GEORGIA DOT RESEARCH PROJECT 23-11

Final Report

ROADWAY RUNOFF IMPACTS TO TROUT STREAMS STUDIES FOR MS4 PERMIT

Office of Performance-based Management and Research
600 West Peachtree Street NW | Atlanta, GA 30308

February 2026

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.:
FHWA-GA-26-2311

2. Government Accession No.:
N/A

3. Recipient’s Catalog No.:
N/A

4. Title and Subtitle:
Roadway Runoff Impacts to Trout Streams Studies for MS4 Permit

5. Report Date:
February 2026

6. Performing Organization Code:
N/A

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8. Performing Organization Report No.:
23-11

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10. Work Unit No.:
0190501

11. Contract or Grant No.:
--0019911

12. Sponsoring Agency Name and Address:
Georgia Department of Transportation
Office of Performance-based Management and Research
600 West Peachtree St. NW
Atlanta, GA 30308

13. Type of Report and Period Covered:
Final; Start February 2024 – End February 2026

14. Sponsoring Agency Code:
000031

15. Supplementary Notes:
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract:

This study evaluated roadway runoff impacts on trout stream temperature and dissolved oxygen to support GDOT MS4 Permit compliance with Georgia Rule 391-3-6-.03(6) for trout streams. Using YSI® ProDSS, HOBO® MX-801 Dataloggers, and low-cost ESP32-based sensors, the GSU research team collected summer season data over two (2) consecutive years at 2-3 representative GDOT outfalls at each of the three (3) secondary trout streams. Results show that summer rainfall events with precipitation ≥ 0.5 inches produced short-term temperature increases at Sites 1 and 2, with Site 1 (Chattahoochee River) exhibiting brief exceedances above the 2 °F limit for secondary trout waters. Site 2 (Powder Springs Creek) displayed smaller rises that rarely approached the threshold, while Site 3 (Two-Run Creek) showed no measurable temperature increase under any rainfall conditions. DO reductions tracked temperature inversely but remained within regulatory limits after artifact screening. All impacts were event-specific and recovered within hours. The project establishes a scalable monitoring framework that can be applicable nationwide and provides site-specific BMP guidance to strengthen GDOT’s MS4 Permit compliance and protect sensitive secondary trout streams.

17. Keywords:
Roadway Runoff Impact; Outfall; Trout Stream; Temperature; Dissolved Oxygen (DO); MS4 Permit.

18. Distribution Statement:
No Restriction

19. Security Classification (of this report):
Unclassified

20. Security Classification (of this page):
Unclassified

21. No. of Pages:
204

22. Price:
Free

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Final Report

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Contract with
Georgia Department of Transportation

In cooperation with
U.S. Department of Transportation,
Federal Highway Administration

February 2026

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	**Definition**
BMP	Best Management Practice
CC	Cement-Concrete
CFS	Cubic Feet per Second
DO	Dissolved Oxygen
DOT	Department of Transportation
EDT	Eastern Daylight Time
EPA	U.S. Environmental Protection Agency
°F	Degrees Fahrenheit
ft^3/s	Cubic feet per second (unit of discharge)
GA EPD	Georgia Environmental Protection Division
GDOT	Georgia Department of Transportation
GSU	Georgia Southern University
HID	Hydrologic Identification Number (for site code reference)
IDE	Integrated Development Environment

LID	Low-Impact Development
mg/L	Milligrams per Liter (concentration unit for DO)
MS4	Municipal Separate Storm Sewer System
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
NWIS	National Water Information System
QA/QC	Quality Assurance / Quality Control
QAPP	Quality Assurance Project Plan
SWMM	Storm Water Management Model
U/S	Upstream
D/S	Downstream
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WERL	Water and Environmental Research Laboratory

EXECUTIVE SUMMARY

Research project (RP) 23-11, "Roadway Runoff Impacts to Trout Streams Studies for MS4 Permit" was conducted under the direction of the GDOT from February 2024 through February 2026. The general objectives for the research project were: 1) To develop and implement a study plan that evaluates the impacts of roadway runoff through GDOT outfalls to trout streams, focusing on the impacts to water temperature and DO levels, and 2) To determine if GDOT roadway runoff discharges are causing significant adverse impacts to water temperature and DO to trout streams. If this is the case, the proposed research project would recommend BMPs that can be used to mitigate these impacts.

The project aimed to provide GDOT with scientific data, analytical tools, and monitoring strategies to support Municipal Separate Storm Sewer System (MS4) permit compliance and Georgia Rule 391-3-6-.03(6)(ii),(v) related to trout stream protection.

To achieve the objectives, the project implemented a multi-tiered monitoring approach integrating traditional and emerging technologies. For this research project, a total of three (3) secondary trout streams were selected. Each stream receives runoff through water outfalls managed by GDOT at specific identifiable locations. The three (3) outfalls selected for each site are: one (1) at a bridge/culvert crossing, one (1) at about 0.5 mile upstream of the trout stream, and one (1) at about 1.0 mile upstream. The instrumentation suite comprises YSI® ProDSS Multiparameter handheld sensor, ESP32-microcontroller-based remote sensors, and HOBO® MX801 continuous data loggers, which enabled both long-term baseline monitoring and real-time rainfall-event observation.

Field monitoring extended across two (2) years during the summer periods, encompassing baseline dry-weather conditions and multiple rainfall events. Rainfall data from National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS) were used to identify and correlate precipitation thresholds with stream responses. Analyses revealed that roadway runoff caused measurable but transient increases in stream temperature immediately following significant rainfall (precipitation ≥ 0.5 inch/day) events and DO levels showed corresponding short-term decreases consistent with inverse temperature relationships. However, diurnal temperature cycles and seasonal trends remained intact, indicating natural recovery within several hours to a few days after runoff events.

The performance of the low-cost ESP32 sensor systems was particularly noteworthy. These sensors successfully captured rapid changes in roadway runoff water coming to the outfalls during precipitation, providing valuable data that would have been missed through periodic grab sampling alone. Combined with HOBO® and YSI® systems, they demonstrated a scalable monitoring strategy adaptable for GDOT's roadway runoff management and MS4 compliance programs.

Overall Phases of the Project

The project was executed through three (3) structured phases encompassing planning, field implementation, data collection and analysis, and synthesis and reporting.

Phase I: Project Initiation and Planning (January–March 2024)

Following receipt of the Notice to Proceed in February 2024, the research team conducted administrative coordination, literature review, and development of the QAPP. The QAPP, approved by Georgia EPD in the second quarter of 2024, established standardized calibration, sampling, and data management procedures consistent with GDOT and US EPA requirements. Field reconnaissance with GDOT personnel led to the selection of three representative trout stream sites influenced by roadway runoff. Site layouts were finalized, and ProDSS instrumentation was bench tested prior to use in the field sites.

Phase II: Field Deployment and Monitoring (April 2024–October 2025)

Field activities were conducted over two (2) consecutive monitoring years. The first year focused on ProDSS-based grab sampling to characterize baseline temperature and DO conditions and to refine deployment protocols. Logistical constraints and limited storm access during this period highlighted the need for continuous monitoring. In the first year of 2024, the GSU research team were able to get runoff data during or immediately after rainfall only on two (2) days among five (5) days they travelled to the sites from the GSU campus in Statesboro, GA. In response, HOBO® continuous loggers were incorporated. During the second year, a fully integrated monitoring network consisting of ProDSS instruments, HOBO® loggers, and low-cost remote sensors was deployed. This approach enabled high resolution characterization of diurnal conditions and rainfall driven responses, supported by routine QA/QC field verification.

Phase III: Data Analysis and Reporting (July–November 2025)

Multi source temperature, DO, and rainfall datasets were integrated to evaluate roadway runoff effects across sites. Event based analyses were conducted to assess response magnitude and duration, and a preliminary mass balance framework using the Rational Method was developed to estimate runoff mixing potential and its temperature impact. Results were synthesized into comparative figures and tables and documented in the final report.

Key Findings

The RP 23-11 project provides GDOT with a comprehensive, field-verified assessment of roadway-runoff effects on temperature and DO in trout streams regulated under Georgia Rule 391-3-6-.03(6). Two years of integrated monitoring at three representative GDOT outfalls captured both baseline conditions and rainfall-driven responses, directly addressing GDOT's regulatory compliance questions.

Temperature Compliance

- Short-duration temperature increases were observed only at larger, hydraulically connected outfalls
- Site 1 exhibited brief ΔT exceedances of the 2 °F secondary-trout stream standard during moderate to large summer storms, with complete recovery within hours
- Site 2 showed smaller, infrequent warming that rarely approached the standard
- Site 3 exhibited no measurable temperature increase under any monitored event

Interpretation: Temperature impacts were localized, event-specific, and rapidly attenuated. No persistent or cumulative thermal impairment was observed.

DO Compliance

- DO concentrations at all sites remained within regulatory limits throughout the study
- Short-lived DO depressions coincided with temperature peaks at Sites 1 and 2 but did not result in verified standard violations
- Site 3 maintained consistently stable DO conditions

Interpretation: No roadway-runoff-related DO violations were documented at any site.

Integrated Site Sensitivity

Observed responses followed a clear gradient of sensitivity:

Site 1 (highest) > Site 2 (moderate) > Site 3 (none).

This pattern reflects differences in baseflow dilution, riparian shading, drainage pathway length and vegetation, outfall connectivity, and watershed imperviousness. Site 3 effectively functions as a natural BMP, while Sites 1 and 2 respond measurably only during intense summer rainfall events.

Project Accomplishments

- Development of a scalable, MS4-ready monitoring framework combining grab sampling, continuous logging, and event-triggered remote sensing
- Demonstration that continuous and event-based monitoring is essential for resolving short-term thermal and DO dynamics
- Establishment of a preliminary temperature mass-balance approach for a GDOT trout stream outfall, providing a foundation for future predictive tools

Recommendations

- Focus monitoring and adaptive management at hydraulically efficient outfalls where short-term thermal responses are most likely
- Preserve and enhance riparian shading and vegetated flow paths as primary thermal controls
- Use rainfall thresholds to guide targeted monitoring and BMP evaluation
- Expand continuous monitoring and advance predictive and performance-based tools to support long-term MS4 compliance and trout stream protection

Conclusion

The RP 23-11 Project successfully fulfilled its objectives by quantifying how roadway runoff affects trout stream temperature and DO dynamics and by demonstrating a robust, replicable monitoring framework for GDOT's MS4 program. The project produced clear regulatory-relevant findings: short-term temperature increases can occur at selected GDOT outfalls during summer rainfall, but DO standards remained in compliance across all sites, and natural recovery was rapid.

Through the integration of advanced and low-cost sensor technologies, detailed event analyses, and site-specific mass balance insights, this project equips GDOT with a scientifically defensible foundation for evidence-based BMP deployment, enhanced permit compliance, and long-term adaptive management in Georgia's trout stream watersheds. The methods and tools developed here establish a scalable model for future GDOT research and operational planning, supporting both transportation infrastructure reliability and protection of sensitive aquatic resources.

CHAPTER 1. INTRODUCTION

Trout streams in northern Georgia represent some of the state's most ecologically and economically valuable freshwater resources. These cold-water ecosystems sustain three (3) primary trout species; rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*); that depend on narrow ranges of water temperature and DO to survive and reproduce. Optimum temperature conditions for trout are typically below 67 °F (19 °C), while DO concentrations must remain above 6 mg/L on a daily average basis to prevent hypoxia [1], [2]. When water temperatures exceed 70 °F (21 °C), trout experience metabolic stress, impaired growth, and reduced spawning success; exposures above 72 °F (22.2 °C) for more than 48 hours can be lethal [3], [4]. Because temperature and DO are inversely related, even modest warming can trigger severe oxygen reduction, magnifying physiological stress during summer low-flow periods [5].

From a regulatory standpoint, the GA EPD enforces stringent standards to preserve these sensitive waters. Under Georgia Rule 391-3-6-.03(6)(ii),(v), streams designated as secondary trout waters must not exhibit temperature elevations exceeding 2 °F above natural background, and primary trout waters must show no human-induced temperature increase at all. Trout waters must maintain a daily average DO concentration of 6.0 mg/L and a minimum of 5.0 mg/L at all times [6]. These thresholds are integrated into MS4 permits administered by GDOT to ensure that roadway runoff does not cause violations of state water-quality standards or degrade designated trout habitats [1], [7].

Emerging evidence indicates that roadway runoff poses a growing threat to the temperature and DO stability of trout streams. Impervious surfaces such as asphalt and concrete absorb solar radiation and retain heat; during rainfall events, this stored heat is rapidly transferred to receiving waters, producing temperature differences that can exceed regulatory limits [8], [9]. Simultaneously, runoff transports organic matter, nutrients, and trace metals that elevate biochemical oxygen demand (BOD) and intensify microbial respiration, resulting in DO depletion [10], [11].

Urbanization further amplifies these risks. Expanding roadway networks and reduced riparian canopy cover diminish natural shading and infiltration capacity, leading to elevated stream temperatures and increased sediment loads [12], [13]. Studies in urbanized watersheds have shown that runoff water outfalls can raise stream temperatures downstream by 4-6 °F following rainfall events, occasionally surpassing the 2 °F limit specified by Georgia's trout stream criteria [8], [9]. Concomitant DO reductions driven by heated, DO-poor runoff and organic contamination can temporarily drop concentrations below 5.0 mg/L [14]. These short-duration events may not cause immediate mortality but can impose repeated sub-lethal stress on trout populations, weakening long-term reproductive viability [15], [16].

The ecological and economic consequences of such degradation are substantial. Trout angling contributes between US $72 million and $200 million annually to Georgia's economy [17], supporting rural tourism, recreation, and local livelihoods. Loss of viable trout habitat due to roadway-induced warming, sedimentation, or DO depletion threatens not only biodiversity but also this significant economic sector [2], [8]. Moreover, climate projections suggest that by 2050, temperature habitat for trout in Georgia could decline by more than 70 percent as air temperatures and land-use intensification increase [15]. These projections underscore the urgency of integrating rainfall runoff water temperature and DO management into GDOT's roadway design and maintenance practices.

Although national and international studies have examined highway runoff chemistry and contaminant toxicity [18], [19], quantitative data on GDOT's roadway-runoff impacts on trout stream temperature and DO remain scarce in the southeastern United States. Prior monitoring programs often relied solely on on-site sampling, which lacks the temporal resolution to detect sub-daily temperature or DO fluctuations. As a result, critical knowledge gaps persist regarding (1) the magnitude and duration of runoff-induced temperature shocks, (2) the recovery period for DO concentrations following rainfall events, and (3) spatial variability among GDOT outfalls across differing watershed settings.

To address these gaps, GDOT Research Project 23-11, "Roadway Runoff Impacts to Trout Streams Studies for MS4 Permit," was initiated to generate high-frequency, field-based measurements of temperature and DO changes downstream of roadway outfalls. By integrating traditional grab-sampling techniques with continuous sensor monitoring, this study provides the empirical foundation necessary to evaluate compliance with Georgia's trout stream standards and to inform the design of BMPs that mitigate roadway runoff impacts while ensuring the long-term sustainability of Georgia's cold-water ecosystems.

PROJECT OBJECTIVES

RP 23-11 was initiated in direct response to “Part 5.5: Special Condition for Trout Streams” of Georgia EPD’s General NPDES Stormwater Permit No. GAR041000 (permit issuance year 2022), which requires GDOT to prepare and implement a study plan assessing roadway runoff discharge through GDOT-managed outfalls to trout streams and to identify appropriate BMPs when necessary. To meet these regulatory obligations, the study established the following general and specific objectives, as approved in the project’s Statement of Work in 2023.

General Objectives

1. Develop and implement a study framework that systematically evaluates the temperature and DO-demand effects of roadway runoff discharges from GDOT outfalls to trout streams across North Georgia.

2. Determine whether GDOT roadway discharges are measurably affecting water temperature or DO concentrations in receiving trout waters and, if impacts are confirmed, identify feasible BMPs that can mitigate these effects.

Specific Objectives

1. Conduct field sampling and analysis of roadway runoff and instream water temperature and DO using traditional instrumentation, specifically, YSI® ProDSS multiparameter digital water quality meters to characterize baseline and rainfall-event conditions at representative GDOT outfalls and adjacent trout stream reaches.

2. Develop and deploy a novel, low-cost, remote-sensing system based on ESP32 microcontroller-controlled temperature and DO sensors to collect continuous, high-frequency water-quality data during rainfall events. This system leverages Internet-of-Things (IoT) connectivity for remote data acquisition, allowing comparison with field-validated YSI® ProDSS measurements.

3. Establish a direct comparison method between roadway-runoff and instream conditions by simultaneously measuring temperature and DO upstream, at, and downstream of GDOT discharge points. This approach enables quantification of the magnitude, duration, and recovery behavior of roadway-induced temperature and DO fluctuations.

These objectives were designed to generate a robust scientific basis for evaluating roadway-runoff impacts on sensitive cold-water ecosystems and to equip GDOT with practical, scalable monitoring and modeling tools. The outcomes directly support GDOT's mission to maintain safe transportation infrastructure while protecting Georgia's aquatic resources under state and federal environmental regulations.

RESEARCH TASKS

The RP 23-11, “Roadway Runoff Impacts to Trout Streams Studies for MS4 Permit,” was structured into five (5) major tasks designed to achieve the study’s objectives systematically while ensuring compliance with Georgia EPD’s NPDES Stormwater Permit (GAR041000) and Rule 391-3-6-.03(6)(ii),(v) governing trout stream water quality. Each task addressed a critical element of the project’s technical workflow from conceptual design through field implementation, data analysis, and reporting.

Task 1 – Literature Review

The GSU Research Project Team would collect and review relevant and up-to-date literature, research findings, and information pertaining to roadway runoff impacts on water temperature and DO level to trout streams from other State agencies, National Cooperative Highway Research Program, the Federal Highway Administration, and the USGS, and other sources. It would include on-site sampling and testing; novel use of remotely operated, low-cost water temperature and DO sensors controlled by an ESP32 system; and assessment methods for determining roadway runoff impacts to trout streams. This information would be obtained from published and unpublished reports, and peer-reviewed journal papers and conference proceedings via the university and on-line libraries such as Transportation Research Board, and contacts with neighboring DOTs and, if necessary, other public and private organizations. A literature review report would be prepared and delivered by the end of the third month.

Delivered: Comprehensive Literature Review submitted in the second quarter of 2024.

Task 2 – Site Visits of the Three (3) Selected Trout Streams and Finalization of Three (3) GDOT Outfalls at Each Trout Stream

There are only secondary trout streams within the GDOT's MS4 areas. The site visits of the three (3) selected trout streams in the Study Plan would be conducted in the second (2nd) Month. The major purpose for the site visits is to finalize the location of three (3) GDOT outfalls at each trout stream: one (1) at a bridge crossing, one (1) at about 0.5 mile upstream of the trout stream, and one (1) at about 1.0 mile upstream. The GDOT outfall at a bridge crossing is obvious to locate, but the other two (2) are not obvious and need to have a site visit to find the paths of roadway runoff from the GDOT outfalls located at about 0.5 mile upstream of the trout streams, and at about 1.0 mile upstream, respectively. The three (3) GDOT outfalls at each trout stream would be finalized after the site visits and consulting with GDOT's Technical/Implementation Manager, Brad McManus; Senior Ecology Team Leader, Jaime Collazo; Research Implementation Manager, Md Sabbir Ahmed; and representatives from other related GDOT's offices and resource agencies.

