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A Nearly Decade-Long Assessment of Urban Stream Physicochemical Responses to a Regional-Scale Wastewater Infrastructure Renovation

Carly R. Finegan[1,2] | Elizabeth A. Hasenmueller[1,2]

[1]Department of Earth, Environmental, and Geospatial Science, Saint Louis University, St. Louis, Missouri, USA | [2]WATER Institute, Saint Louis University, St. Louis, Missouri, USA

Correspondence: Elizabeth A. Hasenmueller (elizabeth.hasenmueller@slu.edu)

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ABSTRACT

As populations shift towards urban areas and precipitation patterns alter with climate change, the demands on ageing sewer infrastructure increase. These strains have led to more frequent occurrences of sewer overflows and leaks that adversely impact water resources. To address water quality challenges, ecosystem degradation, and human health risks associated with outdated wastewater infrastructure, cities worldwide are modernising their wastewater systems (e.g., removing sewer overflows and installing sanitary tunnel systems). However, critical information regarding the immediate and long-term impacts of these regional-scale infrastructure projects on urban waterbodies remains limited. Our study therefore evaluated changes in water quality and wastewater tracers in response to a regional-scale sewer renovation project in St. Louis, Missouri, United States. The project was designed to reduce untreated wastewater inputs to stream systems through the removal of sewer overflow sites and the construction of a sanitary tunnel. To accomplish our study objectives, we collected weekly physicochemical data from an urban stream within the renovation project area over an 8.7-year period (i.e., from 2 September 2016 to 1 May 2025), encompassing 2.5 years before, 3.4 years during, and 2.8 years after the infrastructure updates. Our results demonstrated that the sewer infrastructure renovation effort successfully reduced the amount of untreated wastewater in the stream as evidenced by significant decreases in the average values for wastewater tracers like optical brighteners (15%) and potassium (K) (13%), along with a significant 26% increase in average dissolved oxygen (O_2) saturation from pre-construction to post-construction conditions. While the sanitary tunnel project effectively reduced untreated wastewater contributions to the urban stream, it also had immediate impacts on certain stream physicochemical variables during the construction phase of the renovation, including increases in turbidity and major element (e.g., calcium [Ca], magnesium [Mg], strontium [Sr], and silicon [Si]) concentrations. Our findings highlight the importance of designing major wastewater infrastructure projects that protect surface waterbodies from the immediate impacts of construction while still addressing pervasive and long-term water quality concerns.

1 | Introduction

Water-related infrastructure in urban areas has become increasingly strained due to expanding populations, changing precipitation amounts, and ageing systems. Untreated wastewater from deteriorating sewer networks can enter surface waters through pipe failures or constructed sewer overflows, degrading water quality by introducing pathogenic bacteria, nutrients, toxic metals, and contaminants of emerging concern (Cheung et al. 1990; Petelet-Giraud et al. 2009; Dickenson et al. 2011; McCance et al. 2018; Fennell et al. 2021). To address the challenges associated with sewers overflowing into surface water systems, cities worldwide are actively updating their wastewater infrastructure (Table 1).

A common approach to modernising outdated wastewater infrastructure is the construction of sanitary tunnels that serve as underground reservoirs, temporarily storing wastewater that would otherwise discharge from sewer overflow sites. The excess sewage stored in such tunnels is eventually pumped to treatment facilities at manageable rates (Ab Razak and Christensen 2001). These sanitary tunnel projects aim to protect drinking water supplies, mitigate water quality issues affecting surface waters, and reduce urban flooding (Day 2004; Pluth et al. 2021; Miller et al. 2022), but they are often expensive. For example, the Washington, District of Columbia, Potomac River Tunnel Project in the United States is projected to cost over $819 million (DC Water 2024). Despite these costs, completed renovation projects have demonstrated success in reducing wastewater inputs to the environment. Indeed, a sanitary tunnel in Milwaukee, Wisconsin, United States, reduced sanitary sewer overflow (SSO) incidences from an average of 33 per year to a maximum of 6 per year (Ab Razak and Christensen 2001; Soonthornnonda and Christensen 2008), and multiple sanitary tunnels in Atlanta, Georgia, United States, decreased the number of combined sewer overflow (CSO) events from 2.31 to 0.49 per week (Miller et al. 2022). More sanitary tunnel projects are underway globally, driven by the modelled reductions in sewage pollution in major cities such as London, United Kingdom (Thomas and Crawford 2011), Washington, District of Columbia, United States (DC Water 2024), and Seattle, Washington, United States (Seattle Public Utilities 2024).

Despite the widespread implementation of sanitary tunnel projects to mitigate the environmental impacts of wastewater discharges, relatively few studies have assessed their effectiveness at improving water quality. Among the limited research available, some studies have reported reductions in faecal coliform bacteria concentrations (Ab Razak and Christensen 2001) and increases in dissolved oxygen (O_2) levels (Ab Razak and Christensen 2001; Pluth et al. 2021) for proximal surface waters following the sanitary tunnel construction. However, these infrastructure updates have not been shown to decrease the occurrence of gastrointestinal illness (Miller et al. 2022). Researchers have also reached conflicting conclusions regarding the impact of sanitary tunnel projects on total suspended solids (TSS) levels in surface waters, with reports of both decreasing (Pluth et al. 2021) and increasing (Ab Razak and Christensen 2001) TSS values depending on the location.

The immediate impacts of construction activities associated with sewer renovation projects on streams have similarly received little attention. Other types of construction, such as oil and gas pipeline development, increase surface water TSS concentrations due to infrastructure installation and on-site equipment use (Reid et al. 2002), which stress aquatic species (Lévesque and Dubé 2007). Nevertheless, most research assessing the effects of construction on surface water systems has focused primarily on sediment loading, often neglecting other physicochemical impacts (e.g., changes in temperature, specific conductivity, dissolved O_2, or solute chemistry; Lévesque and Dubé 2007). To date, the construction phase impacts of wastewater infrastructure projects remain largely unexamined.

We therefore lack a comprehensive understanding of both the immediate and long-term water quality implications of regional-scale sewer renovations. Nevertheless, such projects are implemented globally with the goal of mitigating the harmful effects of wastewater on human and aquatic health. Our research thus evaluates the physicochemical changes in a stream system affected by a major sewer modernisation project by examining both the short-term (i.e., during construction) and long-term (i.e., the years following the project's completion) outcomes.

