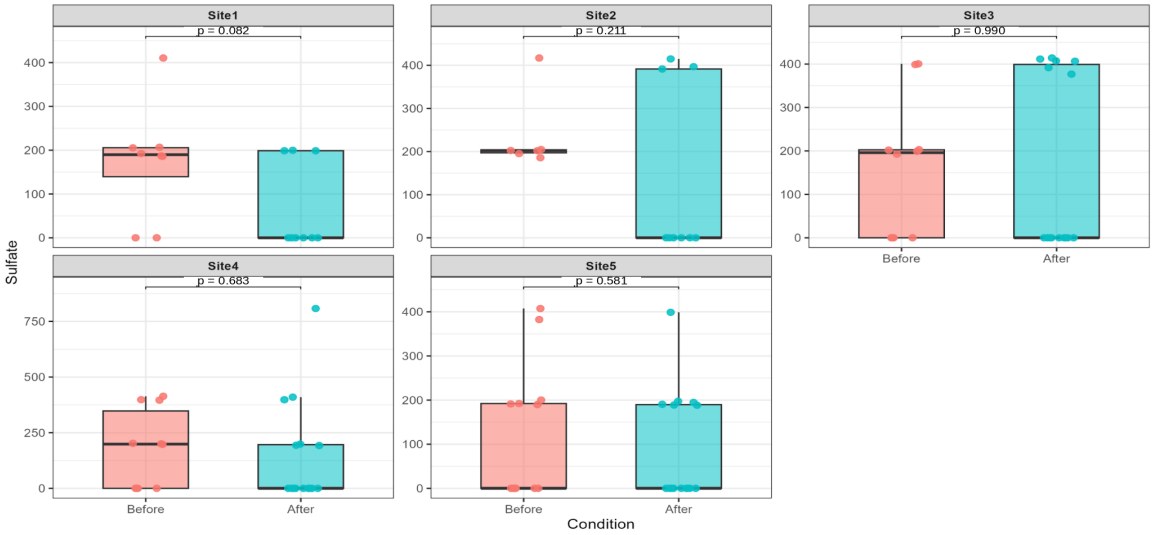
Phosphate

Phosphate concentrations showed minimal variation before and after precipitation events (Figure 4D). Within the reservoir system, Sites 2–4 exhibited slight increases in phosphate concentrations, although none of the changes were statistically significant (Site 2: $p = 0.061$; Site 3: $p = 0.333$; Site 4: $p = 0.412$). Downstream sites showed similarly small changes. Site 1 exhibited a slight decrease, while Site 5 remained nearly unchanged. Neither site showed a statistically significant difference following precipitation (Site 1: $p = 0.169$; Site 5: $p = 0.993$).