Delivered: The GSU research team conducted site reconnaissance on 3/1/2024 for the very first time and on 5/21/2024 for the second time. After coordination meetings with GDOT Office of Design Policy and Support, Office of Environmental Services, and Office of Research to finalize three (3) representative trout stream sites in the GDOT MS4 area. Site selection was based on trout stream classification, watershed size, riparian shading, accessibility, and proximity of GDOT outfalls within 1.0 mile upstream. The final study locations were:

Site 1: GA State Route 141 (Medlock Bridge Road) bridge crossing the Chattahoochee River

Site 2: GA State Route 120 (Charles Hardy Parkway) culvert crossing Powder Springs Creek

Site 3: GA State Route 293 (Kingston Highway NW) bridge crossing Two-Run Creek

These three (3) sites are shown in Figure 1 below which is taken from Google Earth Engine.

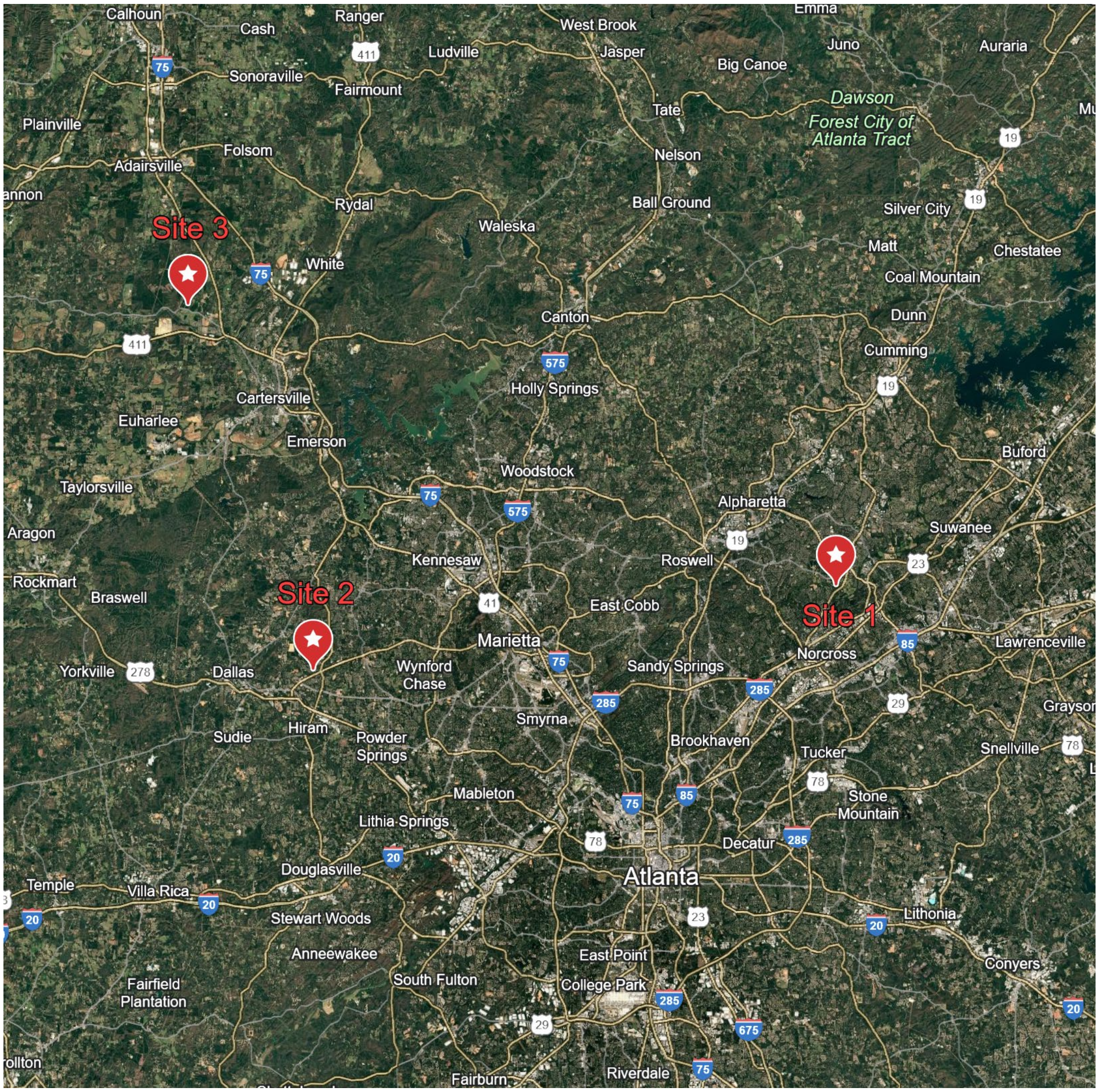


Figure 1. Map. Overview Map of Three (3) Sites Locations in the North of Atlanta, GA.

By design, each site included three (3) GDOT outfalls, one (1) at the bridge or culvert, one (1) approximately 0.5 mile upstream, and one (1) about 1.0 mile upstream to evaluate the spatial extent of roadway influence. Field visits ensured safe access, documented hydraulic connectivity between roadways and streams, and confirmed the presence of an USGS Gage Station providing supplemental discharge and precipitation data.

Task 3 – Purchase of YSI® ProDSS Multiparameter Digital Water Quality Meter and Low-Cost Water Temperature and DO Sensors with ESP32-Microcontroller System

Task 3 involved the purchase, design, fabrication, and calibration of three (3) complementary sensor systems to measure temperature and DO at multiple temporal resolutions. The instrumentation suite comprised:

1. YSI® ProDSS Multiparameter Digital Water Quality Meter for grab sample reference measurements.
2. ESP32-based remote sensors for real-time rainfall-event tracking; and
3. HOBO® continuous data loggers for long-term monitoring of diurnal temperature and DO fluctuations.

The key instrument used for on-site sampling and testing of water temperature and DO is YSI® ProDSS Multiparameter Digital Water Quality Meter, which includes ProDSS Handheld with GPS, ProDSS Optical DO Sensor, ProDSS combined Conductivity and Temperature Sensor. The key components for the remote water temperature and DO monitor include the low-cost water temperature and DO sensors and an ESP32 microcontroller system. The water temperature and DO sensors would be purchased from DFRobot®. ESP32 control board would be used as the brain of the remote sensor system paired with an external battery of at least 20,000 mAh for power. An external SD card would be used to log and store the data. Additionally, the ESP32 system would be outfitted with an onboard 2.4 GHz WiFi dual cores microcontroller integrated with an antenna. This board would allow for the system to have an internet connection through an on-site cellular hotspot. This remote sensor system would allow for remote monitoring of the data continually. Remote monitoring can inform about performance and ensure the system is properly functioning.

All sensors would be calibrated following procedures outlined in the Project's QAPP, which adhered to EPA and GA EPD QA/QC standards. Remote systems were equipped with batteries and cellular telemetry for continuous field operation and data transmission. The combined instrumentation ensured accurate, redundant, and spatially distributed data collection across variable flow and weather conditions.

Delivered: GSU research team received the newly purchased YSI® ProDSS with sensors and complete parts for remote sensors in the 2nd quarter of 2024. The research team calibrated and prepared field-ready instrumentation with QA/QC documentation.

Task 4 – Field Monitoring and Data Collection

The core part of the proposed research project was the field work required for on-site sampling and testing as well as deploying, maintaining, and operating the water temperature and DO sensors controlled by the ESP32 system.

According to the proposal, in the first year of the study, Site 1 with three (3) selected GDOT outfalls would be first studied with the additional tasks of assessing and perfecting the proposed monitoring protocols for on-site sampling and testing, deployment of remote water temperature and DO sensors, and setting up the ESP32 Control System. These tasks were anticipated to take about five (5) months. The developed protocols will then be applied to the three (3) sites alternately monthly. The goal was to make sure each site has a complete set of monthly data covering all the seven (7) months from late Spring in April to late Fall in October during the 2-year period.

Delivered: The monitoring campaign extended from April 2024 through October 2024 in the first year and similarly from April 2025 through October 2025 in the second year, covering two (2) full summer seasons for sampling. During the first monitoring year (2024), grab-sample data were collected using the YSI® ProDSS instrument at upstream, outfall, and downstream stations.

In the second monitoring year (2025), the GSU research team deployed the complete suite of YSI®, HOBO®, and ESP32-based systems. Continuous HOBO® data loggers recorded 5-minute-interval data, while the ESP32 sensors captured high-frequency (10-minute-interval) rainfall responses during precipitation. Field maintenance, calibration verification, and data retrieval were conducted twice monthly. Sampling focused on capturing both dry-weather baseline and rainfall-event conditions, enabling direct comparisons between roadway-runoff influences and natural stream fluctuations.

Task 5 – Development and Application of a Direct Comparison Method between the Water Temperature and DO in GDOT Roadway Runoff and Those in Instreams – Data Analysis and Assessment

A direct comparison method between the water temperature and DO in GDOT roadway runoff and those in instream (including immediately upstream and immediately downstream of the discharging point from GDOT outfalls into trout streams) will be developed in order to determine GDOT's roadway runoff impacts to trout streams, based on the relevant criteria for water temperature and DO level in trout streams in Georgia Rule 391-3-6-.03(6)(ii),(v). According to the proposal, data will be analyzed and summarized in the third (3rd) Month and used for the direct comparison method, which will be applied to all of the selected three (3) trout streams with three (3) GDOT outfalls at each trout stream.

Delivered: Field observations, rainfall data, and hydrologic parameters used to evaluate roadway runoff impacts and assess compliance with Georgia trout stream standards. Analytical methods included time-series and event-based analysis of temperature and DO variations; correlation of rainfall intensity and antecedent temperature with downstream responses; and application of the Rational Method to estimate roadway runoff flow rates and their mixing potential with streamflow.

A direct comparison framework was used to quantify temperature and DO differences between upstream, at-outfall, and downstream locations during both dry and wet conditions. The resulting data supported a preliminary mass balance model linking runoff temperature inputs to observed stream-temperature responses. A comprehensive report and result summary were delivered quarterly.

These five research tasks established a comprehensive technical framework for assessing roadway-runoff impacts on trout stream temperature and DO conditions. The methodology developed under RP 23-11 is scalable, reproducible, and directly applicable to GDOT’s ongoing efforts to maintain MS4 permit compliance and aquatic habitat protection throughout Georgia’s mountain and Piedmont regions.

CHAPTER 2. LITERATURE REVIEW

Trout streams are among the most temperature-sensitive aquatic ecosystems in the southeastern United States. Maintaining stable temperature and DO regimes is essential to preserving habitat quality, supporting native biodiversity, and sustaining the economic value of recreational trout fisheries. GDOT operates an extensive roadway network that intersects numerous trout-designated streams in the Blue Ridge and Ridge-and-Valley ecoregions, where steep terrain, shallow soils, and impervious roadway surfaces can intensify roadway runoff. These discharges, when untreated, can alter temperature conditions and reduce DO concentrations in receiving waters, potentially violating Georgia Rule 391-3-6-.03(6)(ii),(v) and endangering cold-water biota. [6]

Understanding the mechanisms and magnitude of roadway-runoff impacts on stream temperature and DO dynamics has therefore become a priority under GDOT's MS4 Permit (GAR041000, Part 5.5), which requires the agency to evaluate roadway discharges into trout streams and to identify best management practices (BMPs) that minimize potential harm. The literature reviewed herein summarizes the physical processes, ecological implications, and knowledge gaps relevant to the RP 23-11 study objectives.

IMPORTANCE OF TROUT

Trout are among the most sensitive and ecologically valuable cold-water species in North America, serving as bioindicators of freshwater ecosystem health and water-quality integrity. In Georgia, native brook trout (*Salvelinus fontinalis*) (see Figure 2) along with introduced rainbow trout (*Oncorhynchus mykiss*) (see Figure 3) and brown trout (*Salmo trutta*) (see Figure 4) inhabit headwater streams of the

Blue Ridge and Ridge-and-Valley ecoregions, where consistently cool, DO-rich conditions are required for survival and reproduction [2], [15]. These species thrive in water temperatures generally below 67 °F (19 °C) and begin to experience temperature stress at temperatures exceeding 70 °F (21 °C), with lethal effects possible above 72 °F (22 °C) [3], [4].

Figure 2. Illustration. Brook Trout (*Salvelinus fontinalis*)

Figure 3. Illustration. Rainbow Trout (*Oncorhynchus mykiss)*

Figure 4. Illustration. Brown Trout (*Salmo trutta*)

The importance of trout as bioindicators extends beyond temperature and DO. As top predators and nutrient recyclers, trout regulate aquatic invertebrate populations and influence energy flow through food webs, maintaining balance within cold-water stream ecosystems [20]. Their presence signifies stable hydrologic and temperature regimes, effective riparian shading, and low nutrient enrichment conditions characteristic of minimally disturbed mountain headwaters. Consequently, trout populations are widely used as biological indicators of watershed integrity and environmental change [2], [16].

From an economic and cultural perspective, trout fisheries are of substantial importance to Georgia and the broader Appalachian region. Recreational angling in North Georgia's trout streams contributes an estimated $72–200 million annually to the State's economy through tourism, equipment sales, and local business revenue [17]. The Georgia Wildlife Resources Division stocks more than one (1) million trout each year to support this industry, underscoring its significance to both rural economies and state-level recreation management. Maintaining cold-water habitat quality is therefore essential not only for ecological conservation but also for sustaining long-term economic benefits tied to outdoor recreation and natural resource stewardship.

Trout are also sentinel species for climate and land-use change. Projected increases in air temperature and altered hydrologic regimes may reduce the extent of viable trout habitat by up to 70 percent by 2050 in parts of the southern Appalachians [5], [15]. These pressures compound the localized impacts of roadway runoff, riparian deforestation, and urban development. The cumulative result is a narrowing temperature margin between suitable and marginal habitat conditions. Because of their strict temperature and DO requirements, trout serve as an early-warning indicator of hydrologic and land-use stress in Georgia's headwater systems.

For GDOT, the ecological and regulatory significance of trout streams is twofold. First, these waters are subject to enhanced protections under Georgia Rule 391-3-6-.03(6)(ii),(v), which prohibits any anthropogenic temperature increase greater than 2 °F (1.1 °C) in secondary trout waters and none in primary trout waters. Second, maintaining these standards is integral to MS4 permit compliance, which requires GDOT to demonstrate that roadway runoff water discharges do not adversely affect temperature or DO in designated trout habitats. Compliance is not only a legal obligation but also a reflection of environmental stewardship, aligning with GDOT's broader mission to integrate transportation safety with ecosystem protection.

In summary, trout occupy a pivotal ecological, economic, and regulatory role in Georgia's mountain watersheds. Their sensitivity to small-scale temperature and DO fluctuations makes them ideal indicators for assessing the environmental performance of transportation infrastructure. The protection of trout streams, therefore, represents both a scientific imperative to preserve cold-water biodiversity and a policy requirement to ensure GDOT's operational compliance and sustainable management of roadway runoff in sensitive aquatic environments.

TROUT HABITAT REQUIREMENTS

Trout habitat quality in cold-water streams is determined primarily by the interaction of temperature, DO, streamflow, substrate composition, and riparian cover. Among these, temperature and DO are the two (2) most sensitive and tightly coupled environmental parameters influencing trout distribution, metabolism, and reproduction [2], [20]. Trout species native and introduced to Georgia have evolved to occupy headwater systems where temperatures remain consistently cool and DO concentrations high throughout the year.

Temperature Tolerance

Numerous laboratory and field studies have established that trout prefer temperatures between 50–64 °F (10–18 °C) for optimal growth and feeding efficiency [3], [4]. Metabolic rates increase rapidly above 68 °F (20 °C), causing higher oxygen demand and reduced aerobic performance [15]. Temperatures exceeding 72 °F (22 °C) for sustained periods are typically lethal for most trout life stages, particularly juveniles and eggs [2]. Short-term exposure above these thresholds can lead to behavioral avoidance, migration to cooler refugia, or local displacement from preferred reaches.

The Georgia Rule 391-3-6-.03(6)(ii),(v) reflects these biological limits by requiring that primary trout waters show no measurable temperature increase and that secondary trout waters exhibit no elevation greater than 2 °F (1.1 °C) above natural background conditions. These criteria ensure that human activities including roadway runoff discharges do not disrupt the narrow temperature envelope necessary to sustain cold-water species.

DO Requirements

Trout requires abundant and stable oxygen concentration levels to support high metabolic and reproductive rates. The Georgia trout stream standard mandates a daily average of 6.0 mg/L and a minimum of 5.0 mg/L DO at all times, consistent with ecological thresholds identified in national fisheries studies [3]. Empirical observations indicate that when DO falls below 5.0 mg/L, trout exhibit reduced feeding, increased respiration stress, and impaired egg development [16]. Chronic exposure to even mild hypoxia (< 6.0 mg/L) over repeated rainfall events can suppress growth and weaken disease resistance [5].

Diurnal DO cycles are a critical aspect of trout stream dynamics. Concentrations typically peak in the afternoon due to photosynthesis and reach minimum before dawn. During summer low-flow conditions, nighttime DO concentrations may approach regulatory limits even in pristine systems. Roadway runoff that introduces warm, DO-poor water or organic matter at these times can push DO below critical thresholds, compounding physiological stress [14].

IMPACTS OF ROADWAY RUNOFF ON WATER TEMPERATURE AND DO IN TROUT STREAMS

The interaction between roadway runoff water and receiving trout streams is governed by a combination of temperature, hydrologic, and biochemical processes that influence the stream's temperature regime and DO dynamics. While these processes are often transient, their magnitude and recurrence can have cumulative ecological consequences for cold-water species such as trout. The literature consistently identifies runoff water temperature enrichment and DO depletion as two of the most significant and under-quantified impacts of roadway discharges into sensitive headwater systems [2], [8], [9].

Temperature Enrichment and Heat Transfer Mechanisms

Impervious roadway surfaces including asphalt, concrete, and metal culverts absorb and store large quantities of solar radiation during daylight hours. When rainfall occurs, this stored heat is rapidly transferred to the runoff water, resulting in elevated runoff temperatures that can be several degrees higher than ambient stream conditions [8]. The warmed runoff enters trout streams through direct outfalls, bridge scuppers, and culvert discharges, producing temperature differences that can raise instream temperatures by 2–6 °F (1–3 °C) within minutes of rainfall onset [9].

The degree of stream heating depends on a combination of factors, including (1) antecedent pavement temperature, (2) rainfall intensity and duration, (3) drainage area size, (4) baseflow volume of the receiving stream, and (5) shading and riparian cover [13], [15]. Small streams with limited dilution capacity are particularly vulnerable, as even low-volume discharges can overwhelm the stream's temperature equilibrium.

In Georgia's mountain regions, where baseflows are low during summer months, rainfall on hot pavement can produce short-lived but ecologically meaningful temperature excursions. Earlier studies have reported similar magnitudes in other temperate regions. Herb et al. [8] observed a 5 °F rise in small Minnesota streams within 15 minutes of rainfall on sun-heated pavement, while Runge et al. [9] found a 3–4 °F increase in midwestern rainfall events with minimal canopy cover. Although these short-term spikes may not exceed lethal thresholds, repeated temperature shocks can induce physiological stress, disrupt feeding behavior, and reduce trout reproductive success [3], [4].

Riparian canopy removal adjacent to transportation corridors exacerbates this warming effect. Loss of shading increases incoming solar radiation and reduces nocturnal cooling, extending diurnal temperature amplitudes and further narrowing the margin for trout temperature tolerance [2]. In such conditions, roadway runoff acts as both a direct temperature input and an indirect amplifier of broader watershed warming trends.

DO Dynamics and DO Demand

The inverse relationship between temperature and DO solubility amplifies the ecological risk of roadway runoff. As water temperature rises, DO saturation decreases by approximately 0.4 mg/L for each 1 °C increase, meaning even modest warming can reduce available DO by 10–15 % [5], [15]. In addition to temperature effects, roadway runoff introduces BOD through organic particulates, fine sediments, and hydrocarbons that fuel microbial respiration and accelerate DO depletion [10], [11].