2 | Data and Methods

2.1 | Study Area

To evaluate both the efficacy of a regional-scale sewer infrastructure renovation project in reducing untreated wastewater contributions to surface water as well as the short-term impacts of its construction on stream physicochemical attributes, we focused on the metropolitan area of St. Louis, Missouri, United States (Figure 1a). In the St. Louis region, the utility responsible for the interception, collection, and treatment of stormwater and sanitary wastewater is the Metropolitan St. Louis Sewer District (MSD), which services 1.4 million people across 2192 km^2 (USEPA 2018; MSD 2023; Figure 1b). The oldest portion of the service area features a combined sewer system that has had historical issues with CSO contributions to regional streams during and following precipitation events (Figure 1b). Newer sections of the service area have separate stormwater and sanitary sewer systems (Figure 1b), but SSO events increased as developments expanded without the necessary increase in pipe capacity, leading to periodic discharges of raw sewage into local streams (MCE 2019; MSD 2025a). Such wastewater inputs were identified as potential reasons for local water quantity and quality problems, leading to a legal settlement to improve the sewer system across the region (United States District Court for the Eastern District of Missouri Eastern Division 2012). To remediate these issues associated with sewer overflows, MSD's Project Clear initiative invested in grey infrastructure renovations to replace sewer overflow outfalls with collection tunnels as well as green infrastructure projects to reduce stormwater volumes that can overwhelm the sewer system (e.g., rain garden installations; Harding 2020; Deer Creek Watershed Alliance 2023).

TABLE 1 | Summary of global wastewater renovation projects sorted by country and extent.

Location	Project	Tunnel length	Project completion	Citations
Guangzhou, China	Donghao Chong Deep Tunnel	1.8 km	Unknown	Wu et al. (2016)
Germany	Emscher Sewer Tunnel	51 km	2021	Tröltzsch et al. (2020), Zimmermann (2023)
Auckland, New Zealand	Central Interceptor Wastewater Tunnel	14.7 km	Ongoing	Giacomin et al. (2023)
Manhoufs, Saudi Arabia	Saudi Wastewater Tunnel	11.9 km	2017	Rizzani De Eccher (2025)
London, United Kingdom	Thames Tideway Tunnel	25 km	2024	Thomas and Crawford (2011)
Seattle, Washington, United States	Ship Canal Water Quality Project	4.3 km	Ongoing	Seattle Public Utilities (2024)
St. Louis, Missouri, United States	Maline Creek Storage Facility	0.8 km	2020	Harding (2020), MSD (2020a), MSD (2020b), MSD (2025a)
	Jefferson Barracks Tunnel	5.4 km	2024	
	Deer Creek Sanitary Tunnel	6.3 km	2022	
Louisville, Kentucky, United States	Waterway Protection Tunnel	6.4 km	2022	Rudisell and Mathis (2019)
Washington, District of Columbia, United States	Potomac River Tunnel Project	8.9 km	Ongoing	DC Water (2024)
Atlanta, Georgia, United States	Nancy Creek Sanitary Tunnel	12.9 km	2005	Chattahoochee Riverkeeper (2019), Miller et al. (2022)
	West Area CSO Storage Tunnel	13.7 km	2008	
Pittsburgh, Pennsylvania, United States	Allegheny County Regional Tunnel System	> 17.9 km	Ongoing	ALCOSAN (2025)
Milwaukee, Wisconsin, United States	Milwaukee Deep Tunnels	45.9 km	1993, 2006, 2010	Ab Razak and Christensen (2001), Day (2004), Soonthornnonda and Christensen (2008)
Chicago, Illinois, United States	Tunnel and Reservoir Plan	177 km of tunnels across four systems	1998, 2006, 2015, 2020, ongoing	Scalise and Fitzpatrick (2012), Pluth et al. (2021), MWRD (2024), MWRD (2025)

We selected the urban Deer Creek watershed (total basin area = 95.3 km^2; Figure 1b) for our study due to documented water quality impairments in both Deer Creek and its mainstem, the River des Peres. Both streams are contaminated with *Escherichia coli* (*E. coli*) and chloride (Cl^-), while the River des Peres has historically had low dissolved O_2 levels (MoDNR 2023, 2024). These water quality problems are believed to stem from urban runoff and sewer infrastructure (MoDNR 2023, 2024). Our monitoring site is near the centre of the Deer Creek watershed (total subbasin area = 31.1 km^2; Figure 1b) at the Litzsinger Road Ecology Center, which is a non-profit organisation focused on environmental education and ecological restoration. The selected subcatchment of Deer Creek is entirely within the separate sewer system network (Figure 1b), which helped us avoid the confounding influences of multiple sewer infrastructure types on our physicochemical datasets. A United States Geological Survey (USGS) stream stage and discharge gauge (station 07010055; USGS 2025a) is situated just ~150 m downstream of our monitoring site (Figure 1c).

During the wastewater infrastructure renovation efforts at the study site (occurring from 21 February 2019 to 31 July 2022), 12 SSO outfalls upstream of our study site were removed and the Deer Creek Sanitary Tunnel (which is 6.3 km long and 5.8 m in diameter; Figure 1b) was constructed downstream of our site to collect and temporarily store untreated wastewater, particularly during and following high volume events in portions of the watershed that have combined sewer systems (MSD 2020a; Figure 1b). The elimination of the SSO sites and the creation of a new 4.1-km trunk sewer network to divert sanitary sewage into the new sanitary tunnel prevent sewer overflows from directly supplying wastewater to Deer Creek (USEPA 2018;