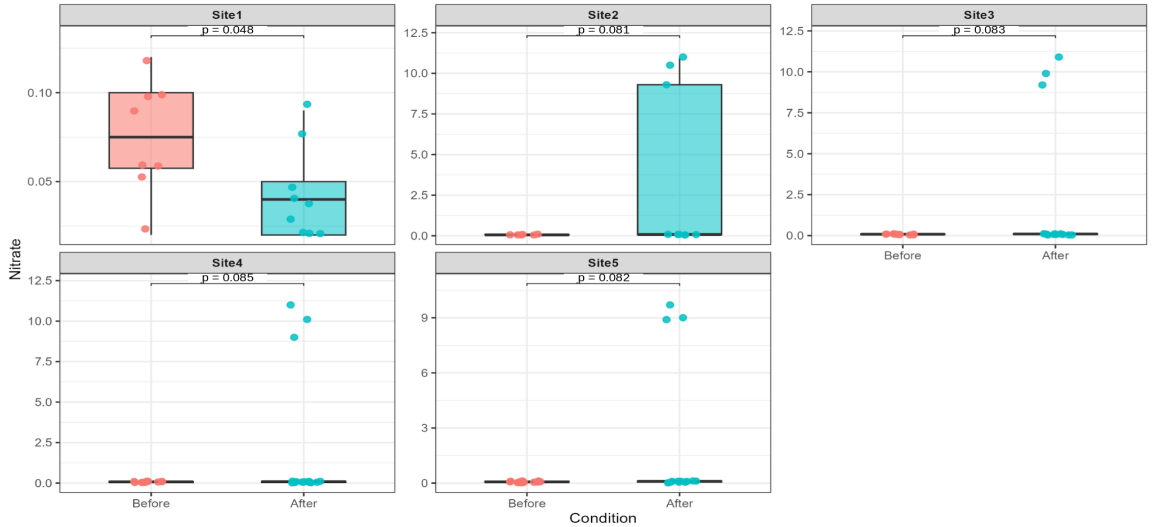


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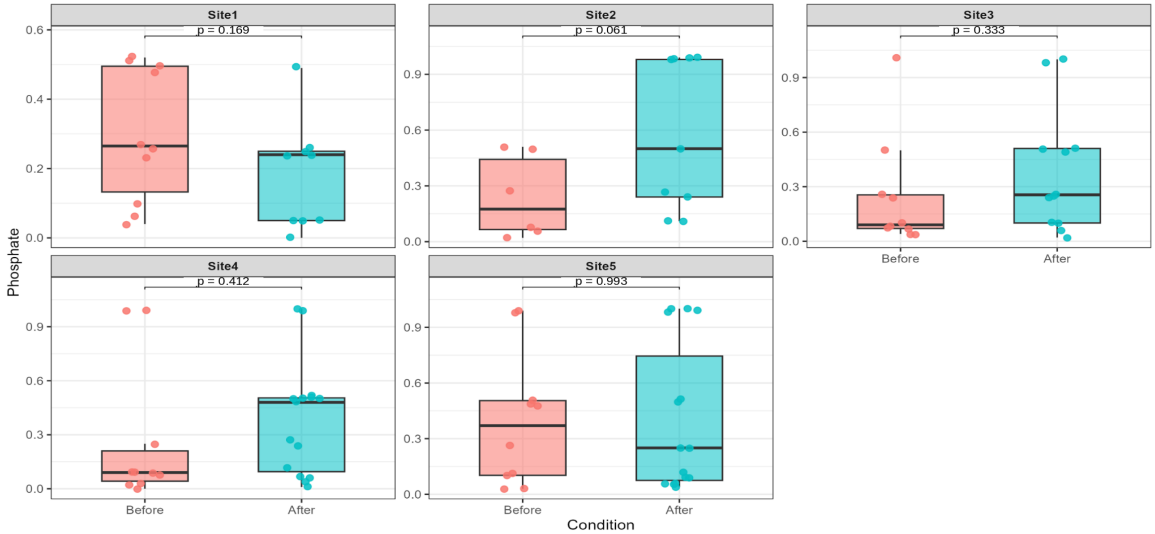
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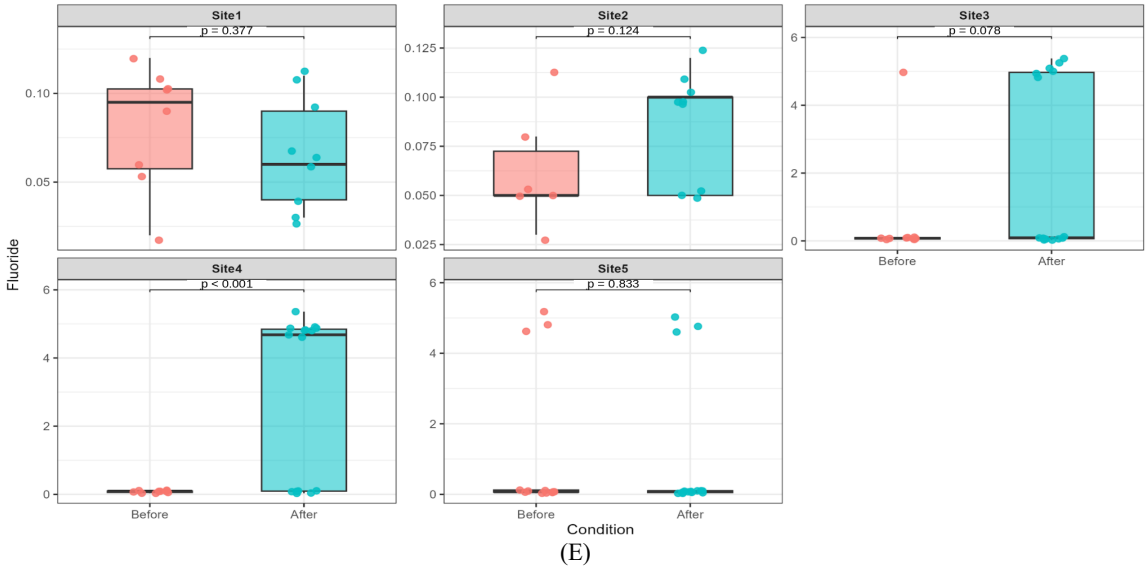


(C)



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(E)

Figure 4. Ion- and nutrient-related water quality parameters before and after precipitation events at five sampling locations within the Tarrytown Reservoir system and downstream waters. (A) chloride; (B) sulfate; (C) nitrate; (D) phosphate; and (E) fluoride.