Several studies have demonstrated measurable DO reductions in receiving waters following rainfall events. Sullivan et al. [14] reported DO depressions exceeding 1.5 mg/L within an hour of runoff water discharge in small urban streams. Similarly, Haag et al. [16] observed that post-rainfall DO minima frequently occurred at night when respiration rates peak and photosynthetic DO production ceases.

Combined Temperature–DO Stress and Ecological Implications

The combined effect of elevated temperature and reduced DO poses a dual threat to trout populations. Warmer water increases metabolic DO demand while simultaneously decreasing DO availability, an imbalance that leads to metabolic exhaustion, altered behavior, and, under severe conditions, mortality [3], [15]. Temperature events accompanied by DO depletion are particularly detrimental to juvenile trout and eggs, which require stable DO concentrations above 7 mg/L for normal development [20]. In the southeastern Appalachian region, where summer baseflows are already low, roadway-runoff events can exacerbate hypoxic stress precisely when natural DO levels are at their seasonal minimum. Moreover, these impacts are often spatially localized and confined to zones within 50–100 meters downstream of outfalls; however, they can recur frequently during rainfall seasons, cumulatively degrading habitat quality [16].

PRIOR DOT AND ACADEMIC STUDIES ON ROADWAY RUNOFF WATER IMPACTS

Numerous state Departments of Transportation (DOTs) and academic institutions have investigated the relationship between roadway runoff water discharges and receiving-water impacts, with particular emphasis on temperature, DO, and aquatic ecosystem health. Early investigations by the Minnesota DOT and Wisconsin DOT established that heated runoff from impervious pavements can raise small stream temperatures by 3–6 °F (1.5–3.3 °C) following summer rainfall events [8], [9]. These studies confirmed that temperature loading from highway surfaces is largely a function of solar radiation, pavement type, and rainfall duration, with the most significant impacts observed in shallow headwater systems.

The Oregon DOT and Washington State DOT later expanded on these findings by integrating temperature modeling into environmental compliance frameworks for salmonid streams, demonstrating that modest reductions in impervious surface area or increases in riparian shading can mitigate roadway-related warming [21]. The North Carolina DOT evaluated stream temperature and DO near highway outfalls and reported transient temperature differences of 1–2 °F and short-term DO declines of 0.5–1 mg/L following convective rainfalls [16]. However, no research work was found to be done in trout waterbodies of the northern Georgia region, and none from GDOT's roadway runoff.

REGULATORY CONTEXT AND MS4 PERMIT FOCUS

The regulatory framework for this study is anchored in GA EPD Rule 391-3-6-.03(6)(ii),(v), which defines temperature and DO standards for trout streams, and in Part 5.5 of the General NPDES Stormwater Permit No. GAR041000, governing GDOT's MS4 operations. Under this permit, GDOT must evaluate the effects of roadway runoff water discharges on trout stream water quality and implement control measures where exceedances of temperature or DO criteria are observed. Specifically, the rule requires that primary trout waters exhibit no human-induced temperature increase above natural background; and secondary trout waters exhibit no temperature increase greater than 2 °F (1.1 °C) and maintain daily average DO ≥ 6.0 mg/L, with a minimum of 5.0 mg/L always. There are only secondary trout streams within the GDOT's MS4 areas.

The MS4 program mandates that GDOT integrate monitoring, modeling, and BMPs into its storm water system to ensure compliance with these criteria. Within this context, RP 23-11 supports GDOT's regulatory responsibilities by generating empirical data to confirm whether roadway discharges alter trout stream temperature and DO regimes and by providing analytical tools for assessing compliance across varying climatic and hydrologic conditions. The project also contributes to broader federal mandates under the Clean Water Act §402(p), ensuring that transportation infrastructure development remains consistent with aquatic-life protection standards.

PRELIMINARY MITIGATION AND BMP STRATEGIES

A review of prior literature and DOT studies reveals several effective mitigation strategies for minimizing the temperature and DO impacts of roadway runoff on cold-water streams.

Green Infrastructure and Riparian Restoration

Riparian vegetation provides shading that reduces solar heating of both pavement and stream surfaces. Re-establishing forested buffers can lower near-stream air temperatures by up to 4 °F and reduce diurnal temperature variability [2]. Vegetated swales and infiltration trenches promote subsurface cooling and oxygenation by enhancing infiltration and delaying runoff water delivery to the stream [16].

Structural BMPs

Detention ponds, wet ponds, and constructed wetlands act as temperature buffers by allowing heat dissipation before discharge [21]. Bioswales and permeable pavements have demonstrated efficacy in reducing peak flow and initial runoff temperature through increased contact with cooler soil layers [9].

Hydrologic and Flow-Control Measures

Controlled outlet designs and reservoir-release management can attenuate flow velocities and minimize erosive and temperature shock to receiving waters [22]. Incorporating these systems into roadway drainage retrofits can substantially mitigate temperature impacts when coupled with upstream vegetative shading.

Operational and Maintenance Practices

Regular inspection of culverts and sediment basins, debris removal, and targeted application of de-icing compounds can reduce pollutant loads that indirectly influence DO levels by increasing BOD [10].

CHAPTER 3. METHODOLOGY

STUDY SITES AND OUTFALL SELECTION

The study site selection process for GDOT RP 23-11 was designed to ensure that monitoring locations accurately represent the range of roadway–stream interactions found within Georgia's trout stream regions covered under the GDOT MS4 Permit (GAR041000, Part 5.5). Site selection and outfall prioritization were conducted jointly by the Georgia Southern University (GSU) Research Team and the GDOT Office of Design Policy & Support with its coordination with the relevant district maintenance personnel.

Criteria for Site Selection

The selection criteria were guided by the Study Plan, which specifies that representative trout streams be chosen within GDOT's MS4 area to capture variations in stream size, gradient, canopy cover, and roadway proximity. The primary criteria used to identify suitable sites included:

Official Designation as Trout Waters – The selected sites needed to be located at streams officially designated as trout waters by the GA EPD under Rule 391-3-6-.03(15).

Presence of GDOT Outfalls within One (1) Mile of Trout Waters – Candidate locations were screened using GDOT's drainage inventory and GIS data to identify roadway outfalls that discharge directly to or within one (1) linear mile upstream of trout stream segments. Priority was given to outfalls associated with state routes or bridge crossings to ensure accessibility and relevance to transportation infrastructure.

Hydrologic and Monitoring Infrastructure – Preference was given to sites with nearby USGS gaging stations providing continuous data on streamflow, precipitation, and instream temperature, enabling integration of hydrologic context with field observations.

Outfall Area Representativeness – Outfalls were selected to represent a deliberate gradient of watershed scales, from narrow, shaded headwater channels to broader, higher-baseflow main stems, ensuring that the monitored sites captured the full range of temperature buffering capacities and runoff-response behaviors characteristic of Georgia's trout stream systems

Field Accessibility and Safety – Each site was evaluated for safe access, and adequate space for deploying multiple sensor systems (YSI®, HOBO®, and ESP32-based instruments). Consideration was also given to minimizing vandalism risk and ensuring stable power and mounting configurations for long-term sensor deployment.

Coordination with GDOT District Engineers – Final site confirmation occurred following field reconnaissance conducted jointly with GDOT district staff. Locations were reviewed to ensure that field work would not interfere with roadway operations or maintenance activities.

Selected Trout Stream Sites

Based on these criteria, three (3) trout streams were selected to represent a range of geographic, hydrologic, and roadway conditions within GDOT's MS4 jurisdiction. Each site includes three (3) GDOT outfalls: one (1) located near a bridge or culvert crossing, one (1) approximately 0.5 mile upstream, and one (1) approximately 1.0 mile upstream. This spatial arrangement allowed the research team to evaluate temperature and DO gradients along the flow path and to distinguish roadway-runoff influences from natural background variation.

Site 1 – GA State Route 141 (Medlock Bridge Road) bridge crossing the Chattahoochee River

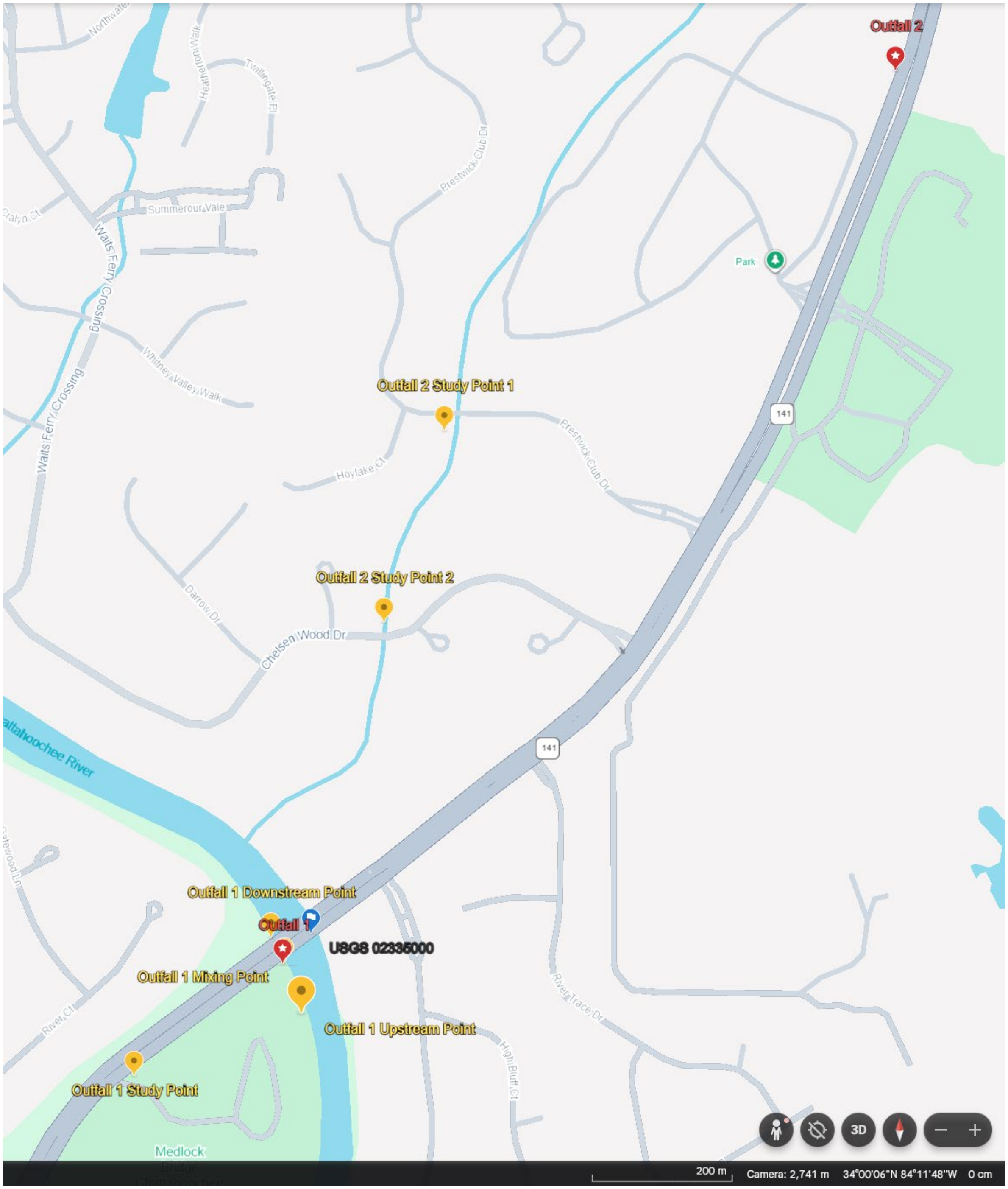


Figure 5. Map. Site 1 adjacent area: two (2) outfall and six (6) study points with nearby USGS base station on Chattahoochee River

Stream Type: Large, secondary trout stream with mixed urban and forested land cover.

Hydrologic Reference: USGS 02335000 – Chattahoochee River near Norcross, GA.

Site Description: Located in Fulton County, Site 1 represents a broad, high-baseflow system influenced by multiple roadway discharges within a one-mile reach. Two (2) GDOT Outfalls near the bridge and road, three (3) Study Points along the path of runoff drainage and additional upstream and downstream structures along the River provide opportunities for assessing cumulative runoff effects from impervious surfaces.

Purpose: Serves as a reference for large riverine trout waters receiving urban roadway inputs under regulated flow conditions.

Buford Dam Influence: Site 1 is strongly moderated by cold-water releases from Buford Dam, which discharges hypolimnetic water from Lake Lanier according to daily hydropower and flow-management schedules. These releases maintain a year-round cool temperature in the Chattahoochee River, with release waters typically 45–60 °F depending on season and generation patterns. Travel time from Buford Dam to Site 1 is approximately 2.5–3 hours, allowing released water to propagate downstream while preserving much of its cold-water signature. As a result, Site 1 experiences reduced diurnal variability, enhanced thermal buffering capacity, and a stable temperature baseline that limits long-duration warming. Without the influence of releases from Buford Dam, trout would not be able to survive in this reach of the Chattahoochee.

Site 2 – GA State Route 120 (Charles Hardy Parkway) culvert crossing Powder Springs Creek

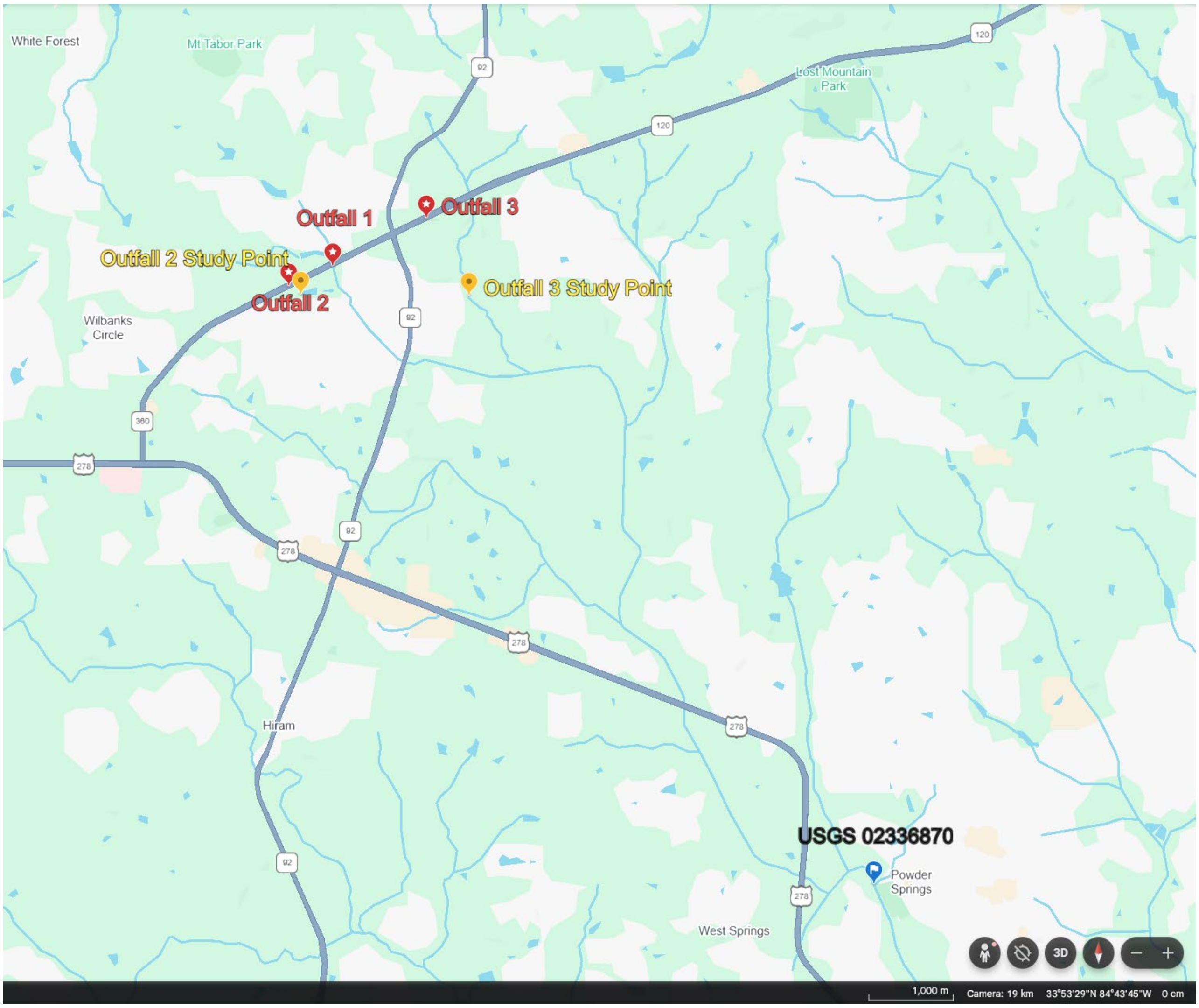


Figure 6. Map. Site 2 adjacent area: three (3) GDOT outfalls and two (2) study points with the nearest USGS base station

Stream Type: Medium-sized secondary trout stream with suburban watershed and moderate canopy cover.

Hydrologic Reference: USGS 02336870 – Powder Springs Creek near Powder Springs, GA.

Site Description: Located in Cobb County, Site 2 includes three (3) GDOT Outfalls and two (2) adjacent Outfall Study Points discharging through culverts along the highway corridor. The stream's moderate slope and partial shading make it sensitive to both temperature and DO fluctuations during summer rainfall events.

Purpose: Represents a mid-sized, semi-urban trout stream, which is typical of GDOT's northern MS4 area.

Site 3 – GA State Route 293 (Kingston Highway NW) culvert crossing Two-Run Creek

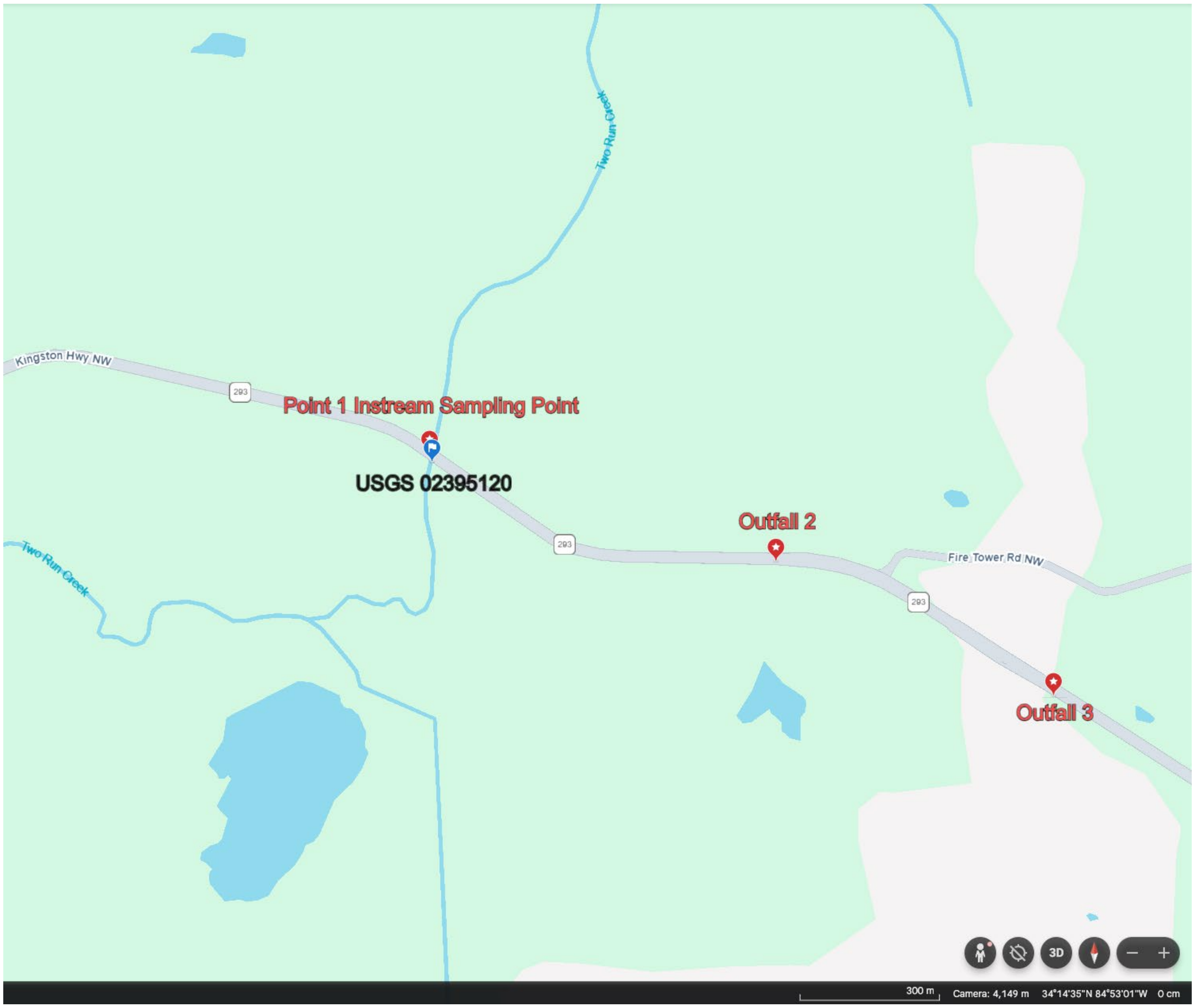


Figure 7. Map. Site 3 adjacent area: two (2) Outfalls and one (1) in-stream monitoring point with nearby USGS base station on Two-Run Creek

Stream Type: Small, high-gradient secondary trout stream in predominantly rural watershed conditions.