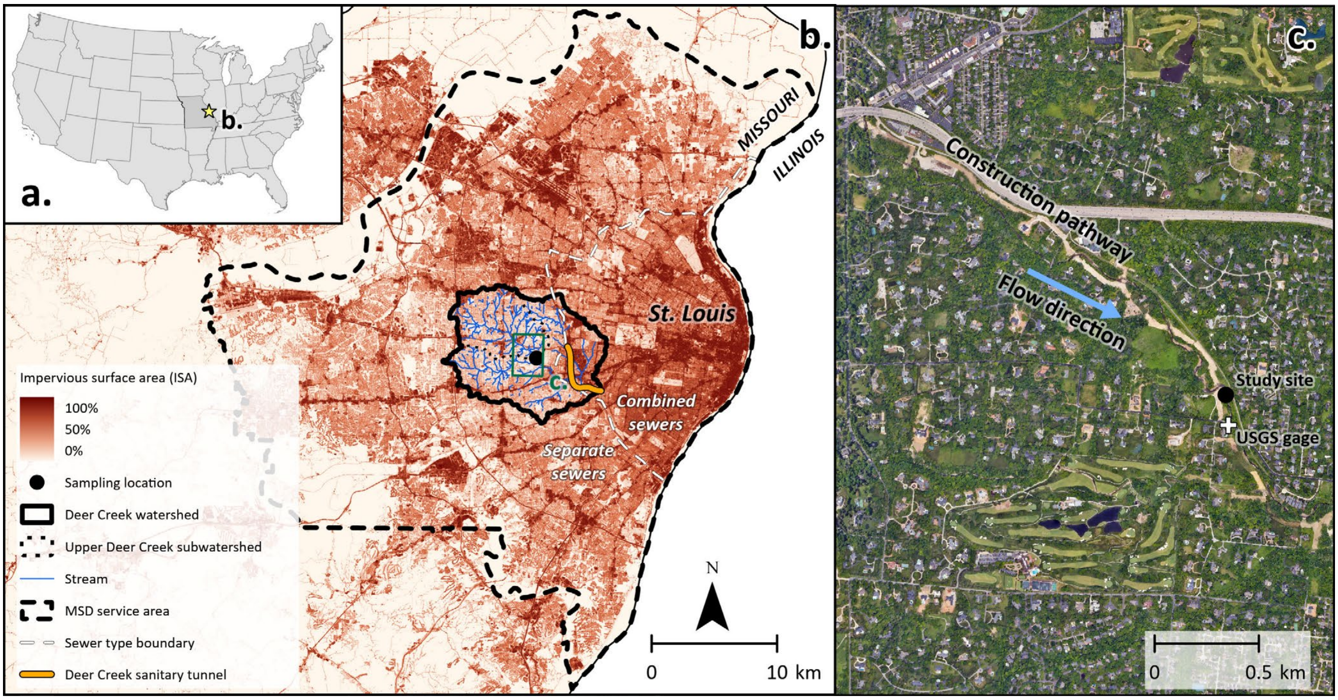

FIGURE 1 | (a) The location of the study in St. Louis, Missouri (indicated by a star), relative to the contiguous United States. (b) A map of impervious surface area in the St. Louis metropolitan region (USGS 2024), highlighting the sampling site in the context of the Deer Creek basin, the subwatershed within the Deer Creek basin that drains to our sampling location, and the stream channels for Deer Creek and its tributaries. Stream flow in the basin generally proceeds from the northwest to the southeast. The MSD service area, sewer network type, and the Deer Creek sanitary tunnel are also delineated on the map. (c) Satellite imagery (from March 2022; Google Earth 2024) of the area surrounding our study site (see the green box in (b)), showing a portion of the construction pathway, local stream flow direction, and the nearby USGS gauging station (USGS 2025a).

Harding 2020; MSD 2020a). However, these sewer upgrades necessitated construction efforts that frequently intersected the Deer Creek channel upstream of our sample site (Figure 1c). Further details on the sewer infrastructure upgrade timeline can be found in Table S1.

2.2 | Field Data and Sample Collection

We collected physicochemical data, including analytes that are either associated with or influenced by sewage contributions (e.g., MoDNR 2023, 2024), from Deer Creek approximately weekly from 2 September 2016 through 1 May 2025 ($n = 435$ site visits), totalling 8.7 years. Sampling was conducted primarily between 10:30 and 14:30 to capture consistent diurnal conditions. We note that our dataset has a small gap from 18 March 2020 to 23 July 2020 when access to our monitoring site was prohibited due to the COVID-19 pandemic. We acquired all measurements and samples from the stream during low flow conditions (i.e., discharge of $< 5.00\,m^3/s$) to avoid the complicating effects of the stream's flood responses on its physicochemical attributes.

Across the entire monitoring period, in situ measurements for common physicochemical parameters were obtained using a handheld YSI Professional Plus Multiparameter Instrument (for temperature, specific conductivity, pH, and dissolved O_2) and a Hach 2100P or 2100Q Portable Turbidimeter (for turbidity). Starting on 14 September 2017 and continuing until the end of the monitoring period, field measurements for optical brighteners ($n = 367$) were also collected during our trips to Deer Creek using a Turner Designs AquaFluor Handheld Fluorometer. The instrument features an excitation window of 350 ± 40 nm, has an emission detection window of 440 ± 7.5 nm, and records values in reference fluorescence units (RFUs). We monitored optical brighteners, which are synthetic brightening agents present in many laundry detergents, because they are robust tracers that can be used to detect the presence of untreated wastewater in surface waterbodies (Dubber and Gill 2017; Lockmiller et al. 2019; McCurdy et al. 2021; Niloy et al. 2021; Finegan and Hasenmueller 2023a; Vucinic et al. 2023).

Because *E. coli* is a common biological indicator for faecal contamination of surface waters (Tavares et al. 2008), we obtained stream water samples for *E. coli* concentration analysis for a subset of our sample dates ($n = 80$, with samples collected from 23 September 2016 to 12 January 2017, 27 September 2017 to 14 March 2018, and 27 October 2022 to 21 December 2023). Water samples for our *E. coli* analyses were collected into 500-mL high-density polyethylene bottles (that had been autoclaved before use) and transported on ice from the field to the laboratory. We also acquired stream water samples for ex situ geochemical analyses across the entire monitoring period. Stream water for these measurements was field-filtered with a 0.2-μm cellulose acetate filter into two 50-mL polypropylene sample vials that were transported on ice to the laboratory. One of these 50-mL aliquots was frozen, then thawed immediately before analysis on an ion chromatograph (IC). The other aliquot was acidified to 1% nitric acid (HNO_3) and stored at 4°C until analysis on an inductively coupled plasma optical emission spectrometer (ICP-OES).

2.3 | Laboratory Analyses

Stream samples for *E. coli* assessments were processed immediately upon our return to the laboratory using the United States Environmental Protection Agency (USEPA)-approved IDEXX Colilert Quanti-Tray system (USEPA 2017). Fluoride (F^-) concentrations in our water samples were analysed using a Thermo Scientific Dionex Integrion High Pressure IC. In many locations, including our study area, F^- is added to drinking water to improve dental health (Meenakshi and Maheshwari 2006). Its levels remain elevated in wastewater, making F^- a tracer of both drinking water and sewage inputs to aquatic systems (Lockmiller et al. 2019; Finegan and Hasenmueller 2023a; Welty et al. 2023). The IC's accuracy and precision were within 5% based on blanks, check standards, and sample replicates. Total elemental concentrations of boron (B), calcium (Ca), magnesium (Mg), strontium (Sr), potassium (K), and silicon (Si) were measured on a PerkinElmer Optima 8300 ICP-OES. These analytes were selected to assess contributions from construction activities (e.g., Ca, Mg, Sr, and Si) and municipal water sources (e.g., B). We note that B concentrations are elevated in both local drinking water (due to the Missouri River source) and wastewater (due to the use of B as a bleaching agent in household cleaners and detergents; Vengosh et al. 1994; Stueber and Criss 2005; Kot 2009; Hasenmueller and Criss 2013; Lockmiller et al. 2019). The ICP-OES also gave us concentrations of K, which can be elevated due to construction activities (e.g., inputs of K-rich clay minerals from construction materials or the soil and rock in the watershed) or wastewater-related inputs (e.g., elevated K concentrations in water resources have been attributed to wastewater contributions due to the high concentrations of K in urine; Eiswirth and Hötzl 1997; Hamdan et al. 2020). Instrument accuracy and precision for the ICP-OES were within 10% based on blanks, check standards, and sample replicates.