Fluoride

Fluoride concentrations remained relatively consistent across most sampling sites (Figure 4E). Within the reservoir system, Site 4 exhibited a significant increase in fluoride concentration following precipitation ($p < 0.001$), whereas Sites 2 and 3 showed no statistically significant changes ($p = 0.124$ and $p = 0.078$, respectively). At downstream locations, fluoride concentrations remained relatively stable before and after precipitation events at both Site 5 ($p = 0.833$) and Site 1 ($p = 0.377$). Significant changes in fluoride concentration were therefore limited to a single reservoir site.

3.4 Principal Component Analysis

Principal component analysis (PCA) was conducted to summarize overall variation in water quality before and after precipitation events (Figure 5). The first two principal components explained 45.1% of the total variation, with Dim1 accounting for 25.8% and Dim2 accounting for 19.3%. Before- and after-precipitation samples showed substantial overlap. However, the after-precipitation ellipse was larger than the before-precipitation ellipse, showing greater spread among post-precipitation samples.

The loading vectors represent the direction and strength of the association between each water quality parameter and the principal components. Variables with arrows pointing in similar directions were positively associated, whereas variables pointing in opposite directions showed contrasting associations. Longer loading vectors indicate stronger associations with the

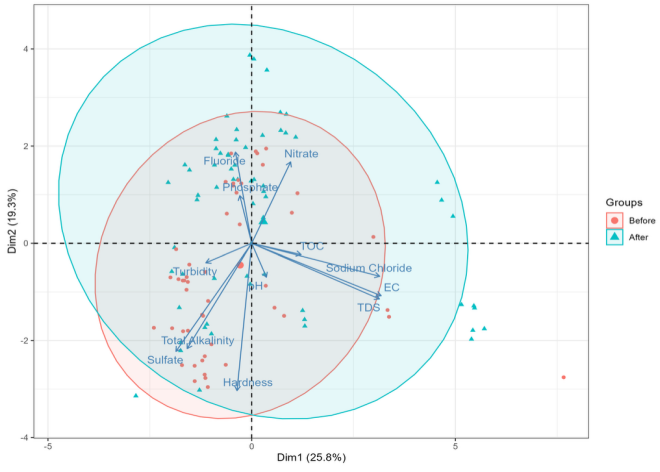


Figure 5. Principal component analysis (PCA) of water quality parameters measured before and after precipitation events. Red circles represent pre-precipitation samples, blue triangles represent post-precipitation samples, and arrows represent loading vectors of the measured water quality parameters. The direction of each vector indicates its association with the principal components, while longer vectors indicate stronger associations with the principal components displayed in the biplot.

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principal components displayed in the biplot and better representation of those variables in the two-dimensional PCA space. EC, TDS, chloride, and TOC pointed in a similar direction along positive Dim1, whereas sulfate, total alkalinity, turbidity, and hardness were positioned toward negative Dim1 and negative Dim2. Fluoride, phosphate, and nitrate were positioned toward positive Dim2.

Among the measured parameters, EC, TDS, chloride, sulfate, total alkalinity, and hardness had relatively long loading vectors, indicating that these variables were more strongly associated with the principal components shown in the biplot.

4. Discussion

4.1 Contrasting Responses Between Reservoir and Downstream Sites

One of the most notable findings of this study was the differing response of reservoir and downstream sites to winter precipitation events. Electrical conductivity (EC) and total dissolved solids (TDS) decreased significantly at all reservoir sites (Sites 2–4) following precipitation, whereas Site 5 (Saw Mill River) exhibited significant increases in both parameters. Similar decreases in EC and TDS have been reported in freshwater systems following rainfall and snowmelt because additional water inputs dilute dissolved ions within the water column (Huang et al., 2020). In contrast, increases in EC and TDS have been observed when runoff transports dissolved ions and inorganic materials into rivers and streams (Hamid et al., 2020).

The Hudson River site (Site 1) exhibited relatively small changes in EC and TDS despite precipitation events. Compared with the reservoir and Saw Mill River sites, the Hudson River is substantially larger and experiences greater mixing, which may reduce the influence of short-term precipitation events. These results demonstrate that winter precipitation did not affect all parts of the watershed equally and that responses differed between reservoir and downstream environments.

4.2 Effects of Precipitation on Dissolved Chemicals

Hardness and total alkalinity generally decreased following precipitation events. Significant reductions in hardness were observed at Sites 1 and 2, and total alkalinity decreased significantly at Sites 1, 2, and 3. Similar reductions have been reported following precipitation because rainfall and snowmelt dilute dissolved minerals and buffering ions within surface waters (Peters, 1984).