Hydrologic Reference: USGS 02395120 – Two-Run Creek near Kingston, GA.

Site Description: Located in Bartow County, Site 3 features two (2) GDOT outfalls and one (1) Instream Sampling Point along the GA state route 293. The stream is characterized by shallow riffle-pool morphology and dense riparian shading.

Purpose: Serves as a representative headwater site for evaluating localized roadway runoff impacts in smaller trout stream systems with limited mixing potential.

Table 1. Outfall and Study Point features table for Three Sites

Site No.	Outfall No.	Location Coordinates	Approx. Total Drainage Area (Acres)	Approx. Distance from River/Creek (feet)
Site 1	Outfall 1	33° 59’ 48.4” N 84° 12’ 08.5” W	16.7	7
	Outfall 1 Study Point	33° 59’ 32.2” N 84° 12’ 26.2” W	10.2	740
	Outfall 2	34° 00’ 28.7” N 84° 11’ 35.2” W	9.6	4,992
	Outfall 2 Study Point 1	34° 00’ 13.0” N 84° 11’ 58.9” W		2,140
	Outfall 2 Study Point 2	34° 00’ 03.8” N 84° 12’ 03.0” W		1,175
Site 2	Outfall 1	33° 55’ 22.3” N 84° 45’ 19.4” W	22.4	5
	Outfall 2	33° 55’ 14.1” N 84° 45’ 38.9” W	6.3	2,315
	Outfall 2 Study Point	33° 55’ 11.0” N 84° 45’ 34.9” W		1,490
	Outfall 3	33° 55’ 39.5” N 84° 44’ 37.5” W	15	6,670
	Outfall 3 Study Point	33° 55’ 10.6” N 84° 44’ 18.5” W		3,380
Site 3	Instream Sampling Point	34° 14’ 34.5” N 84° 53’ 23.1” W	0	0
	Outfall 2	34° 14’ 27.3” N 84° 52’ 55.7” W	13.7	2,550

	Outfall 3	34° 14’ 18.0” N 84° 52’ 31.7” W	1.5	4,700

Rationale for Multi-Site Design

The three (3) site configuration was selected to ensure that the study captures both spatial and hydrologic diversity. Site 1 provides insight into urbanized, high-baseflow systems where roadway discharges are diffused; Site 2 reflects intermediate conditions with mixed land use; and Site 3 exemplifies smaller, steep-gradient systems where runoff effects are most pronounced.

This nested monitoring design enables cross-site comparison of roadway-runoff impacts as a function of stream size, canopy cover, and watershed imperviousness. It also supports transferability of findings to other GDOT districts and facilitates the development of region-specific management recommendations for trout stream protection under the MS4 program.

INSTRUMENTATION AND SENSOR SYSTEMS

A multi-platform sensor framework was developed for RP 23-11 to accurately capture both long-term baseline conditions and short-term rainfall-event responses in trout streams. This integrated system combined three (3) complementary monitoring technologies: (1) high-accuracy YSI® ProDSS handheld instruments, (2) custom-built ESP32-based remote sensors, and (3) HOBO® continuous DO/temperature data loggers. Each system played a distinct role in ensuring comprehensive temporal coverage, redundancy, and cross-validation of temperature and DO data.

Figure 8. Photo. YSI® ProDSS Multiparameter Instrument Reading Screen

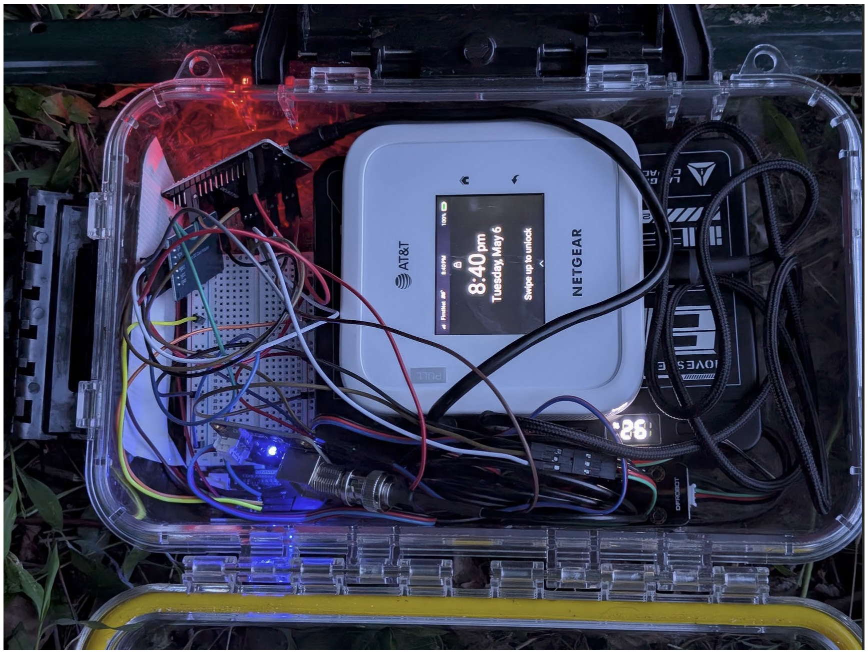


Figure 9. Photo. ESP32-based Remote Sensor System

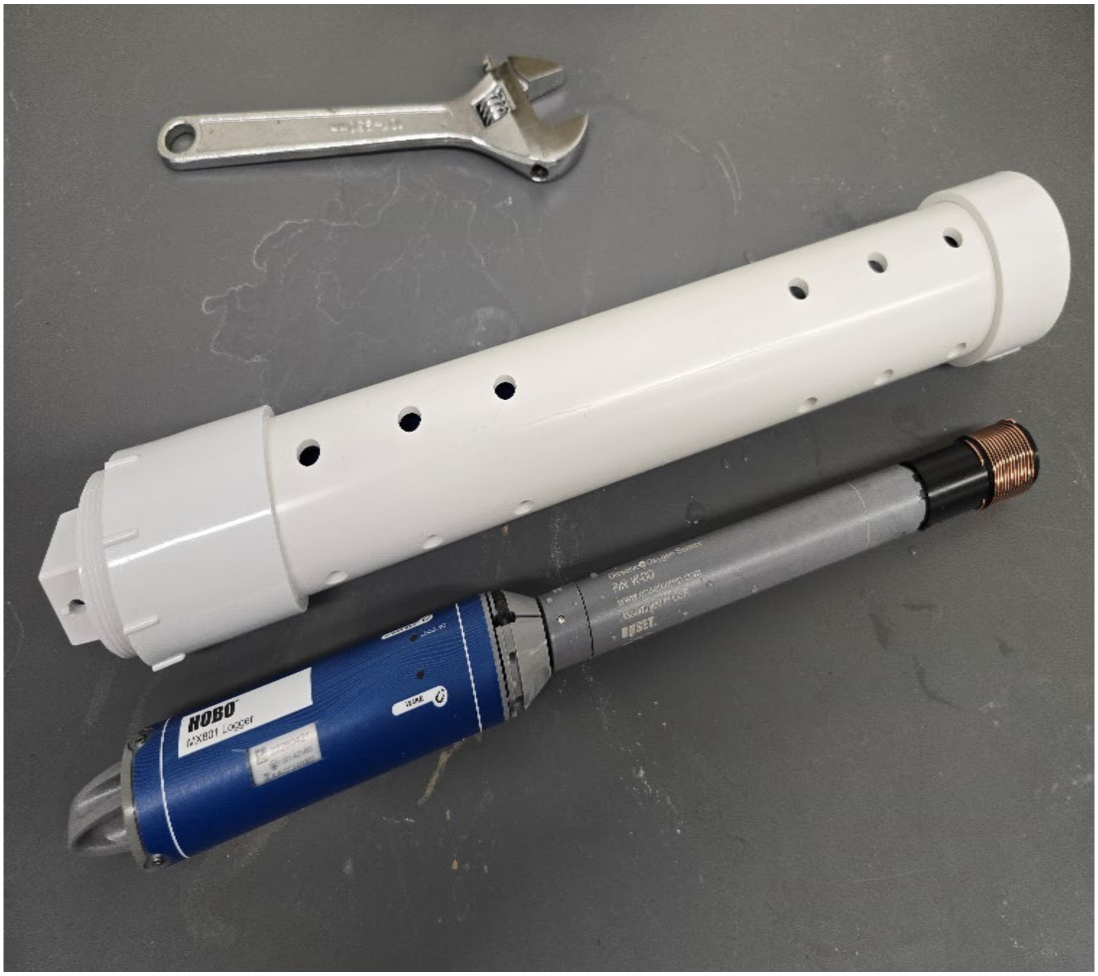


Figure 10. Photo. HOBO® Data Logger with DO/Temperature Sensor Attached and PVC Protective Housing

All instruments and sensors were deployed and maintained under the quality-assurance procedures established in the QAPP, which specified calibration frequency, data verification steps, and performance acceptance criteria in accordance with EPA QA/R-5 and GA EPD environmental monitoring standards.

YSI® ProDSS Multiparameter Handheld Instrument

The YSI® ProDSS Multiparameter Instrument served as the reference-grade instrument for grab-sample measurements and field calibrations. Each ProDSS unit was equipped with digital optical DO, temperature/conductivity, and pH sensors. The instrument's ±0.1 °F temperature accuracy and ±0.1 mg/L DO precision provided the baseline against which all other sensors were verified.

During field campaigns, ProDSS readings were collected at upstream, outfall, and downstream stations immediately before, during, and after rainfall events. Measurements were taken at mid-depth, away from turbulence and air entrainment, to ensure representative values of in-stream conditions. The handheld meters also supported on-site calibration checks of the HOBO® and ESP32 systems prior to each deployment. All readings were automatically geotagged and timestamped using the in-built GPS system for traceability in data analysis.

HOBO® MX-801 Data Loggers

To establish long-term temporal trends and diurnal variability, in the second year, HOBO® MX-801 Optical DO and temperature loggers (by Onset Computer Corp., MA, USA) were deployed continuously at each study site. These loggers provided 5-minute-interval recordings of DO 0–20 mg/L range, ±0.1 mg/L accuracy and temperature -40°F to 122°F (-40°C to 50°C), ±0.1 °F accuracy.

Figure 11. Photo. HOBO® Datalogger Attached with Concrete Block (25 lb) Locked in Place with Zip-Tie Cables.

Sensors were installed in protective PVC housings attached to concrete blocks to minimize movement during high-flow events. Deployment depths ranged between 0.25 and 0.5 m below the water surface, depending on local hydraulic conditions. Each HOBO® logger was factory-calibrated and field-validated against the YSI® ProDSS sensor prior to installation.

Biweekly maintenance visits included:

- Retrieval and data offload using HOBO® Connect software on smartphone
- Visual inspection and cleaning for fouling, sediment accumulation, or biofilm growth

This continuous monitoring system provided baseline DO and temperature datasets that enabled evaluation of seasonal variation, diurnal cycles, and recovery behavior following rainfall-induced disturbances.

ESP32-Based Remote Sensors

To capture rapid hydrologic and temperature responses during rainfall events, the project developed and deployed low-cost ESP32 microcontroller–based remote sensors using the ESP32 DevKit V1 platform integrated with DFRobot® waterproof temperature probes and DFRobot® Galvanic DO sensors. Each unit operated on a 3.7 V lithium battery supported by a 20,000 mAh external power bank and featured on-board micro-SD data logging with cellular telemetry for near real-time monitoring. To supply Wi-Fi connectivity, a mobile data hotspot was installed within each deployed sensor box to transmit collected data to a cloud-based storage server for remote access and redundancy. However, field deployment revealed significant performance limitations. The study sites were located in low-signal areas near rivers and creeks, resulting in intermittent connectivity and frequent data transmission failures. The constant reconnection attempts caused the hotspot to draw excessive power, fully discharging the 20,000 mAh battery within approximately 10 hours of operation. To extend operational longevity, the battery capacity was increased by 3.5 times (to 70,000 mAh), and a hotspot device with roughly three (3) times higher energy efficiency was adopted. These modifications improved total runtime to about 70 hours, though some variability in data continuity remained.

Figure 12. Photo. Deployed ESP32-based Remote Sensor System at Site 1 Outfall 2

These compact sensors were programmed to log data at 10-minute-intervals, ensuring sufficient resolution to capture short-duration temperature differences often missed by hourly instruments. The sensor housings were constructed from weatherproof ABS enclosures and mounted on steel deployment rods at outfalls.

Prior to field use, each ESP32 unit underwent bench-scale calibration in the GSU on-campus creek and GSU Water and Environmental Research Laboratory (WERL), where both readings were compared to those from YSI® ProDSS.

Field validation during the 2025 monitoring season confirmed that ESP32 sensors accurately tracked temperature increases of 1–2 °F within 10-minute resolution during rainfall events, aligning with simultaneous YSI® observations. These systems proved invaluable for quantifying rainfall-event timing, intensity, and recovery, while offering a scalable and cost-effective monitoring option for GDOT's MS4 compliance network.

Calibration and Cross-Validation Protocols

Calibration procedures were implemented through a combination of laboratory pre-deployment checks and field verification routines as detailed in the QAPP.

Laboratory Calibration:

YSI® ProDSS sensors were cross validated for calibration accuracy daily using manufacturer-supplied standards for DO (100-% air saturation), pH (4, 7, 10 buffers), and conductivity (1,000 micro-Siemens/cm). HOBO® and ESP32 sensors were simultaneously submerged in a temperature-controlled calibration bath and compared to YSI® reference readings. Correction coefficients were applied as needed before field deployment.

Field Calibration and Validation:

At each deployment, YSI® spot measurements were taken immediately adjacent to HOBO® and ESP32 sensors to confirm field accuracy. Deviations greater than ±0.2 °F (temperature) or ±0.3 mg/L (DO) triggered recalibration. Pre-and post-deployment two-point calibration checks for DO ensured data consistency and accounted for potential drift or fouling.

FIELD MONITORING PROTOCOLS

All field data collection under RP 23-11 was conducted in accordance with the approved QAPP, which was developed jointly by the GSU Research Team and GDOT's Office of Design Policy & Support. The QAPP established uniform procedures for site preparation, sample collection, sensor deployment, calibration verification, data logging, and safety management. The protocols ensured that all data collected were scientifically defensible, comparable across sites, and compliant with EPA QA/R-5 and GA EPD standards for water-quality monitoring.

The field monitoring program combined manual grab sampling, continuous on-site logging, and event-based rainfall monitoring to capture both baseline and transient roadway runoff impacts on trout stream temperature and DO. Sampling was performed during the warm season (April–October) over two (2) consecutive years to coincide with the period of greatest temperature stress for trout streams.

On-Site Sampling Using YSI® ProDSS Instruments

Manual on-site sampling was performed using YSI® ProDSS multiparameter handheld instruments at all three (3) study sites to obtain reference-grade temperature and DO measurements. Sampling events were scheduled to capture pre-rainfall, active rainfall, and post-rainfall recovery conditions.

- **Pre-rainfall sampling:** Conducted within 12 hours before forecasted rainfall to establish baseline conditions
- **During-rainfall sampling:** Performed when rainfall exceeded 0.5 inch in 24 hours or during active runoff discharge from GDOT outfalls
- **Post-rainfall sampling:** Conducted 6-12 hours after rainfall cessation to document stream recovery and DO re-aeration

At each sampling visit, readings were taken at three (3) standard stations, upstream (background reference), outfall (mixing zone), and downstream (impact reach), using mid-depth immersion to avoid surface turbulence or substrate interference. YSI® ProDSS measurements were recorded to 0.1

°F (temperature) and 0.1 mg/L (DO) precision, with duplicate readings collected to take average and for verification.

All grab-sample data were logged with auto GPS coordinates, date, time, and rainfall context. These discrete measurements served as calibration and QA/QC benchmarks for both continuous HOBO® loggers and remote ESP32 sensors.

Remote Sensor Rainfall-Event Deployments

To capture rapid rainfall responses often missed by manual sampling, ESP32-based remote sensors were deployed at outfall and downstream stations during periods of forecasted rainfall. These units, powered by rechargeable batteries and equipped with on-board micro-SD cards for on-board data storage, recorded temperature and DO at 10-minute intervals. A hotspot device also deployed with each ESP32-based sensor system to secure connection to the cloud data logging servers and to monitor live activity.

Deployment protocols included:

- Pre-event inspection to confirm waterproof integrity, sensor calibration (against YSI® reference), and battery charge.
- Event activation upon NOAA rainfall forecast ≥ 0.5 inch within 12 hours, with real-time monitoring via cellular telemetry.

- Post-event retrieval within 24-48 hours for data download and sensor maintenance.

Continuous HOBO® Logger Deployment and Retrieval

Continuous background monitoring was achieved through HOBO® MX-801 DO and temperature loggers, which operated uninterrupted for the duration of each monitoring season. At Site 1, three (3) HOBO® loggers were deployed at all three (3) standard monitoring points (upstream, outfall, downstream). However, in Site 2 and 3, only one (1) HOBO® data logger was placed at Outfall 1 and at Point 1 Instream Sampling, respectively.

Recording interval: 5 minutes for both temperature and DO.

Deployment duration: Typically, two (2) to four (4) weeks between maintenance intervals.

Retrieval frequency: Biweekly or after major rainfall events causing elevated turbidity or debris accumulation.

During each retrieval visit, data were downloaded via HOBO® Connect software, and instruments were visually inspected and cleaned using soft brushes and deionized water. Biofilm, sediment, or algae accumulation was carefully removed to prevent optical interference. After cleaning, loggers were re-deployed at the same depth and position to maintain consistency.