2.4 | Climate, Hydrological, and Land Use and Land Cover Data Acquisition

We assessed climate, hydrological, and land use and land cover data over the monitoring period to determine their potential influence on stream physicochemical conditions. Climate data were obtained through the National Oceanic and Atmospheric Administration's (NOAA) Climate Data Online tool (NOAA 2025). We downloaded average temperature and daily total precipitation values from the St. Louis Lambert International Airport weather station (NOAA 2025), which is the weather station nearest to our site. Discharge data were acquired from the USGS's stream stage and discharge gauging station 07010055 (USGS 2025a), which is located ~150 m downstream of our site (Figure 1c). These 5-min interval discharge data were downloaded using the dataRetrieval package in R (De Cicco et al. 2018). Land use and land cover data for the subbasin were obtained from the National Land Cover Database (USGS 2024).

2.5 | Statistical Analyses

Using the ggpubr package (Kassambara 2020) in R (version 3.6.1; R Core Team 2019), Kruskal–Wallis tests were applied to the non-normally distributed stream physicochemical data to determine if significant differences existed among test groups (i.e., the periods before, during, and after the sewer renovations in our subwatershed of Deer Creek). Dunn's tests were then used to identify the statistically different data groups using the 'dunn_test' function of the rstatix package (Kassambara 2023). We also conducted linear regression analyses to evaluate the associations among physicochemical parameters over the course of the study. These analyses were performed using ggplot2's 'geom_smooth' function with a linear model (lm) method. Pearson correlation coefficients were calculated using the 'stat_cor' function of the ggpubr package. A significance level of $\alpha = 0.01$ was applied to all statistical analyses, so any results reported as statistically significant meet or exceed this threshold.

3 | Results

3.1 | Climate, Hydrological, and Land Use and Land Cover Conditions

The region had an average daily air temperature of 16.1°C across the entire monitoring period, with air temperatures ranging from −18.6°C during the winter to 34.2°C during the summer (NOAA 2025). We observed no significant differences in air temperature for the pre-construction, construction, and post-construction periods of the wastewater renovation project ($p = 0.02$ for the Kruskal–Wallis test). The study region had an average of 3.1 mm/day of precipitation (range = 0.0–219.5 mm/day; NOAA 2025). We likewise found no significant differences in the daily precipitation among the periods before, during, and after the sewer infrastructure renovation ($p = 0.05$ for the Kruskal–Wallis test). Additionally, we observed minimal changes in land use and land cover across the study period (e.g., < 0.5% change for all the developed land classifications; USGS 2024).

The USGS's 5-min interval stream discharge data collected throughout the entire study period showed that Deer Creek had a median discharge value of 0.04 m^3/s and an average discharge value of 0.44 m^3/s, with values ranging from 0.00 to 212.34 m^3/s (USGS 2025a; Figure 2a inset). However, the discharge during our sampling events was always < 5.00 m^3/s, ranging from 0.00 to 2.40 m^3/s for the pre-construction period, from 0.00 to 2.15 m^3/s for the construction period, and from 0.00 to 4.96 m^3/s for the post-construction period. Overall, 51% and 94% of the site visits occurred when the discharge was respectively below the median and average values calculated from the continuous data collected by the USGS. Nevertheless, two post-construction site visits had discharge values that were elevated relative to the other sampling events (Figure 2a), leading to significantly higher average discharge during that period compared to the pre-construction and construction periods (Table 2). These two discharge measurements are nonetheless relatively low in the context of the full range of stream flow recorded by the USGS during the study (Figure 2a).

3.2 | Stream Physicochemical Attributes

The selected physicochemical parameters demonstrated a variety of responses over our monitoring period (Table 2;

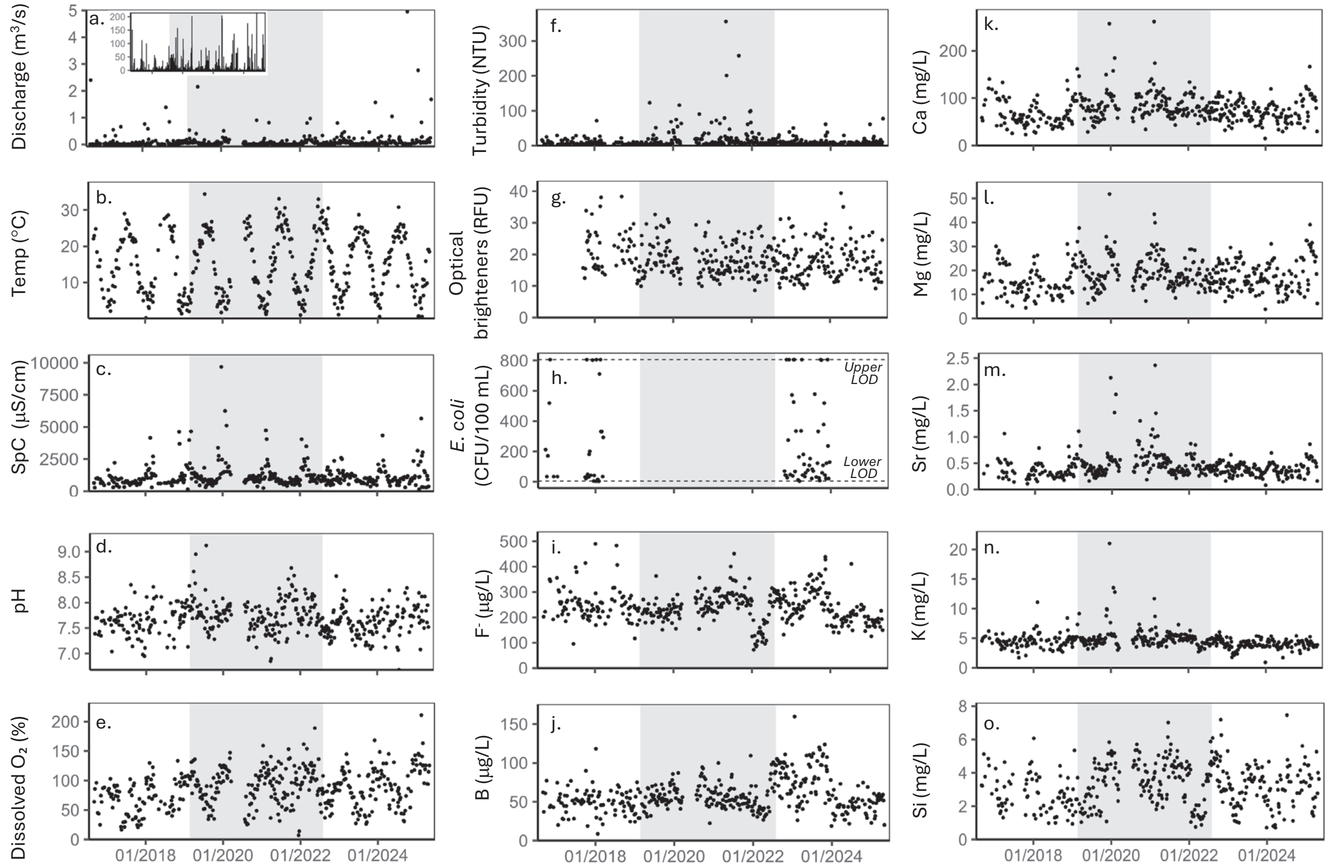

FIGURE 2 | Stream (a) discharge at the time of sampling, with the inset showing continuous discharge data (USGS 2025a), (b) temperature (temp), (c) specific conductivity (SpC), (d) pH, (e) dissolved O_2, (f) turbidity, (g) optical brighteners, (h) *E. coli* (with the upper and lower limits of detection [LOD] as dashed lines), (i) F^-, (j) B, (k) Ca, (l) Mg, (m) Sr, (n) K, and (o) Si for the monitoring period. The construction period for the sewer renovation project is indicated with grey shading.