The similar behavior of hardness and alkalinity suggests that both parameters responded to changes in dissolved mineral concentrations following precipitation. Reservoir sites generally exhibited greater reductions than downstream locations, indicating that winter precipitation had a stronger influence on dissolved minerals within the reservoir system. These findings are also consistent with the decreases observed in EC and TDS, which similarly reflect changes in dissolved constituents.

4.3 Chloride and Organic Carbon Responses to Winter Runoff

Chloride concentrations increased significantly at Sites 2 and 5 following precipitation. During winter months, road salt is commonly applied to roads and parking areas and may be transported into nearby water bodies through rainfall and snowmelt runoff (Pascotto, 2020). The significant increases observed at Sites 2 and 5 are consistent with this process. In contrast, Site 4 showed little change in chloride concentration, indicating that precipitation effects on chloride were not uniform across sampling locations.

Total organic carbon (TOC) exhibited relatively small changes throughout most of the sampling sites. However, Site 5 showed a significant increase in TOC following precipitation. Organic matter transported from surrounding vegetation during runoff events has been reported as an important source of TOC in surface waters (Gulis & Suberkropp, 2003; Vidon et al., 2012). The increase observed at Site 5 may therefore be associated with greater transport of organic material into the Saw Mill River during precipitation events.

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4.4 Water Quality Parameters Showing Limited Responses to Precipitation

Several water quality parameters exhibited relatively limited responses to precipitation events. Turbidity showed no statistically significant changes at any sampling location despite precipitation. Previous studies have reported that precipitation can both increase turbidity through sediment transport and decrease turbidity through dilution, depending on local watershed conditions (Mishra et al., 2024). The absence of significant changes in turbidity suggests that these processes may have balanced one another during the study period.

Similarly, sulfate and phosphate concentrations remained relatively stable before and after precipitation events. Although runoff can introduce sulfate- and phosphorus-containing materials into aquatic systems, dilution processes may reduce their concentrations, resulting in relatively small net changes. Nitrate concentrations also exhibited limited responses to precipitation, with a significant decrease observed only at Site 1. Fluoride concentrations remained relatively stable throughout the sampling sites except for Site 4, where a significant increase was observed following precipitation. The reason for this site-specific increase remains unclear. Local differences in runoff pathways or other unmeasured site-specific environmental factors may have contributed to the observed change; however, these factors were not directly evaluated in this study.

pH responses also varied among sampling locations. Site 2 exhibited a significant decrease in pH following precipitation, whereas Site 4 showed an increase that was not statistically significant under Welch's two-sample t-test ($p = 0.051$). Other sites showed only minor changes. These results suggest that local site characteristics may influence pH responses to precipitation events, although no consistent watershed-wide pattern was observed.

4.5 Overall Patterns in Water Quality Variation

The PCA results supported the patterns observed in the individual parameter analyses. Although samples collected before and after precipitation showed substantial overlap, post-precipitation samples occupied a broader area within the ordination space, indicating greater variability following precipitation events. Parameters including EC, TDS, chloride, hardness, sulfate, and total alkalinity exhibited relatively strong contributions to overall variation within the dataset. However, while EC, TDS, hardness, total alkalinity, and chloride showed notable responses to precipitation, sulfate concentrations remained relatively stable, suggesting that sulfate contributed primarily to spatial variation among sampling locations rather than precipitation-driven temporal variation.

Overall, winter precipitation influenced dissolved ionic constituents more strongly than suspended solids or nutrient-related parameters. Parameters associated with dissolved minerals and ions, including EC, TDS, hardness, total alkalinity, and chloride, exhibited the most pronounced responses to precipitation events. Furthermore, reservoir and downstream sites responded differently to winter environmental events, demonstrating the importance of considering spatial location when evaluating winter water quality dynamics within reservoir watersheds.

5. Conclusions and limitations

This study examined the effects of winter precipitation events on water quality in the Tarrytown Reservoir and its downstream waters. Among the measured parameters, EC, TDS, hardness, total alkalinity, chloride, and TOC showed the strongest responses to precipitation, whereas turbidity, sulfate, phosphate, nitrate, and fluoride exhibited relatively minor changes. Reservoir sites generally showed decreases in dissolved constituents following precipitation, while downstream sites exhibited different responses, particularly at the Saw Mill River site. Overall, the results demonstrate that winter precipitation influences water quality differently across locations and water quality parameters, highlighting the importance of considering both temporal and spatial variation in watershed monitoring and management.

This study was conducted during a single winter season and included a limited number of sampling sites. In addition, factors such as runoff volume, land use, road salt application, and pollutant loading were not directly measured. Future studies should include longer monitoring periods, additional sampling locations, and hydrological measurements to better understand the mechanisms driving winter water quality changes in reservoir and downstream systems.

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