Safety and Anti-Tampering Considerations

Given that field work occurred along active roadways and angling water bodies, strict adherence to GDOT and GSU safety policies was maintained throughout all field activities. Key safety measures included:

- Use of high-visibility vests, steel-toe boots, personal flotation devices (PFDs), and hard hats when working near bridges or culverts
- Implementation of traffic-control procedures in coordination with GDOT district offices for work zones near state routes if necessary
- Deployment scheduling during daylight hours and moderate flow conditions to minimize risk from flash floods or slippery substrates
- Mandatory two (2) person field teams for all major site visits to ensure mutual assistance and emergency response capability

To minimize tampering or vandalism, all permanent and temporary sensors were:

- Installed using low-profile housing and neutral-colored PVC and green-colored stainless steel to blend with the stream environment
- Labeled with discreet GDOT and GSU contact information
- Secured using stainless-steel cables and lock mechanisms anchored to rebar or boulders; and

- Documented in a GPS-based site inventory for efficient retrieval and maintenance tracking

Despite minor disturbances observed at Site 3 Point 1 Instream Sampling during summer 2025, no significant data loss occurred due to redundant deployment and consistent field oversight.

DATA SOURCES AND ANCILLARY INPUTS

To complement the field sensor data collected under RP 23-11, multiple external and observational data sources were utilized to provide hydrologic, meteorological, and qualitative context for interpreting roadway-runoff impacts on trout stream temperature and DO. These ancillary datasets were critical for identifying rainfall events, evaluating baseflow conditions, and correlating instream responses with watershed and environmental factors.

USGS Precipitation and Streamflow Data

Hydrologic reference data were obtained from the USGS National Water Information System (NWIS) for each monitored watershed. Continuous records of hourly precipitation, discharge, and stage height were downloaded from gaging stations located at or near each study Site:

- **Site 1:** USGS 02335000 – Chattahoochee River near Norcross, GA
- **Site 2:** USGS 02336870 – Powder Springs Creek near Powder Springs, GA
- **Site 3:** USGS 02395120 – Two-Run Creek near Kingston, GA

Precipitation and discharge data were used to delineate rainfall events, establish rainfall intensity–duration relationships, and determine antecedent moisture conditions prior to each monitored event. Hourly discharge data provided a hydrologic baseline for evaluating the dilution and recovery behavior of temperature and DO following roadway runoff inflows.

To ensure temporal consistency, all field and USGS data were converted to Eastern Daylight Time (EDT) and interpolated to uniform hourly or sub-hourly intervals. All data were quality-screened to remove missing or flagged values and cross-checked against NOAA station records for accuracy. Streamflow measurements were normalized by drainage-area size to facilitate comparison among the three (3) sites, representing high-flow (Chattahoochee River), moderate-flow (Powder Springs Creek), and low-flow (Two-Run Creek) conditions.

Local Weather and Rainfall Records

Local meteorological data were obtained from the NOAA National Centers for Environmental Information (NCEI) and regional Weather Underground (WU) network stations situated within 10 miles of each Site. Rainfall thresholds identified in these datasets particularly events ≥ 0.5 inch within 24 hours were used as triggers for checking roadway runoff temperature and DO impact on trout stream from these significant rainfall events, and intensifying sampling and rainfall-event deployments of ESP32 sensors.

In several cases where USGS rainfall data were unavailable or incomplete, nearby NOAA cooperative observer stations were used for data substitution and gap filling. All rainfall data were summarized using Python-based processing scripts developed by the GSU Research Team to generate standardized graphs and inputs for the mass-balance and Rational-Method.

Field Notes and Observational Records

In addition to quantitative sensor and hydrologic data, the GSU Research Team maintained detailed field observation logs during each monitoring and maintenance visit. These qualitative records provided context for interpreting anomalies in sensor data and for documenting physical site conditions throughout the two (2) year study period.

Key recurring observations included:

- **Sedimentation:** Accumulation of fine sediments was frequently observed near outfall zones particularly at Site 1 following high-intensity rainfalls. Sediment deposits occasionally covered the sensor housing, resulting in poor DO response. Sediment depths of 0.25-0.5 inch were typically removed during biweekly maintenance.

- **Biofilm Growth:** Site 2 experienced biofilm growth and algal colonization on optical sensor surfaces, where nutrient-rich baseflow from upstream urban areas promoted algal growth, especially during low-flow periods. Regular cleaning was performed during biweekly maintenance trips to minimize DO signal drift.

- **Vandalism and Tampering:** Two (2) minor incidents of sensor displacement occurred at Site 3 instream sampling point, likely caused by recreational users accessing the stream corridor. The affected sensors were recovered and redeployed with enhanced anchoring and labeled housing. These events reinforced the importance of redundant sensor placement and discreet labeling practices.

Integration with Analytical Framework

The combined use of USGS, NOAA, and field observation data allowed for a comprehensive event-scale interpretation of roadway-runoff impacts. Precipitation and streamflow datasets define rainfall timing and magnitude; air-temperature records established antecedent temperature conditions; and field notes clarified localized influences such as shading, sedimentation, or equipment disturbance.

This multi-source integration strengthened the reliability of the mass-balance and correlation analyses conducted in subsequent chapters and ensured that observed temperature and DO responses could be attributed confidently to roadway-runoff processes rather than external or site-specific artifacts.

DATA ANALYSIS AND ASSESSMENT FRAMEWORK

The analytical framework for RP 23-11 was designed to evaluate roadway-runoff impacts on trout stream temperature and DO through a combination of direct measurement comparison, time-series visualization, event-based hydrologic assessment, and mass-balance modeling. All analyses were conducted following protocols established in the QAPP to ensure data consistency, accuracy, and traceability across instruments, sites, and sampling years.

The assessment approach was both comparative and integrative, linking empirical field measurements (YSI®, HOBO®, ESP32) with external hydrologic datasets (USGS, NOAA) to quantify temperature and DO changes resulting from roadway runoff and to determine compliance with Georgia trout stream water-quality standards under Rule 391-3-6-.03(6)(ii),(v).

Direct Comparison Method

The primary analytical approach employed a direct comparison method between roadway-runoff and instream conditions at each site. For every monitored rainfall and baseline event, temperature and DO data were grouped by location: upstream (reference), outfall (mixing zone), and downstream (impact reach), and summarized using bar graphs and paired plots.

Each plot displayed instantaneous reading to illustrate the magnitude and direction of change across sampling points.

Differences in mean temperature ($\Delta T = T_{\text{Downstream}} - T_{\text{Upstream}}$) were calculated for each event to quantify roadway-runoff influence. Positive ΔT values indicated potential warming and DO depletion associated with roadway runoff. Bar-graph visualizations were produced using Python-based scripts in matplotlib and pandas, allowing for rapid event-to-event comparison and consistency with data.

Time-Series Plotting of Temperature and DO

Continuous temperature and DO data from HOBO® loggers and high-frequency ESP32 sensors were plotted as time-series graphs to evaluate diurnal variation, rainfall-response timing, and recovery duration.

Separate time-series were generated for each site and station (upstream, outfall, downstream), with overlays of hourly rainfall from USGS or NOAA records to correlate hydrologic forcing with instream temperature and DO responses.

Each time-series visualization featured:

- Single or dual *y*-axes representing temperature (°F) and DO (mg/L)
- Shaded rainfall bars indicating event timing and magnitude and
- Color-coded line segments distinguishing upstream, outfall, and downstream records

Data were aggregated at 5-minute resolution for HOBO® loggers and 10-minute resolution for ESP32 rainfall-event datasets. The combination of these datasets provided a full temporal range from short-term rainfall events to seasonal and diurnal cycles allowing detection of subtle yet relevant fluctuations in trout stream conditions.

Event-Based Analysis for Rainfall

To isolate roadway runoff impacts, event-based analyses focused on significant rainfall events equal to or exceeding 0.5 inch in 24 hours, which was determined by the GSU Research Team in consultation with GDOT based on the USGS daily precipitation data in 2025, for determining significant hydrologic responses. Each qualifying event was treated as a discrete analytical unit comprising pre-rainfall (baseline), during-rainfall (active discharge), and post-rainfall (recovery) phases.

For each event:

- Rainfall intensity and timing were obtained from nearby USGS and NOAA stations
- Corresponding temperature and DO data were extracted from continuous and event-based sensors
- Temporal lag between rainfall onset and stream response was calculated to characterize runoff-mixing dynamics
- Maximum ΔT and minimum DO were recorded and compared across sites to evaluate variability due to watershed size, canopy cover, and drainage characteristics

Event datasets were subsequently compiled into summary tables and cumulative plots that displayed the frequency and magnitude of exceedances relative to regulatory thresholds.

Threshold Compliance Assessment

All observed and modeled temperature and DO data were evaluated against Georgia trout stream water-quality criteria (GA Rule 391-3-6-.03(6)(ii),(v)) to determine potential compliance exceedances.

Compliance assessment involved computing hourly moving averages and event-scale deviations from upstream baselines.

Instances where downstream temperature exceeded the 2 °F criterion or DO dropped below 5.0 mg/L were flagged as temporary exceedances and summarized by frequency, duration, and recovery time. These metrics provided GDOT with a defensible means of evaluating roadway-runoff influences relative to statutory standards.

Normalization and Integration of Datasets

To ensure comparability among instruments and sites, all datasets were standardized and integrated into a unified analytical framework.

- **Temporal Alignment:** All timestamps were converted to EDT and interpolated at consistent 10-minute intervals using Python's pandas resampling functions
- **Data Normalization:** Sensor outputs from ProDSS, HOBO®, and ESP32 systems were normalized through offset correction derived from laboratory cross-calibration results
- **Hydrologic Context Integration:** Precipitation data from USGS were appended to each dataset to provide rainfall intensity, cumulative depth, and baseflow indices
- **Data Quality Assurance:** Outliers exceeding ± 3 standard deviations or corresponding to instrument malfunction periods were removed following QAPP guidelines

The integrated dataset allowed for cross-comparison across sites and instruments, enabling consistent statistical analyses such as correlation, regression, and recovery-time estimation.

MASS BALANCE APPROACH

To evaluate roadway runoff contributions to instream temperature dynamics at Site 1 Outfall 1, a simplified mass-balance framework was developed using the Rational Method to estimate roadway runoff water inflows. The governing equation balances temperature loading from the upstream channel and roadway runoff against the downstream temperature signal, expressed as the equation:

$$Q_{US} \times C_{US} + Q_{HR} \times C_{HR} = Q_{DS} \times C_{DS}$$

Where,

Q_{US} = Upstream flow rate (cfs) [USGS daily peak from the onsite base station]

C_{US} = Upstream variable (Temperature, °F) [Measured by ProDSS sensor]

Q_{HR} = Runoff flow rate (cfs) [Calculated by rational method]

C_{HR} = Runoff variable (Temperature, °F) [Measured by ProDSS sensor]

Q_{DS} = Downstream flow rate (cfs) [Calculated by equation]

C_{DS} = Downstream variable (Temperature, °F) [Calculated and measured by ProDSS sensor]

Here, Rational formula for calculating runoff volume $Q_{HR} = CiA$

Where,

C = runoff coefficient [Although C=1 was used for simplicity since it is the most extreme scenario, C is less than 1 for most of these drainage areas.]

i = Rainfall Intensity (inch/hr) [Taken from USGS hourly precipitation data]

A = Runoff generating area (acres) [A_{HR} = 10.2 acres, approximated from GDOT-provided map data]

The mass balance analysis focused on data from five (5) days with measurable rainfall, to compare mass loading contributions under rainfall-event scenarios.

Table 2. Summary of Rational Method Runoff Estimates and Mass-Balance Temperature Calculations for Site 1 Rainfall Events (Part-1)

Date	i (inch/hr)	Q_{US} (cfs)	C_{US} (°F)	$Q_{US} \times C_{US}$ (cfs – °F)	$Q_{HR} = CiA$ (cfs)	% of Q_{HR}/Q_{US}	C_{HR} (°F)	$Q_{HR} \times C_{HR}$ (cfs – °F)	% of $(Q_{HR} \times C_{HR})/(Q_{US} \times C_{US})$
5/7/2025	0.80	7570	54.65	413701	8.16	0.11	54.15	441.86	0.11
5/8/2025	0.08	5290	55.35	292802	0.82	0.02	56.75	46.31	0.02
5/26/2025	0.08	6930	58.95	408524	0.82	0.01	62.35	50.88	0.01
5/27/2025	2.44	9500	57.8	549100	24.89	0.26	64.50	1605.28	0.29
5/28/2025	0.68	8720	60.2	524944	6.94	0.08	62.20	431.42	0.08

Across the selected rainfall days, the relative magnitude of Q_{HR} was consistently small compared to the upstream flow. Even during the largest event on 5/27/2025, where rainfall intensity reached 2.44 in/hour, the roadway runoff represented only about 0.26% of the upstream flow and contributed roughly 1.84% of the combined temperature mass loading. This event produced the only meaningful downstream temperature signal, with a calculated loading influence consistent with the modest observed temperature rise. In contrast, on other rainfall days (e.g., 5/26/2025), the runoff contribution ranged from 0.01–0.1% of upstream flow and produced negligible influence in the mass-balance calculations and in the downstream temperature record. These results indicate that most rainfall events contributed insufficient mass loading to shift downstream conditions in a measurable way.

Table 3. Summary of Rational Method Runoff Estimates and Mass-Balance Temperature Calculations for Site 1 Rainfall Events (Part-2)

Date	$Q_{DS} = Q_{US} + Q_{HR}$ (cfs)	Measured C_{DS} (°F)	Calculated C_{DS} (°F)	% Difference between both C_{DS} (°F)	$Q_{US} \times C_{US} + Q_{HR} \times C_{HR}$ (cfs – °F)	$Q_{DS} \times$ Measured C_{DS} (cfs – °F)	% Error
5/7/2025	7578	53.65	54.65	1.86	414142	406568	1.86
5/8/2025	5291	54.95	55.35	0.73	292848	290730	0.73
5/26/2025	6931	57.10	58.95	3.24	408574	395750	3.24
5/27/2025	9525	58.90	57.82	1.84	550705	561016	1.84
5/28/2025	8727	58.60	60.20	2.73	525375	511398	2.73

Overall, the mass-balance calculations demonstrate that, at Site 1 Outfall 1, only the largest rainfall event produced a detectable impact on downstream temperature, and that this influence was proportionally consistent with the relative fractions of flow and temperature mass contributed by roadway runoff. The other rainfall events, despite measurable precipitation, generated too little hydraulic or temperature loading to affect the downstream signal. This interpretation aligns with field observations and informs the discussion of hydrologic variability and temperature response mechanisms presented in subsequent chapters.

CHAPTER 4. RESULTS AND DISCUSSION

SITE VISIT OUTCOMES

Field reconnaissance and site-verification visits were conducted between February and May 2024 to finalize roadway outfall locations, confirm hydrologic connectivity to trout streams, and identify suitable deployment points for monitoring instrumentation. These visits were completed jointly by the GSU Research Team and the GDOT Office of Design Policy and Support with its coordination with the relevant district maintenance personnel.

The reconnaissance phase resulted in the selection of three (3) representative trout-stream systems and the final designation of GDOT outfalls representing different watershed scales, canopy conditions, and roadway configurations.

Site 1 – GA State Route 141 (Chattahoochee River)

Site 1 represents a large, regulated secondary trout stream within the upper Chattahoochee River corridor, characterized by broad channel geometry, urbanized watershed conditions, and multiple roadway discharges within a 1-mile reach. Four (4) candidate GDOT outfalls were inspected, and two were selected for monitoring based on direct hydraulic connectivity and year-round baseflow. The maps of Site 1 are presented in Figure 13 and Figure 14 below.

Figure 13. Map. Site 1 – Outfall 1 with Upstream and Downstream Monitor Stations and One (1) Study Point

Outfall 1 (Bridge Crossing): Showed in the Figure 13 map above, located at the northbound shoulder scupper of the GA-141 bridge. This outfall conveys the roadway runoff collected from the above road drainage service area highlighted with green and discharges it into Chattahoochee River. The Study Point at the upstream of Outfall 1 by GA-141 road is at about 740 ft distance from Outfall 1 and has a total drainage area of 10.2 acres, which gets discharged through Outfall 1 into the river by the cyan drainage path delineated on the map above.

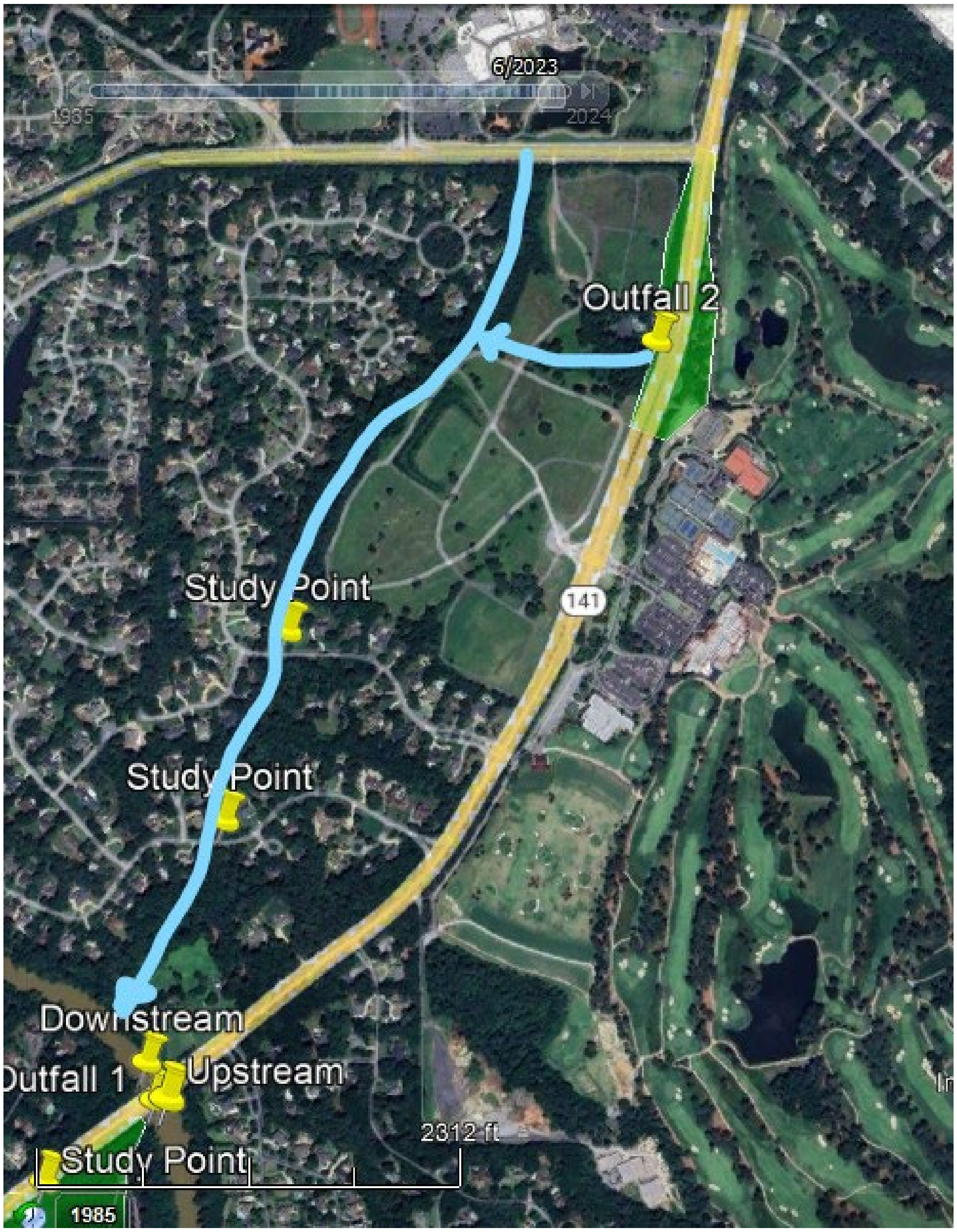


Figure 14. Map. Site 1 – Outfall 2 and Two (2) Study Points

Outfall 2 (0.5 mi Upstream): Shown in the Figure 14 map above, Outfall 2 is a reinforced concrete pipe draining the eastbound ramp area; accessible from the right-of-way shoulder. The Study Points

1 and 2 are in a residential area, which were chosen to be in the cyan drainage pathway of Outfall 2 to monitor the characteristics change of outfall water.