Figures 2b–o and 3). We saw no significant changes (Table 2) to stream temperature (Figure 2b) and specific conductivity (Figure 2c) across the study period. We note, however, that halite (NaCl) is used across the St. Louis area extensively as a roadway de-icing agent in the winter (Baraza and Hasenmueller 2021; Finegan and Hasenmueller 2023b), potentially confounding any changes in the specific conductivity signature from the sewer renovation project. The pH (Figure 2d) significantly decreased between the construction and post-construction phases of the renovation (Table 2). Dissolved O_2 percentages (Figures 2e and 3a) increased significantly by 28% between the pre-construction and construction periods as well as by 26% between the pre-construction and post-construction periods (Table 2). Average turbidity more than doubled from the pre-construction period to the construction period (Figure 2f) and was significantly different between these two segments of the monitoring timeline (Table 2). However, turbidity did not differ significantly between the pre-construction and post-construction periods (Table 2). The construction period accounted for some of the lowest and highest recorded pH and dissolved O_2 values as well as the highest and most variable turbidity levels we observed across the entire study (Table 2; Figure 2d–f).

A significant difference among the timeframes was observed for optical brighteners using the Kruskal–Wallis test, with the Dunn test identifying a significant 14% decrease in their levels between the pre-construction and construction periods as well as a significant 15% decrease in their levels between the pre-construction and post-construction periods (Table 2; Figures 2g and 3b). We also observed that the pre-construction period had the most variable optical brightener levels (Table 2). Analyses of *E. coli* samples were conducted for a subset of the sampling dates during the pre-construction ($n = 29$) and post-construction ($n = 51$) periods (Figure 2h), but the difference between the two sampling intervals was not statistically significant (Table 2).

A Kruskal–Wallis test for the stream F^- concentrations (Figure 2i) indicated no significant differences among the renovation timeline groups (Table 2). However, we saw a significant difference among the groups for our B data (Figure 2j) using the Kruskal–Wallis test, with the Dunn test confirming a significant 14% increase in B concentrations from the pre-construction to construction periods as well as a significant 30% increase from the pre-construction to post-construction periods (Table 2; Figure 3c). Major element concentrations in the stream (Figure 2k–o) commonly increased significantly from the pre-construction to construction periods (i.e., 27% for Ca, 27% for Mg, 35% for Sr, and 21% for Si; Table 2). The K values increased 11%, but the difference between the pre-construction and construction periods was not significant (Table 2; Figure 2n). While concentrations for Ca and Sr returned to their pre-construction levels following the completion of the sewer renovation, Mg values significantly increased by 17% (Figure 3d), K values significantly decreased by 13% (Figure 3e), and Si values significantly

TABLE 2 | Stream physicochemical parameter statistical data for the periods before, during, and after the sewer renovation project.

	Before construction				During construction				After construction				Kruskal–Wallis	Dunn
Parameter	*n*	Mean	Median	Standard deviation	*n*	Mean	Median	Standard deviation	*n*	Mean	Median	Standard deviation	*p*	Groups significantly different
Discharge (m^3/s)[a]	109	0.11	0.02	0.30	175	0.09	0.03	0.22	148	0.19	0.06	0.52	< 0.01	Before—After During—After
Temperature (°C)	104	13.2	11.4	8.5	178	15.5	15.3	8.9	146	15.0	15.2	8.0	0.08	None
Specific conductivity (μS/cm)	104	1069	836	812	178	1273	961	1078	146	1109	914	717	0.02	None
pH	102	7.6	7.7	0.3	177	7.8	7.7	0.3	146	7.6	7.6	0.3	< 0.01	During—After
Dissolved O_2 (%)	104	72.1	74.1	27.5	178	92.5	96.0	31.6	148	90.6	90.6	33.2	< 0.01	Before—During Before—After
Turbidity (NTU)	98	9.19	6.07	9.30	177	21.52	8.75	40.54	143	11.16	7.08	12.70	< 0.01	Before—During
Optical brighteners (RFU)	53	21.3	21.0	6.7	171	18.3	17.4	5.1	143	18.0	17.3	5.7	< 0.01	Before—During Before—After
E. coli (CFU/100 mL)[b,c]	29	84.5	49.0	5.9	0	NA	NA	NA	51	113.3	108.4	4.0	0.47	None
F^- (μg/L)	93	251	241	65	162	239	243	61	143	239	229	64	0.30	None
B (μg/L)	101	50	50	16	171	57	53	16	144	65	59	27	< 0.01	Before—During Before—After
Ca (mg/L)	99	67.4	58.7	28.1	171	85.9	78.7	31.5	144	73.1	70.8	23.8	< 0.01	Before—During During—After
Mg (mg/L)	99	15.2	13.8	6.3	171	19.3	17.8	6.8	144	17.8	16.5	6.4	< 0.01	Before—During Before—After
Sr (mg/L)	82	3.8	3.2	1.8	171	5.1	4.4	3.0	144	3.9	3.7	1.3	< 0.01	Before—During During—After
K (mg/L)	99	4.6	4.6	1.3	171	5.1	4.7	2.0	144	4.0	4.0	0.8	< 0.01	Before—After During—After
Si (mg/L)	88	2.8	2.5	1.1	171	3.4	3.6	1.3	144	3.3	3.4	1.3	< 0.01	Before—During Before—After

[a]Discharge data were obtained for our sample collection times from USGS (2025a).
[b]The geometric mean and geometric standard deviation were used for the *E. coli* data.
[c]Not applicable (NA) indicates that samples for *E. coli* analysis were not collected during the construction period.

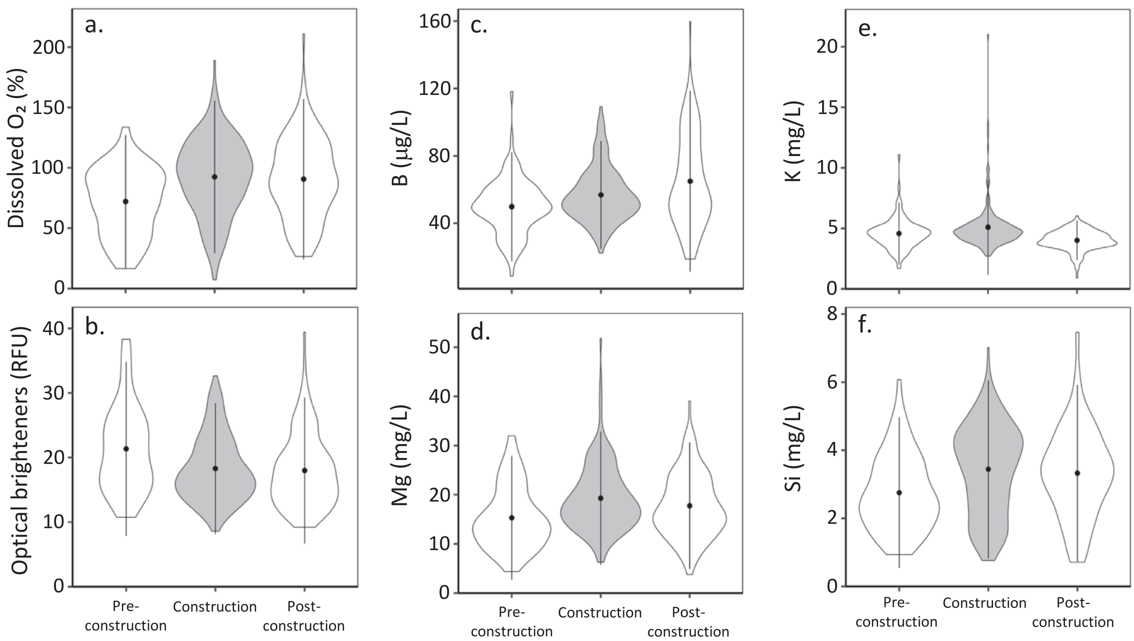

FIGURE 3 | Violin plots showing the mean, standard deviation, and spread for the physicochemical parameters that were significantly different from the pre-construction to post-construction periods per the Dunn test (see Table 2 for more statistical details). These analytes include (a) dissolved O_2, (b) optical brighteners, (c) B, (d) Mg, (e) K, and (f) Si. The construction period is shaded grey for each plot.

increased by 18% (Figure 3f) from their pre-construction concentrations following the project's completion (Table 2). However, only the post-construction K concentrations had a lower standard deviation compared to the pre-construction conditions, while Mg and Si variability slightly increased between these two phases of the monitoring period (Table 2).

4 | Discussion

4.1 | A Large-Scale Sewer Renovation Project Reduced Wastewater Contributions to an Urban Stream

Our selection of the Deer Creek subcatchment for an 8.7-year study of physicochemical dynamics in an urban stream system provided a unique opportunity to assess the impacts of a major sewer infrastructure intervention in the St. Louis region, with potential implications for similar urban watersheds elsewhere. Long-term monitoring data revealed reductions in wastewater inputs to the stream following the construction of the new sewer system. Indeed, we found that wastewater tracers, like optical brighteners (Finegan and Hasenmueller 2023a) and K (Eiswirth and Hötzl 1997; Hamdan et al. 2020), decreased in both concentration and variability after the sewer renovation was complete (Table 2; Figures 2g,n and 3b,e), signifying the reduction of sewage inputs to Deer Creek. The frequently high optical brightener values before the onset of construction may indicate pulses of wastewater to the stream from SSO events before the renovation project began. The gradual decline in optical brightener levels over the monitoring period (as opposed to a threshold response) is likely due to the phased nature of the sewer infrastructure upgrades (i.e., not all of the sewer overflows were addressed simultaneously; see Table S1). Construction-related inputs of K during the project's drilling activities, which corresponded with increases in other major elements and turbidity (Table 2; Figure 2f,k–o), likely explain the observed increase in K concentrations during the renovation efforts. Indeed, our comparison of the K and optical brightener data showed no significant correlation (Figure 4a), indicating a decoupling of their behaviours during the construction period.

The increase in stream dissolved O_2 percentages following the onset of the infrastructure remediation project (Table 2; Figure 2e) similarly implied that sewer inputs to the stream decreased following the renovation as wastewater-related organic matter and nutrient contributions diminished over time. This finding is particularly important given the historical exceedances of dissolved O_2 regulatory criteria in Deer Creek's receiving waterbody, the River des Peres (MoDNR 2023). Our results are also consistent with a study in the metropolitan area of Chicago, Illinois, United States, where dissolved O_2 levels increased and faecal coliform abundances decreased in local rivers following large-scale sewer infrastructure renovations (Pluth et al. 2021; Table 1). Additionally, we found that dissolved O_2 was significantly and negatively correlated with optical brighteners (Figure 4b), further supporting our hypothesis that wastewater contributions to the subcatchment decreased throughout the monitoring period.

While continuous dissolved O_2 datasets are ideal for evaluations of water quality improvements (Beaulieu et al. 2013), many groups responsible for assessing streams, like those in the St. Louis region where our study takes place, rely on even more infrequent stream sampling protocols than the weekly dissolved O_2 data we present here due to time and resource limitations (e.g., MoDNR 2022; MSD 2025b). Thus, we provide dissolved O_2 data at intervals that are often unattainable for parties invested in the stewardship of urban stream systems. We nevertheless acknowledge some challenges associated with our use of weekly point measurements of dissolved O_2 to assess the success of the infrastructure renovation project in reducing wastewater contributions to Deer Creek.