At each outfall and corresponding instream location, anchor blocks and stainless-steel sensor stands were installed along the right descending bank. The installations were designed to keep sensors fully submerged at low flow while preventing displacement during high-stage events. Protective PVC housings with perforations were used to minimize debris accumulation while allowing free water exchange.

Site 2 – GA State Route 120 (Powder Springs Creek)

Site 2 typifies a medium-sized suburban trout stream with moderate canopy cover, sandy substrate, and a mixture of residential and transportation drainage inputs. Three (3) GDOT outfalls along the GA-120 corridor were finalized following consultation with the GDOT District 7. The maps of Site 2 are presented in Figure 15 and Figure 16 below.

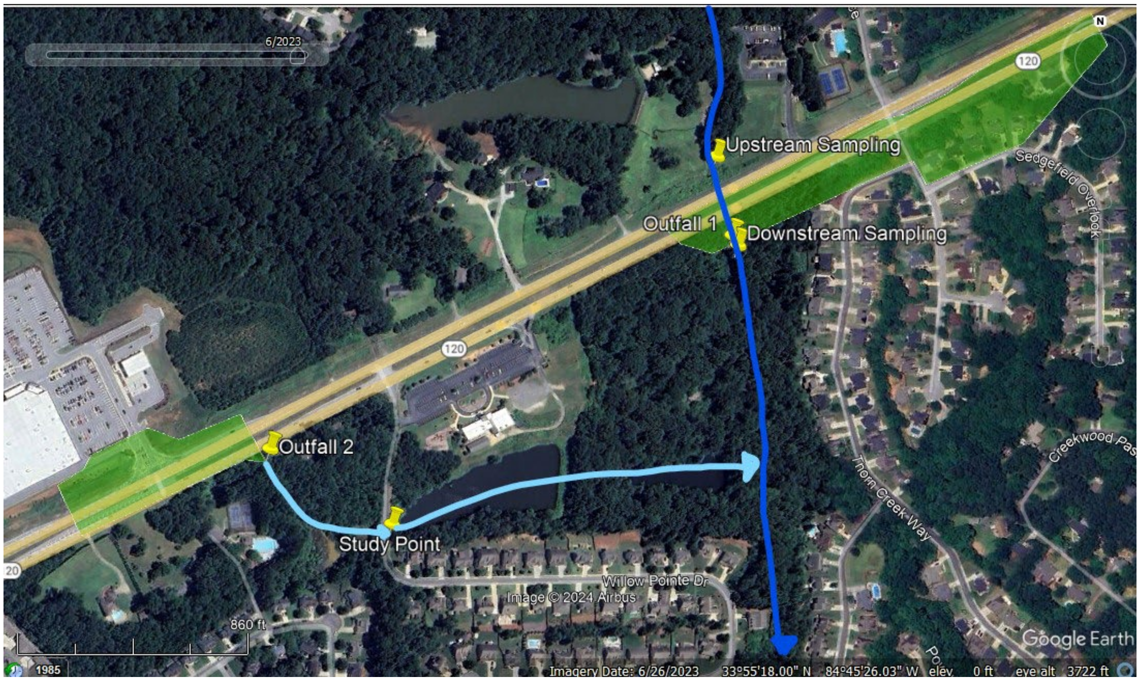


Figure 15. Map. Site 2 – Outfall 1 with Upstream and Downstream Monitoring Stations, and Outfall 2 with One (1) Study Point

Outfall 1: Shown in Figure 15 map above, the Outfall 1 at Site 2 consists of a double reinforced concrete culvert located beneath the main highway bridge, discharging directly into Powder Springs Creek. The outfall serves a drainage area of approximately 22.4 acres. Field inspections conducted during multiple site visits revealed that Outfall 1 lacks a defined drainage channel, with stormwater converging from multiple flow paths before entering the creek.

Outfall 2: Shown in Figure 15 map above, the Outfall 2 at Site 2 is a 36-inch reinforced concrete pipe draining the GA-120 median and westbound embankment area. It has a total drainage area of approximately 6.3 acres and is about 2315 feet away from Powder Springs Creek. Runoff water gets carried to the creek from the west to the east by the cyan line delineated in the map.

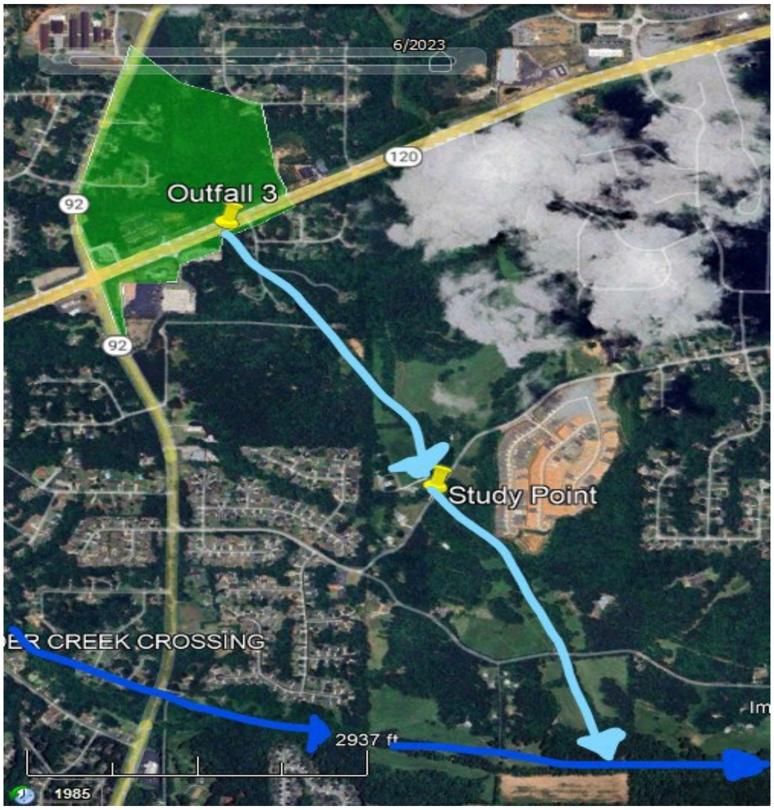


Figure 16. Map. Overview Map for Site 2 – Outfall 3 with Study Point

Outfall 3: A vegetated swale that transitions into a rainfall drain pipe entering the creek via a riprap apron. It has a total drainage area of approximately 15 acres and is about 6670 feet away from the creek. The drainage pathway from the Outfall 3 at Site 2 to the blue-line delineated creek is delineated by the cyan line shown in Figure 16 above.

Each monitoring point was equipped with YSI® ProDSS grab-sampling stations, and at Outfall 1, one (1) HOBO® logger was deployed inside a PVC protective housing anchored to a 25-lb concrete block. ESP32 remote sensors were deployed on temporary steel poles driven into bed gravel near outfall discharge points to record high-frequency rainfall-event data.

Powder Springs Creek's variable baseflow required adaptive mounting heights; therefore, adjustable stainless-steel clamps were used to reposition sensors seasonally to maintain optimal submergence.

Figure 17. Photo. Initial deployed placement of instream sensor concrete (CC) block at Site 2 Outfall 1.

Figure 18. Photo. HOBO® Data logger inside protective housing, anchored with CC block at Site 2 Outfall 1.

Site 3 – GA State Route 293 (Two Run Creek)

Figure 19. Map. Site 3 – Point 1 Instream Sampling and Outfalls 2 and 3

Site 3 represents a small, high-gradient trout stream tributary in a predominantly rural watershed with intact riparian shading. The stream's shallow riffle–pool morphology and low baseflow made it an ideal location for studying localized temperature impacts where dilution capacity is limited. Overview map of Site 3 is shown in Figure 19 above. The cyan-line in the figure delineates the outfall water flow path and direction and the blue-line indicates the creek flow path from upstream to downstream.

Instream Sampling Point 1 (Bridge Crossing): The Two Run Creek outfall at Site 3 was replaced by an Instream Sampling Point, which is directly under the concrete box culvert conveying runoff from both travel lanes of GA-293 directly to the stream under the Kingston Highway bridge shown in Figure 19 above.

Outfall 2 (0.5 mi Upstream): Shown in the Figure 19 above, Outfall 2 at Site 3 is a corrugated metal pipe draining a roadside ditch intersecting the GA-293 highway embankment. It covers a drainage area of 13.5 acres and is about 2250 feet distance from the creek flow path. The water travels from this outfall to the creek by a vegetated channel and reinforced concrete pipe delineated by the cyan flow path shown in the map figure.

Outfall 3 (1.0 mi Upstream): Shown in the Figure 19 above, the Outfall 3 at Site 3 is a small shallow ditch covered by big trees and dense vegetation. The water travels from this outfall to the creek along the cyan flow path shown in the map figure by a vegetated and reinforced concrete channel entering the creek from the left bank through riprap protection. It covers a drainage area of about 1.5 acres and is about 4700 feet away from the creek flow path.

General Installation Observations

Across all three (3) sites, the installation process emphasized stability, safety, and non-intrusiveness. Each deployment adhered to the following best practices established in the QAPP:

- Use of cement-concrete anchor blocks (18 × 18 × 6 in., 25-lb) for permanent sensors
- Stainless-steel or PVC instrument housings with 3 mm perforations to ensure rapid water exchange
- Consistent depth placement (0.25–0.5 m below surface) to standardize measurements among sites

After installation, all coordinates were recorded with sub-meter accuracy using a GPS device, and photographs documented site conditions for QA/QC verification. No major installation failures occurred throughout the study. These finalized installations established the foundation for consistent, high-quality data collection across three (3) study sites during the two-year monitoring period.

INSTRUMENTATION AND CALIBRATION RESULTS

Comprehensive calibration and validation activities were conducted throughout the RP 23-11 Project to ensure the accuracy, consistency, and reliability of field data collected from three (3) sensor platforms: YSI® ProDSS handheld instruments, HOBO® continuous loggers, and ESP32-based remote sensors.

Calibration protocols followed the QAPP and were verified both in the GSU WERL and in the field prior to and following each deployment cycle. These efforts established cross-instrument consistency and confirmed that observed trends in stream temperature and DO were attributable to environmental variation rather than sensor bias.

Calibration Procedures

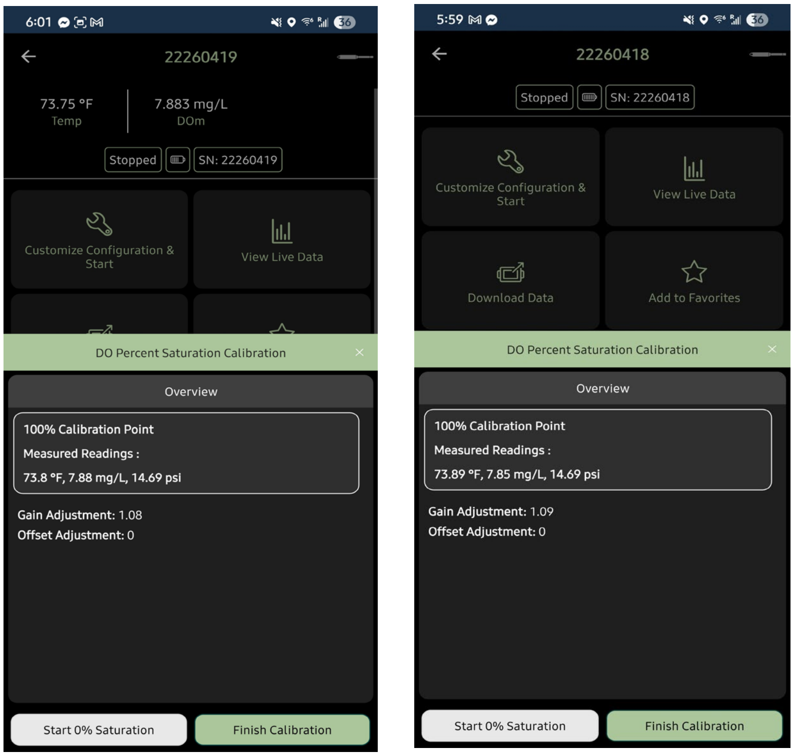
All temperature and DO sensors underwent a two (2) stage calibration process; laboratory calibration prior to field deployment and field verification during installation and retrieval.

YSI® ProDSS instruments were calibrated before each field trip in 100-% air-saturated water for DO and in controlled temperature baths against NIST-traceable thermometers for temperature. Individual ProDSS sensors were tested against standard solutions for their calibration accuracy before using them in the field. The calibration results of the sensors for the YSI® ProDSS Instrument are given in Table 4. Overall, the sensors gave accurate readings for the standard solutions with either the same concentrations or in a range of 0.3 – 0.7 % relative error.

Table 4. Accuracy checking using standard solutions for the YSI® ProDSS Instrument

Parameters	Standard Solutions	Reading after Calibration	Relative Error (%)
pH	4	4	0
	7	7	0
	10	10	0
Conductivity (µS/cm)	1000	1007	0.7
Chloride (mg/L)	10	10	0
	1000	1003	0.3

HOBO® MX-801 DO and temperature loggers were calibrated using the manufacturer's optical DO calibration cap at 100-% oxygen condition and validated against YSI® readings in a stirred calibration tank at 73 ± 0.5 °F. Figure 20 below shows two (2) HOBO® MX-801 DO sensors calibration screens at 100-% calibration point.



73.75 °F Temp

7.883 mg/L DOm

SN: 22260419

100% Calibration Point

Measured Readings :

73.8 °F, 7.88 mg/L, 14.69 psi

Gain Adjustment: 1.08

Offset Adjustment: 0

SN: 22260418

100% Calibration Point

Measured Readings :

73.89 °F, 7.85 mg/L, 14.69 psi

Gain Adjustment: 1.09

Offset Adjustment: 0

Figure 20. Photo. HOBO® MX-801 sensor calibration screen

ESP32-based remote sensors (equipped with DFRobot® Galvanic DO and DS18B20 temperature probes) were bench-tested simultaneously with ProDSS and HOBO® devices across a temperature range of 50–85 °F and DO range of 5–9 mg/L. Calibration coefficients were derived from linear regression relationships between ESP32 sensor outputs and YSI® reference data prior to field deployment.

Field verification was performed during every biweekly maintenance visit. If deviation exceeded ±0.3 mg/L for DO or ±0.2 °F for temperature relative to the YSI® reference, recalibration or replacement was initiated. Instrument drift remained within acceptable limits across all monitoring periods, consistent with manufacturer specifications and QAPP tolerance thresholds.

Calibration Comparison: YSI® ProDSS vs. HOBO® Loggers

Calibration comparison analyses were performed to assess agreement between continuous HOBO® logger data and discrete YSI® ProDSS field measurements. Each month, HOBO® logger readings at the time of retrieval were paired with simultaneous ProDSS readings from the same depth and location.

Temperature Comparison:

In Figure 21 and Figure 22 below the temperature vs time plot before and after calibration of HOBO® data loggers is shown. The HOBO® loggers were factory calibrated to a fair degree of accuracy for the temperature showing only 0.1 – 0.2 °F variation between sensors. However, after recalibration the accuracy improved greatly, and variation was seen to be 0-0.1 °F, which is well within the margin of error. Relative errors of the HOBO® loggers in comparison to the ProDSS sensor were 0.2 – 0.44% after calibration, as shown in Table 5 below.

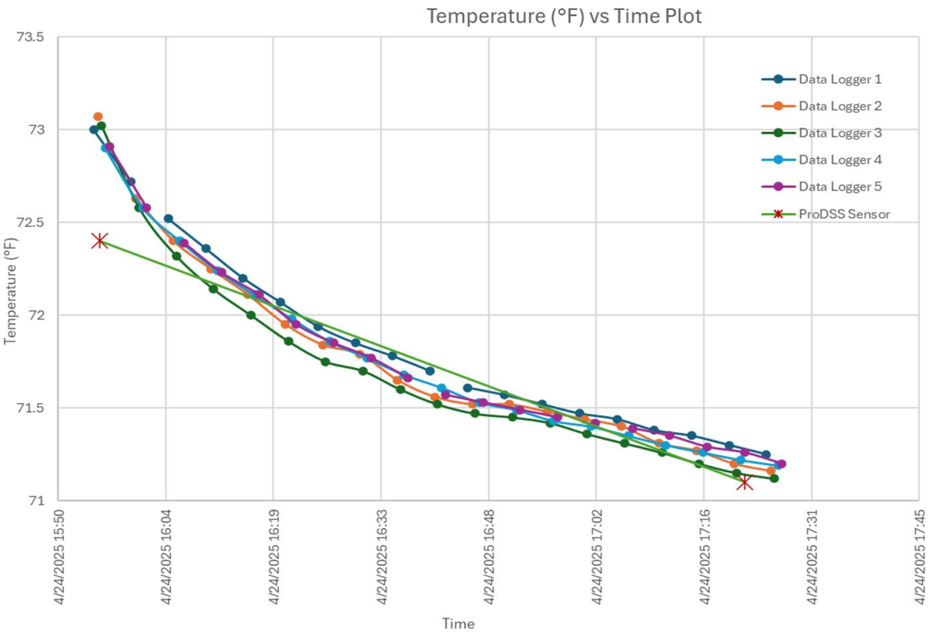


Figure 21. Chart. Temperature vs Time plot for HOBO® data loggers against YSI® ProDSS sensor before calibration.

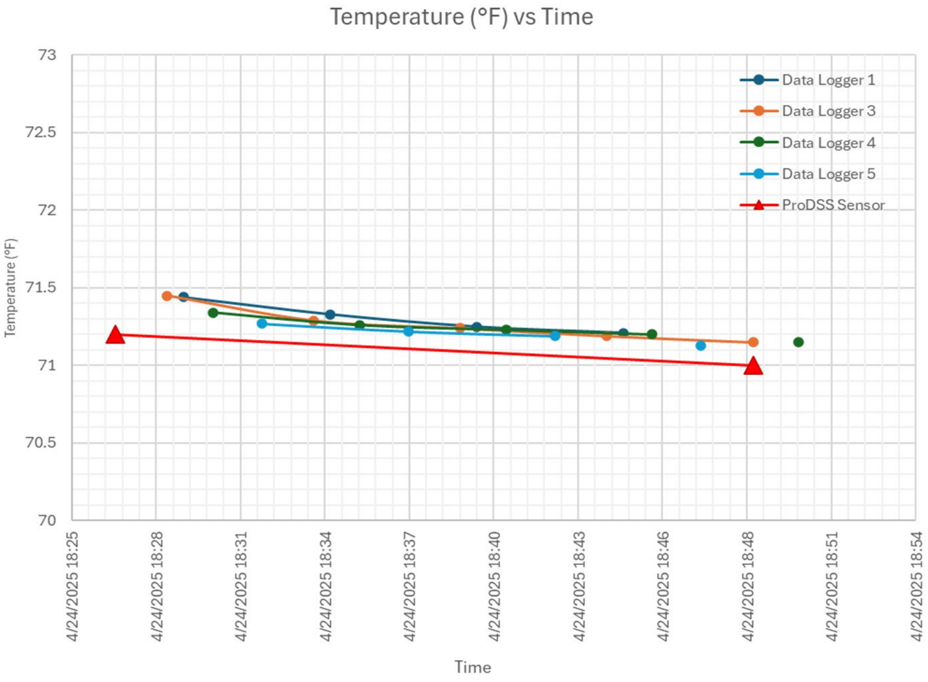


Figure 22. Chart. Temperature vs Time plot for HOBO® data loggers against YSI® ProDSS sensor after calibration.

Table 5. Temperature check during verification of HOBO® systems against ProDSS sensor

Logger	**Avg Temp (°F)**	**Standard Deviation**	**ProDSS Avg (°F)**	**Relative Error (%)**
Logger 1	71.41	0.22	71.1	0.44
Logger 3	71.36	0.225	71.1	0.36
Logger 4	71.3	0.144	71.1	0.27
Logger 5	71.24	0.091	71.1	0.2

DO Comparison:

In Figure 23 and Figure 24 below the DO vs time plot before and after calibration of HOBO® data loggers is shown. The factory calibration of HOBO® loggers was slightly lower in comparison to the ProDSS sensor showing 0.5 – 0.8 mg/L variation between sensors. However, after recalibration the accuracy improved greatly and variation was reduced significantly, and the readings for HOBO® and ProDSS were almost on par and were well within the margin of error. Relative errors of the HOBO® loggers in comparison to the ProDSS sensor were 0.09 – 1.03% after calibration, as shown in Table 6 below.

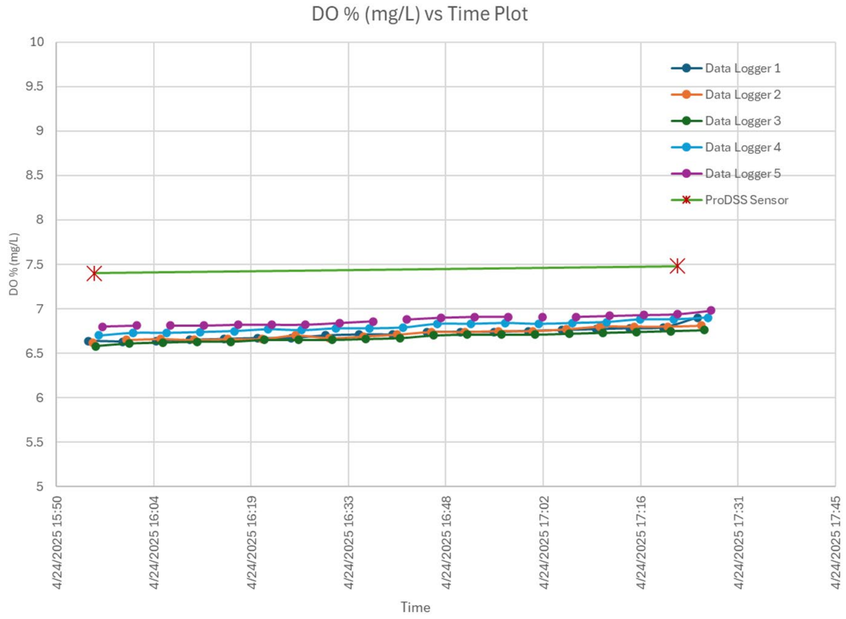


Figure 23. Chart. DO vs Time plot for HOBO® data loggers against YSI® ProDSS sensor before calibration

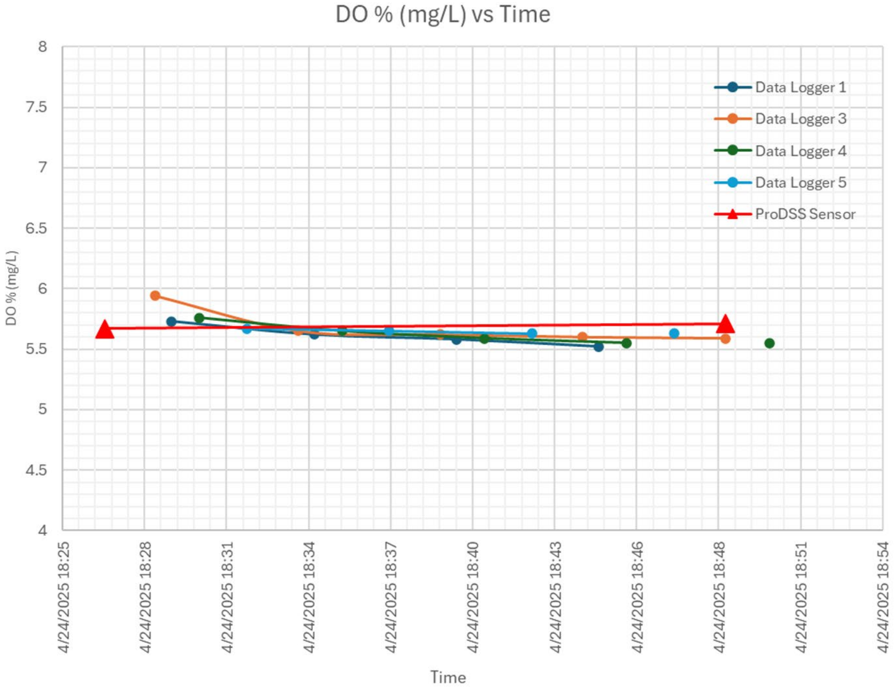


Figure 24. Chart. DO vs Time plot for HOBO® data loggers against YSI® ProDSS sensor after calibration

Table 6. DO check during verification of HOBO® systems against ProDSS sensor

Logger	Avg DO (mg/L)	Standard Deviation	ProDSS Avg (mg/L)	Relative Error (%)
Logger 1	5.67	0.137	5.69	0.32
Logger 3	5.75	0.194	5.69	1.03
Logger 4	5.7	0.183	5.69	0.09
Logger 5	5.68	0.068	5.69	0.21

Calibration plots illustrate the strong correspondence between ProDSS and HOBO® temperature and DO readings, respectively. These results confirm that continuous loggers successfully maintained accuracy, validating their use as baseline instruments for trend and compliance analysis.

Remote Sensor Performance Validation

Performance validation of the ESP32 microcontroller based remote sensors was a critical component of the RP 23-11 Project, as these low-cost systems were intended to supplement high-precision instruments during short-duration rainfall events. Validation consisted of lab calibration and field deployment and comparisons against the YSI® ProDSS system. Prior to field use, ESP32 sensors were calibrated in the WERL in an aerated, temperature-controlled water bath (50–80 °F) with YSI® instruments operating concurrently. Each ESP32 sensor system was programmed with C++ programming script by Arduino IDE and calibrated for DO only. According to the DFRobot® user manual for temperature sensors, it did not need any calibration for temperature other than the factory settings.

Field Validation:

A series of controlled field tests were conducted to evaluate the performance of the ESP32-based remote sensor units under real-world environmental conditions. The first test, shown in Figure 25, involved three (3) sensors deployed simultaneously to record stream temperature variations over several diurnal cycles. All sensors demonstrated consistent temperature response trends, validating the system's basic temperature measurement capability. In the subsequent field trial (Figure 26), a fourth remote sensor was co-located with a YSI® ProDSS unit for calibration comparison. The temperature readings exhibited good agreement with the reference data, confirming acceptable accuracy for short-term deployments. However, as shown in Figure 27, the corresponding DO data revealed greater variability and intermittent gaps, reflecting the sensitivity of the low-cost galvanic DO probe to environmental fluctuations and calibration drift. Overall, the tests confirmed the system's potential for rapid, low-cost data collection, while also highlighting performance limitations that contributed to data variability.

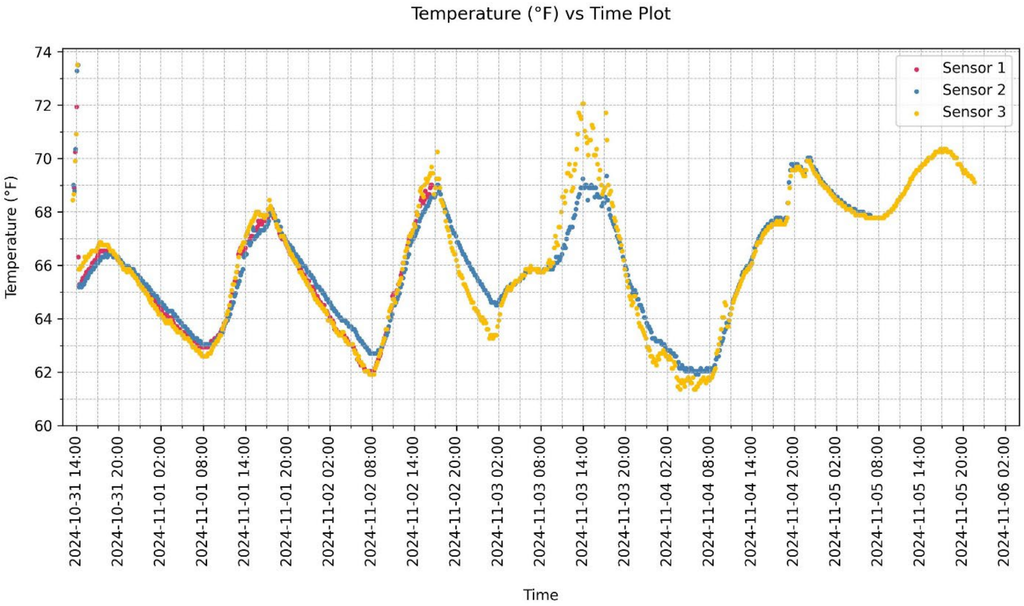


Figure 25. Chart. Temperature vs Time plot for prototype Remote sensor performance comparison during first field deployment

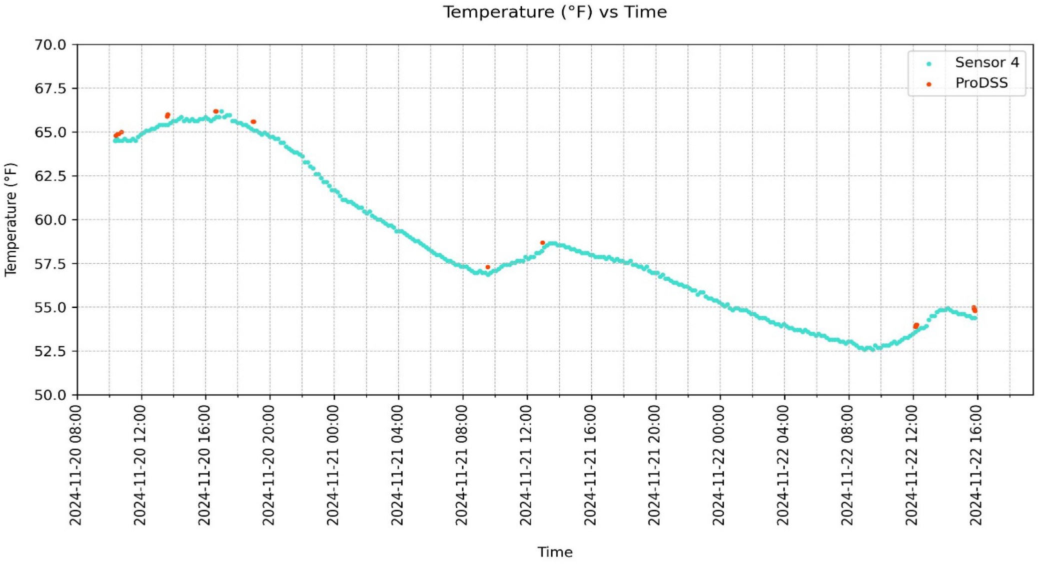


Figure 26. Chart. Temperature vs Time plot for prototype Remote sensor performance against YSI® ProDSS sensor

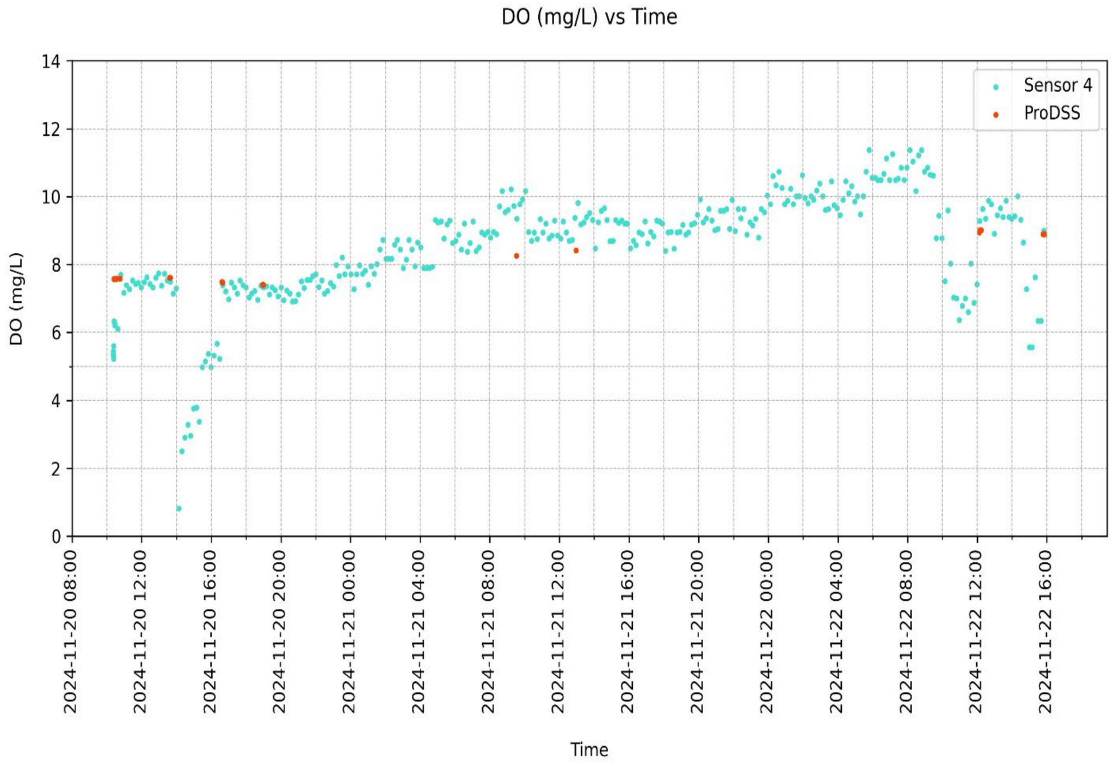


Figure 27. Chart. DO vs Time plot for prototype Remote sensor performance against YSI® ProDSS sensor

Summary of Calibration and Instrument Performance

Across all instruments and sites, calibration and validation results confirmed strong consistency and minimal drift throughout the two-year study period. The cross-instrument comparisons demonstrated that:

- YSI® ProDSS served as an accurate calibration reference and QA/QC benchmark
- HOBO® continuous loggers provided stable, long-term datasets suitable for seasonal and diurnal analyses

- ESP32 remote sensors effectively captured rapid, high-frequency fluctuations of temperature during rainfall events, complementing traditional instruments. However, it failed to have consistency in DO monitoring

The successful integration of these three (3) systems provided a comprehensive, cross-validated image linking continuous background monitoring with rainfall-event dynamics. The verified accuracy of each instrument type ensured that subsequent temperature and DO analyses reflected true environmental responses rather than measurement uncertainty.

FIELD MONITORING RESULTS

The two-year field monitoring program from April 2024 – October 2025, with a break during the dry winter season, produced a comprehensive dataset encompassing grab-sample measurements, continuous logger records, and high-frequency rainfall-event sensor data across three (3) trout stream sites. These data captured both baseline diurnal conditions and rainfall-driven disturbance in stream temperature and DO, enabling a quantitative assessment of roadway runoff impact relative to natural variability and Georgia trout stream standards.

All raw data were screened for quality according to the QAPP (2024). Invalid readings due to sensor fouling, partial submergence, or telemetry dropout were removed (<2.5% of total records). Final processed datasets were visualized using bars, time-series, and event-based plots described below.

YSI® ProDSS Grab-Sample Results

YSI® ProDSS recorded data at Site 1

At Site 1, located along the Chattahoochee River near Medlock Bridge, grab-sample monitoring using the YSI® ProDSS multiparameter handheld instrument was initiated during the 2024 season to evaluate roadway runoff impacts on stream temperature and DO between the upstream and downstream points surrounding Outfall 1. Site 1 represents a high-baseflow, well-mixed secondary trout stream. A total of 290 samples were collected across three study sites over the two-year period, with 94 samples obtained in 2024 and 196 in 2025. In this report, each reported data point for every parameter represents the arithmetic mean calculated from two (2) collected samples. The GSU research team couldn't catch any significant and meaningful rainfall event in 2024. In the first year (2024), downstream point (see Table 10) compared to the baseline reference data collected from bridge top (see Table 12). In a few instances, most notably from early July to August 2024, downstream point temperature saw an increase of 1.5-3.5 °F above the baseline data average of 59.11°F taken for the first year data, except the extreme event monitored on 9/27/2024; whereas the mixing zone temperature (see Table 9) had a temperature increase of 2.1-4 °F and upstream temperature (see Table 8) range difference than baseline was 2.9-5.2 °F.

However, while the ProDSS measurements taken in 2024 provided valuable baseline information, the GSU Research Team determined that grab-sample monitoring alone did not fully capture the transient nature of runoff-driven temperature changes. Because rainfall timing often occurred outside scheduled field visits, it was not always possible to sample all key monitoring points, particularly during the critical onset and peak periods of storm events when temperature impacts were most likely to occur. As a result, the 2024 ProDSS dataset provided only a partial picture of the roadway-runoff temperature dynamics. To address this limitation and improve temporal resolution, the GSU Research Team decided to deploy HOBO® continuous temperature and DO loggers beginning in early 2025. These instruments allowed for uninterrupted 5-minute-interval monitoring, providing a more accurate and complete record of the temperature response associated with roadway discharges. The expanded use of HOBO® sensors in the second monitoring year ultimately offered a clearer, data-driven understanding of how rainfall intensity, pavement heating, and mixing processes influence temperature variation within the Chattahoochee River trout stream system. The research team also decided to simultaneously continue monitoring the sites with ProDSS as cross-reference and to record upstream data further from the shore to get data values closer to the baseline reference.

In 2025, from early May to late May, several rainfall events were monitored by ProDSS during and after the rainfall. This time, upstream data were closer to the baseline data with a difference range of up to 3.8°F. The mixing zone temperature had increased within range of 0-8.14 °F and the downstream had increased up to 2.54°F relative to baseline average of 56.4 °F taken for all the data records except 6/25/2025, which turned out to be a dry-day.

The DO level was consistently above the regulatory requirement of minimum 5.0 mg/L all times at all key monitoring points in 2024 and 2025 at Site 1 Outfall 1.

Table 7. ProDSS grab sample data collected at Site 1 Outfall 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	70.2	8.04	76.5	7.16	0.52	
6/16/2024	Before rainfall						Dry
7/5/2024	Before rainfall						Dry
8/9/2024	Before rainfall						Dry
9/27/2024	After rainfall						Underwater, inaccessible.
5/6/2025	Before rainfall						Dry
5/26/2025	After rainfall	69.6	8.665	84.4	7.295	7.53	
5/28/2025	After rainfall	69.7	8.43	46.6	6.98	7.76	

Table 7 above shows the data for the days when there was visible and measurable runoff flow coming from the Outfall 1 drainage pipe at Site 1. It can be seen that the runoff water at the Outfall 1 pipe was consistently 7.06-7.5 °F higher than the temperature recorded at the mixing point of Outfall 1 on these specific dates.