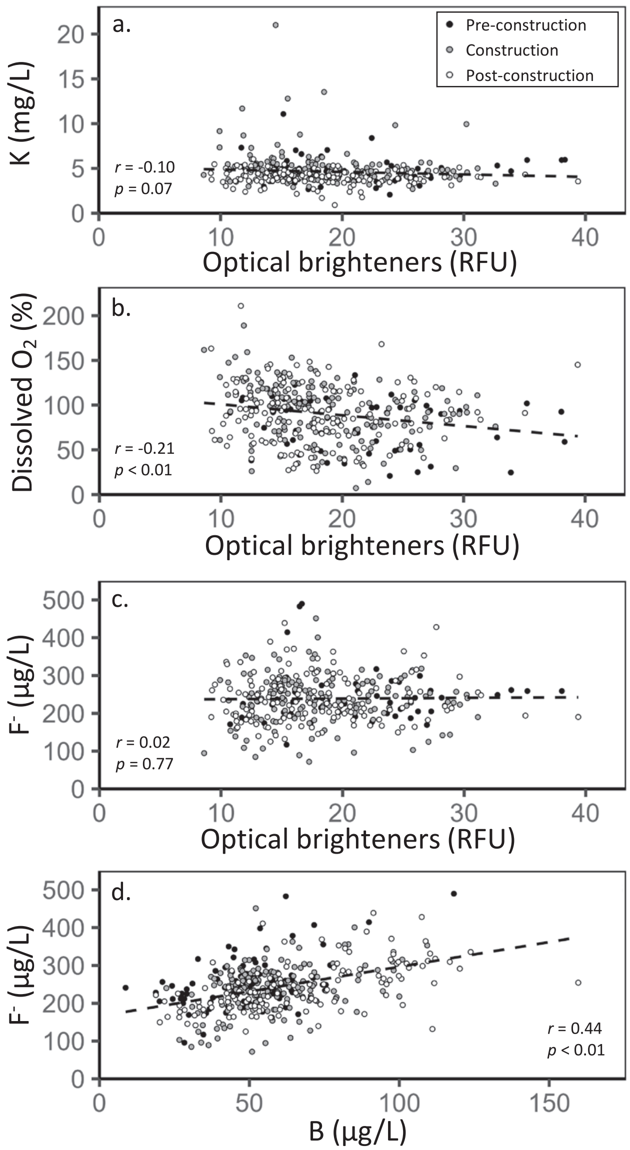

FIGURE 4 | Correlations between (a) K and optical brighteners, (b) dissolved O_2 and optical brighteners, (c) F^- and optical brighteners, and (d) F^- and B across the entire monitoring period.

First, dissolved O_2 often varies diurnally due to aquatic ecosystem metabolism (Jankowski et al. 2021). We typically sampled within the same 4-h window (i.e., 10:30 to 14:30) during our field campaigns. While we recognise that Deer Creek's dissolved O_2 likely varied within that general timeframe, we expect that these fluctuations would have smoothed out over the 8.7 years of the study. In other words, the timing of the data collection was unlikely to introduce bias across the monitoring period. Consequently, our dataset should still capture the overall decreasing trend in dissolved O_2 with time, despite the potential noise from sampling timing variations.

Second, dissolved O_2 is not a direct measure of the impacts that wastewater contributions may have on stream metabolism as it can be influenced by other factors such as lighting and discharge variations (Beaulieu et al. 2013). Although we consistently sampled during low flow conditions (i.e., when discharge was < 5.00 m^3/s; Figure 2a), the sewer renovation project involved the removal of trees, some of which were located along the riparian corridor of Deer Creek (see Figure 1c). However, the tree removals directly adjacent to the stream were limited relative to the total length of the stream, and their impact on dissolved O_2 variation is thus expected to be minimal. Furthermore, our wastewater tracer data (i.e., optical brighteners and K), along with biweekly biological O_2 demand (BOD) and ammonia as nitrogen (NH_3-N) data collected by MSD from 17 September 2013 to 26 December 2023 at the outlet of the entire Deer Creek watershed (MSD 2025b), all declined following the onset of the sewer renovation. Importantly, reductions in BOD and nutrients like NH_3-N are expected to decrease dissolved O_2 consumption as the removal of untreated wastewater sources (that feature high organic matter and nutrient concentrations) lowers microbial O_2 demand. Thus, the decreased BOD and NH_3-N levels align with our observations of increasing dissolved O_2 percentages in the stream.

Additionally, we observed a gradual increase in dissolved O_2 at the onset of the construction phase of the sewer renovation, but the fluctuations in dissolved O_2 levels could be extreme during this period (Table 2; Figure 2e). We suspect these variations resulted from several factors. The incremental elimination of SSOs likely improved dissolved O_2 levels overall by reducing organic matter and nutrient loading, as noted earlier. However, specific construction activities (Table S1) may have influenced the dissolved O_2 variability. For example, runoff from drilling or equipment crossings could have aerated the stream, while temporary dams might have caused stagnation and localised dissolved O_2 depletion.

We did not find a significant difference in *E. coli* levels between the pre-construction and post-construction periods in our data subset (Table 2; Figure 2h). This outcome was likely due to the limited temporal coverage of our *E. coli* dataset, which may have obscured the expected reductions in faecal indicators following the decreases in untreated wastewater inputs that resulted from the sewer network upgrades. Notably, MSD's *E. coli* data from the outlet of the entire Deer Creek watershed (collected only biweekly during the recreational season from 1 April to 31 October each year; MoDNR 2016) showed declining *E. coli* levels over ~10 years of monitoring (MSD 2025b). Similar *E. coli* reductions would have likely been observed at our mid-watershed site had a longer-term dataset been available.

Several other variables could potentially confound the observed effects of the sewer renovation on stream physicochemical properties. To help decouple these influences, we examined average air temperature (NOAA 2025), daily precipitation (NOAA 2025), discharge (USGS 2025a; Figure 2a), and land use and land cover (USGS 2024) across the pre-construction, construction, and post-construction periods. We found that air temperature, daily precipitation, and land use and land cover did not appreciably differ among the renovation phases, suggesting they did not meaningfully affect the trends observed in wastewater tracers or water quality parameters. Although average discharge was higher during the post-construction period compared to the pre-construction and construction phases (Table 2), all sampling was conducted under low flow conditions (i.e., discharge of < 5.00 m^3/s), and this increase was likely driven by two outliers later in the study period (Figure 2a). Green infrastructure projects were implemented by MSD and other institutions within the subwatershed during the monitoring period. However, some of these efforts were poorly documented, and we thus lack sufficient detail to assess their potential influence on stream conditions. Nevertheless, we do not expect the green infrastructure projects to meaningfully affect concentrations of wastewater tracers (e.g., optical brighteners). We also attempted to explore potential population changes, but available data from the United States Census Bureau are collected only once per decade and do not align with the timing of the renovation phases or the watershed's boundaries (United States Census Bureau 2025), limiting their usefulness in this context.

Nonetheless, our combined results for dissolved O_2 percentages, optical brightener levels, and K concentrations indicate that the sanitary tunnel project effectively reduced untreated wastewater inputs to Deer Creek by eliminating their point sources within the subwatershed. Ageing infrastructure, SSO events during low flow conditions, and CSO- or SSO-contaminated groundwater discharge to the stream likely contributed to the water quality impairments we observed at the onset of our study. Despite the high cost of large-scale sewer infrastructure projects, the observed improvements in water quality in surrounding waterbodies underscore their importance. The success of wastewater infrastructure projects has also been demonstrated globally as seen with the 51-km-long Emscher Sewer Tunnel in Germany, which cost €5.5 billion to construct (Zimmermann 2023; Table 1). This project successfully restored the water quality and biodiversity of the Emscher and its tributaries by removing open wastewater channels (Tröltzsch et al. 2020).

While point sources of untreated wastewater to the Deer Creek subbasin have been removed through the sewer renovation efforts, nonpoint sources of wastewater, such as leaking sewer laterals or larger distribution pipes, may still be contributing raw sewage to the stream and nearby shallow groundwater (Finegan and Hasenmueller 2025). Supporting this possibility, we observed that Deer Creek had elevated Si concentrations (a tracer of groundwater inputs; Davis 1964; Marçais et al. 2018) after the onset of the infrastructure upgrades (Table 2; Figures 2o and 3f) alongside relatively low dissolved O_2 percentages (Figures 2e and 3a), elevated optical brightener levels (Figures 2g and 3b), and high *E. coli* concentrations (Figure 2h) following the renovation compared to proximal rural streams. These results suggest ongoing wastewater inputs to the stream, possibly via sewer pipe exfiltration or contaminated shallow groundwater. Portions of the wastewater infrastructure in the catchment are located above the water table, creating a potential pathway for exfiltrated sewage to enter the shallow groundwater and ultimately discharge to the stream (Finegan and Hasenmueller 2025).

4.2 | Geochemical Tracers Suggest Increasing Fractions of Drinking Water in an Urban Stream

Our analysis of geochemical tracers indicated that drinking water inputs were likely a persistent municipal water signal in Deer Creek throughout the monitoring period. Notably, concentrations of F^- did not change from the pre-construction to post-construction periods (Table 2), despite the removal of point sources of untreated wastewater in the subbasin. Since both drinking water and untreated wastewater in our study area contain elevated F^- levels compared to natural waterbodies (Lockmiller et al. 2019; Finegan and Hasenmueller 2023a), F^- could originate from either source. However, linear regression analyses showed no correlation between F^- and optical brighteners (Figure 4c), suggesting that F^- was likely introduced to the stream, at least in part, through drinking water additions.

We also observed a significant increase in B concentrations over the monitoring period (Table 2; Figure 3c). In the St. Louis region, both municipal drinking water and wastewater have elevated B levels relative to natural background values. Drinking water contains high B concentrations due to its Missouri River source, while wastewater is enriched in B from additions of detergents during use (Hasenmueller and Criss 2013; Lockmiller et al. 2019). Although B can also enter streams via rock weathering and fertiliser runoff (Hasenmueller and Criss 2013; Finegan and Hasenmueller 2023a), the positive and significant linear regression between F^- and B (Figure 4d) points to common sources. Prior to the sewer renovation, both drinking water and untreated wastewater probably contributed F^- and B to Deer Creek. After the infrastructure upgrades, the dominant source of these analytes was likely drinking water or possibly a combination of drinking water and B-rich fertilisers mobilised during lawn irrigation in the subwatershed. However, the reason why the F^- concentrations did not significantly change during and after the renovation project, while B concentrations did, remains unclear (Table 2).

Despite these results suggesting increasing proportions of drinking water contributions to Deer Creek during and after the sewer renovation project, the infrastructure update may only be partly responsible for this effect. Drilling activities during the construction phase of the project (Table S1) involved water that may have been sourced from the municipal drinking water supply, potentially explaining an increased drinking water signature from the pre-construction to construction periods (Table 2; Figure 3c). However, the continued presence of drinking water indicators following the renovation project's completion (Table 2; Figure 3c) points to other sourcing mechanisms. For example, unrelated failures of the drinking water infrastructure could instead be the cause of the elevated drinking water signature that we observed in Deer Creek. Indeed, a documented water main break occurred near our sampling site during the post-construction period around 14–16 November 2023, implying that at least some of the observed geochemical signals of drinking water may be coincidental rather than directly related to the sewer renovation project.

4.3 | Large-Scale Sewer Renovation Construction Activities Temporarily Increase Stream Turbidity and Major Element Concentrations

Our study demonstrated that construction-related activities for the wastewater renovation project led to elevated levels of several physicochemical parameters at Deer Creek. Average turbidity levels more than doubled while turbidity variability more than quadrupled from the pre-construction to construction periods (Table 2; Figure 2f). Our turbidity findings correspond with the limited available literature about the impacts of construction-related sewer renovation projects on stream water quality. For example, Ab Razak and Christensen (2001) documented that deep sanitary tunnel construction caused an increase in TSS levels in nearby surface waterbodies, which was probably due to the installation and removal of construction infrastructure and equipment (Reid et al. 2002). We also saw contemporaneous increases in Ca, Mg, Sr, K, and Si levels (Table 2; Figure 2k–o) at the onset of construction. These increases in major elements coincide with the trenching and drilling period for the new sewer infrastructure (Table S1), though we note that other indicators of salinity, like our specific conductivity data, are likely confounded by road salt applications across the subbasin (Baraza and Hasenmueller 2021; Finegan and Hasenmueller 2023b). However, several of these parameters (e.g., turbidity, Ca, and Sr) returned to their pre-construction levels upon project completion (Table 2; Figure 2f,k,m), suggesting that the impacts of the construction may have only been temporary.

Nevertheless, construction-related changes in stream physicochemical properties should not be overlooked as they can impact ecosystem health and water quality. Increased sediment loads have been shown to stress aquatic species, including benthic invertebrates and fish (Lévesque and Dubé 2007). Elevated turbidity also increases the need for more intensive treatment interventions of source waters used for drinking water supply (Gauthier et al. 2003). Although Deer Creek is not a drinking water source, our findings can be broadly applied to surface water systems that are. The construction for the sewer infrastructure renovation project also led to higher concentrations of major elements, resulting in increased water hardness in the stream. For instance, Ca levels peaked during the construction phase, at times reaching threefold the background concentration (Figure 2k). Variations in water hardness can alter the solubility of toxic dissolved metals (USEPA 2025) and create challenges for treatment and use when the waterbody is a drinking water supply (USGS 2025b). Given that similar projects to remediate wastewater-related water quality issues are underway globally, continued monitoring of ecosystem health and water physicochemical parameters during the associated construction activities is essential.

5 | Conclusions

Following a major sewer infrastructure renovation project designed to eliminate sewer overflows to urban stream systems, we observed clear reductions in untreated wastewater inputs to our selected subcatchment of Deer Creek. Concentrations of wastewater tracers (e.g., optical brighteners and K) declined, while water quality indicators (e.g., elevated dissolved O_2 percentages) improved following the project's completion. These trends were consistent with additional observations by local wastewater managers at a downstream site, where other wastewater indicators (e.g., *E. coli*, BOD, and NH_3-N) also consistently decreased. The wastewater reductions we observed over our 8.7-year study demonstrated that the costly sanitary tunnel and associated trunk sewer network project in the Deer Creek subbasin effectively met management goals to reduce raw sewage inputs and improve water quality. However, over shorter timescales, our data showed that such projects can temporarily exacerbate issues with high turbidity and major element concentrations in the stream. These disturbances have broader implications for water treatment, contaminant solubility, and aquatic ecosystem health. While large-scale sewer infrastructure upgrades clearly improve urban stream water quality in the long term, resource managers must remain attentive to construction-related impacts and adopt strategies to mitigate short-term deleterious effects.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** The sewer renovation project timeline.