Table 8. ProDSS grab sample data collected from Upstream of Outfall 1 at Site 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	63.14	8.27	61.7	6.76	1.29	
6/16/2024	Before rainfall	62	8.73	58.85	6.65	1.665	
7/5/2024	Before rainfall	62.85	8.515	64.65	6.745	2.38	
8/9/2024	Before rainfall	64.3	8.03	72	6.89	3.02	
9/27/2024	After rainfall	70.05	7.14	39.55	6.565	1.825	
5/6/2025	Before rainfall	55.9	9.9	63.05	6.925	8.075	
5/7/2025	During rainfall	54.65	9.72	61.4	6.835	10.35	
5/8/2025	After rainfall	55.35	9.155	62.35	6.71	13.96	
5/26/2025	After rainfall	58.95	8.945	62.5	7.315	10.59	
5/27/2025	During rainfall	57.8	8.93	57	6.67	8.29	
5/28/2025	After rainfall	60.2	8.41	62.4	6.94	11.53	
6/25/2025	Before rainfall	60.8	8.68	75	7.21	14.04	

Table 9. ProDSS grab sample data collected from Mixing Point of Outfall 1 at Site 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	63.14	8.27	61.7	6.76	1.29	
6/16/2024	Before rainfall	62.5	7.895	58.1	6.285	1.67	
7/5/2024	Before rainfall	61.25	8.615	44.6	6.68	2.015	
8/9/2024	Before rainfall						Dry
9/27/2024	After rainfall	70.2	6.605	39.8	6.55	2.075	
5/6/2025	Before rainfall	56.4	9.765	63.4	6.885	8.395	
5/7/2025	During Rainfall	54.15	8.5	63.3	6.475	14.5	
5/8/2025	After rainfall	56.75	6.28	71.75	6.165	14.67	
5/26/2025	After rainfall	62.35	7.645	70.25	6.565	9.63	
5/27/2025	During Rainfall	64.5	8.29	55.4	6.55	5.88	
5/28/2025	After rainfall	62.2	8.21	68.7	6.7	7.39	
6/25/2025	Before rainfall	60.4	2.85	93.3	6.21	14.28	

Table 10. ProDSS grab sample data collected from Downstream of Outfall 1 at Site 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						
6/16/2024	Before rainfall	60.65	8.875	56.15	6.63	1.61	
7/5/2024	Before rainfall	59.85	8.76	57.9	6.545	1.975	
8/9/2024	Before rainfall	62.55	8.29	69.95	6.755	3.26	
9/27/2024	After rainfall						Underwater, Inaccessible
5/6/2025	Before rainfall	56	9.88	63.5	6.885	8.325	
5/7/2025	During rainfall	53.65	9.87	60.55	6.78	10.995	
5/8/2025	After rainfall	54.95	9.68	61.15	6.75	11.03	
5/26/2025	After rainfall	57.1	8.945	59	6.735	10.595	
5/27/2025	During rainfall	58.9	9.02	59.4	6.86	8.6	
5/28/2025	After rainfall	58.6	8.76	63.2	6.66	8.4	
6/25/2025	Before rainfall	61.3	8.18	68.7	7.09	13.38	

Table 11. ProDSS grab sample data collected from Study point for Outfall 1 at Site 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						Dry
6/16/2024	Before rainfall						Dry
7/5/2024	Before rainfall						Dry
8/9/2024	Before rainfall						Dry
9/27/2024	After rainfall	70.35	7.205	45.3	6.46	1.54	
5/6/2025	Before Rainfall	61.6	0.34	156.4	6.52	13.59	
5/7/2025	During Rainfall	63.1	0.91	142.7	6.585	12.27	
5/8/2025	After Rainfall	64.2	1.165	145.7	6.5	12.775	
5/26/2025	After Rainfall	74.7	6.68	89.6	6.81	6.75	
5/27/2025	During Rainfall	65.1	7.48	55.1	6.38	5.02	
5/28/2025	After Rainfall	70.9	7.52	74.3	6.81	6.84	
6/25/2025							Dry

Table 12. ProDSS grab sample data collected from Bridge top for Outfall 1 at Site 1 as base-line reference

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	59.72	8.14	58.2	6.75	1.48	
6/16/2024	Before rainfall	58.8	8.66	54.9	6.51	1.6	
7/5/2024	Before rainfall	56.15	8.445	54.95	6.27	2.265	
8/9/2024	Before rainfall	61.8	8.48	68.65	6.79	4.065	
9/27/2024	After rainfall	70.25	6.9	39.9	6.515	2.745	
5/7/2025	During rainfall	53.4	9.905	60.2	6.455	10.17	
5/8/2025	After Rainfall	54.8	9.87	61.3	6.73	10.135	
5/26/2025	After rainfall	57.2	9.1	58.9	6.47	13.1	
5/27/2025	During rainfall	57.8	9.02	59.4	6.86	8.6	
5/28/2025	After rainfall	58.6	9.05	62.9	6.74	10.58	

At Outfall 2 of Site 1, overall, in both 2024 and 2025 monitoring periods, the Outfall 2 had higher temperature than the two (2) Study points on flow pathway shown on 5/7/2025 in Table 13. Study Point 1 (see Table 14) had higher temperature than Study Point 2 (see Table 15) in a range of 0.25 – 1.15 °F, indicating that outfall flow gets cooled down if flow travels further than the initial point naturally. In one (1) instance on 5/26/2025, Outfall 2 had low DO of 4.0 mg/L (see Table 13) 1.0 mg/L below the regulatory limit of 5.0 mg/L at all times; however, the Study Points at the downstream showed DO above the regulatory limit, which indicates that flow distance also helped increase the DO level in the runoff water. At every other point, the DO level was greater than the regulatory limits.

Table 13. ProDSS grab sample data collected from Outfall 2 at Site 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						Dry
6/16/2024	Before rainfall						Dry
7/5/2024	Before rainfall						Dry
8/9/2024	Before rainfall						Dry
9/27/2024	After rainfall	71.55	7.25	68.05	6.915	2.685	
5/6/2025							Dry
5/7/2025	During Rainfall	65.05	7.695	87.25	7.28	5	
5/8/2025	After Rainfall	66.65	5.825	101.4	7.17	5.37	
5/26/2025	After Rainfall	70.3	4	185.4	7.14	7.58	
5/27/2025	During Rainfall	66.3	7.83	95.2	6.85	5.32	
5/28/2025							Dry
6/25/2025							Dry

Table 14. ProDSS grab sample data collected from Study point 1 for Outfall 2 at Site 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	74.7	7.28	54.6	6.71	0.75	
6/16/2024	Before rainfall	75.5	7.49	113.4	7.13	2.07	
7/5/2024	Before rainfall	77.95	7.41	148	7.41	5.09	
8/9/2024	Before rainfall	77.7	7.135	120.35	7	3.37	
9/27/2024	After rainfall	71.6	7.8	34.05	6.69	1.9	
5/6/2025	Before rainfall	63.7	8.21	110.65	6.815	15.395	
5/7/2025	During Rainfall	62.9	8.21	92.25	6.76	9.69	
5/8/2025							No Access
5/26/2025							No Access
5/27/2025							No Access
5/28/2025							No Access
6/25/2025	Before Rainfall	74.5	7.85	116.8	7.34	13.85	

Table 15. ProDSS grab sample data collected from Study point 2 for Outfall 2 at Site 1

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	73.85	7.425	61.7	6.79	0.955	
6/16/2024	Before rainfall	75.25	7.575	126.75	7.02	2.735	
7/5/2024	Before rainfall	76.8	7.065	165.8	7.225	7.005	
8/9/2024	Before rainfall	78.35	6.61	129.95	7.16	4.05	
9/27/2024	After rainfall	71.4	7.755	38.65	6.44	2.915	
5/6/2025	Before rainfall	62.7	7.55	102.45	6.655	11.755	
5/7/2025	During Rainfall	62.5	7.88	103.7	6.735	14.235	
5/8/2025							No Access
5/26/2025							No Access
5/27/2025							No Access
5/28/2025							No Access
6/25/2025	Before Rainfall	75.5	8.66	132.6	7.01	13.85	

YSI® ProDSS Data Bar Plots for Site 1

In the graphs shown below in Figure 28 and Figure 29, the Temperature and DO log from 2024 is presented for Site 1 Outfall 1 and adjacent monitoring points. As all the data taken in 2024 was during a dry scenario, there is no positive temperature delta. However, compared to the baseline data taken from the bridge top, the downstream temperature was higher in almost every instance, which indicated that during the rainfall events there is possibility of higher temperature record showing up at the downstream point when there would be additional warmer inflow from roadway runoff. And on all occasions, the monitored DO data were higher than the regulatory minimum 5.0 mg/L at all times.

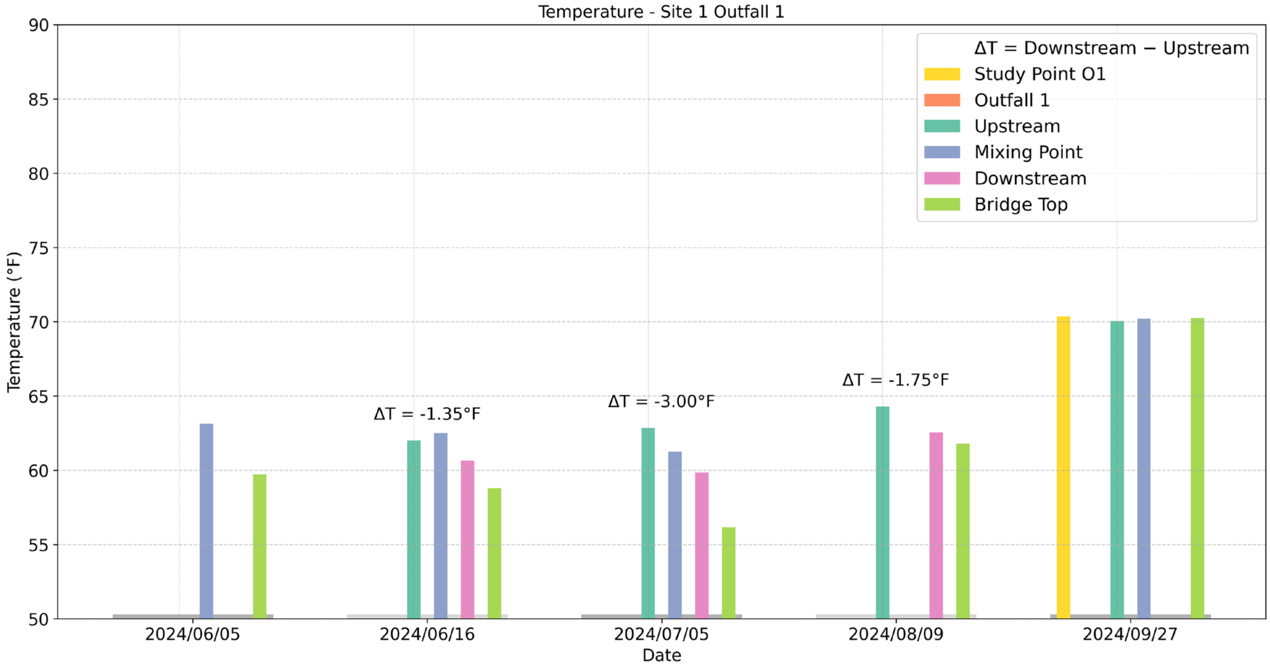


Figure 28. Chart. Temperature data collected at Site 1 Outfall 1 in 2024

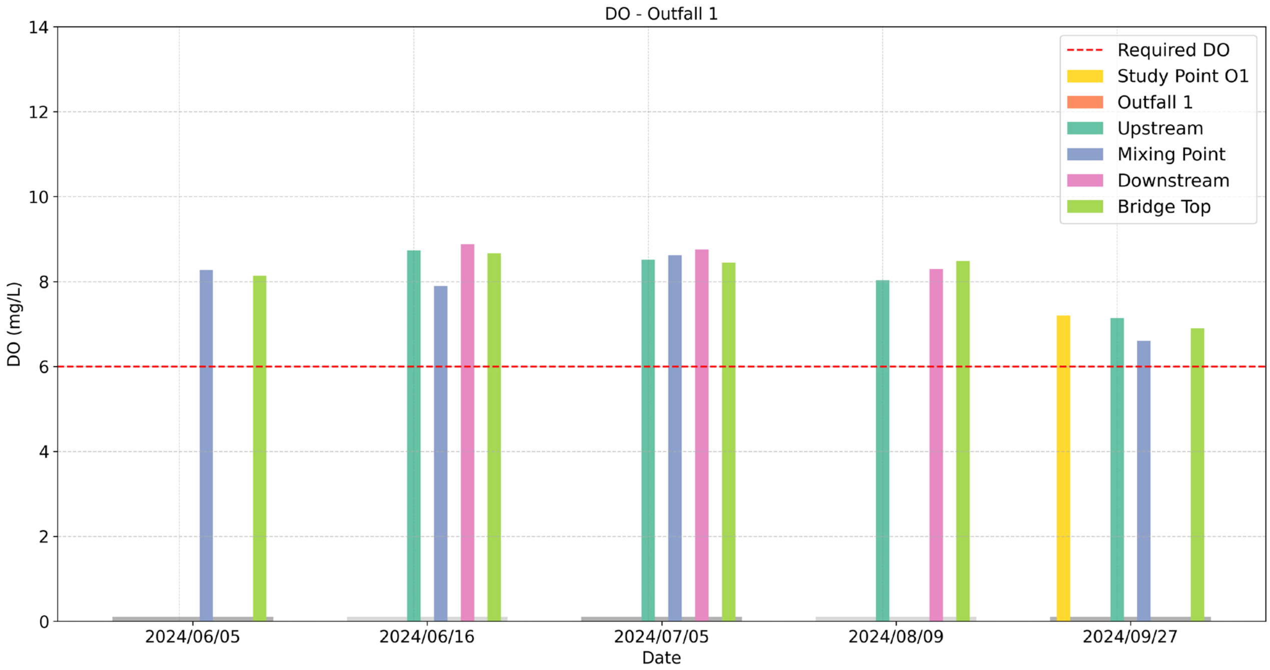


Figure 29. Chart. DO data collected at Site 1 Outfall 1 in 2024

In the graphs shown below in Figure 30 and Figure 31, the Temperature and DO log from 2024 is presented for Site 1 Outfall 2 and adjacent Study Points. In the temperature plot, it’s clearly visible that Study Point 1 had higher temperature than Study Point 2, which indicates a cooling effect along the flow path. And the DO data at all points were always higher than the regulatory minimum daily average of 6.0 mg/L and regulatory minimum 5.0 mg/L.

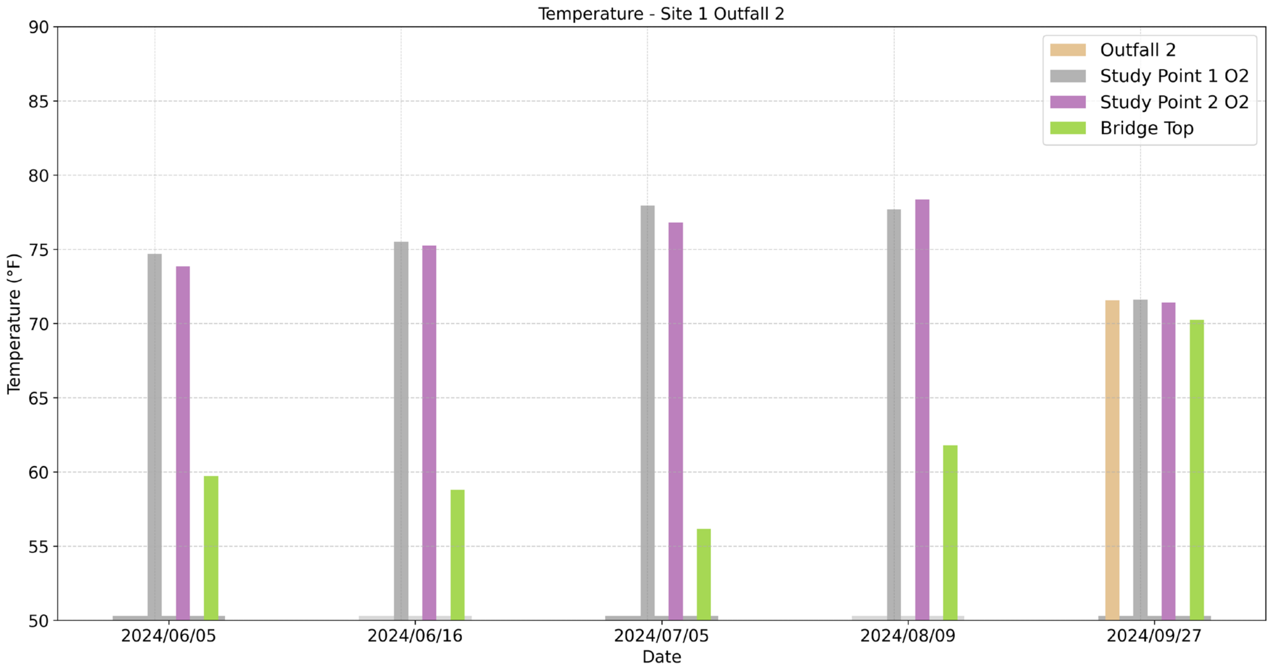


Figure 30. Chart. Temperature data collected at Site 1 Outfall 2 in 2024

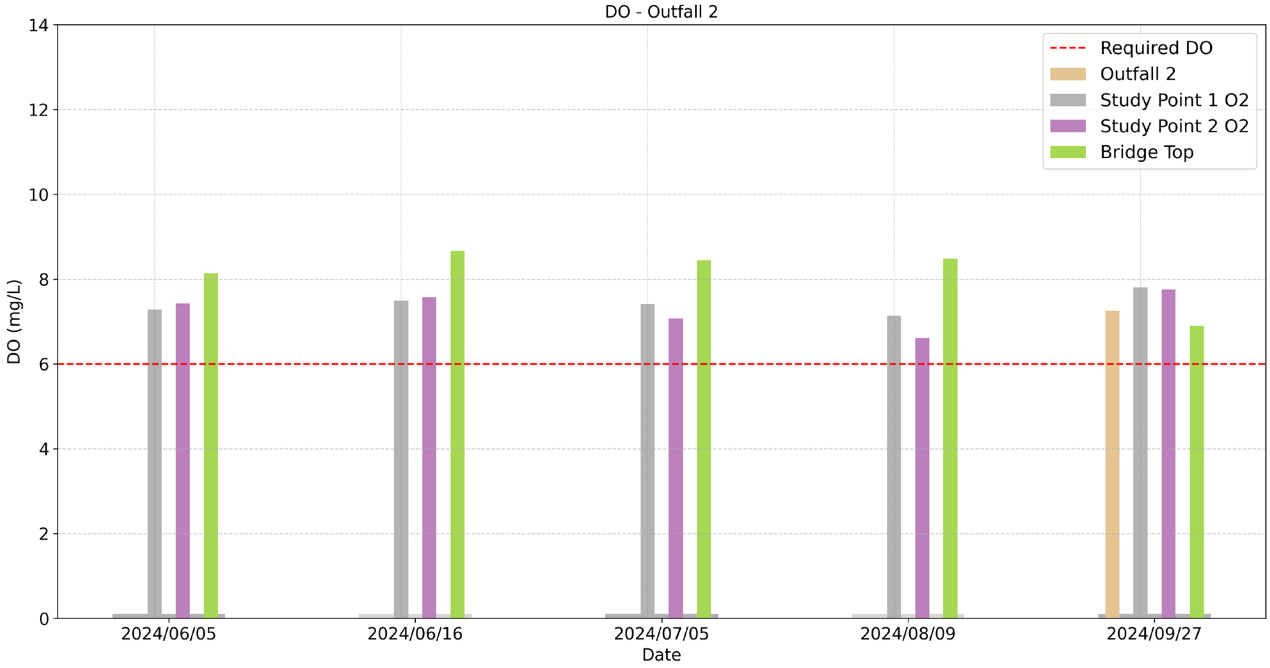


Figure 31. Chart. DO data collected at Site 1 Outfall 2 in 2024

In the graphs shown below in Figure 32 and Figure 33, the Temperature and DO log from 2025 is presented for Site 1 Outfall 1 and adjacent monitoring points. In 2025, the research team was successful in getting data during and immediately after rainfall events, and the data show positive temperature delta of 0.1°F to 1.1°F. At the downstream point, theDO data were always higher than the regulatory minimum daily average of 6.0 mg/L and regulatory minimum 5.0 mg/L.

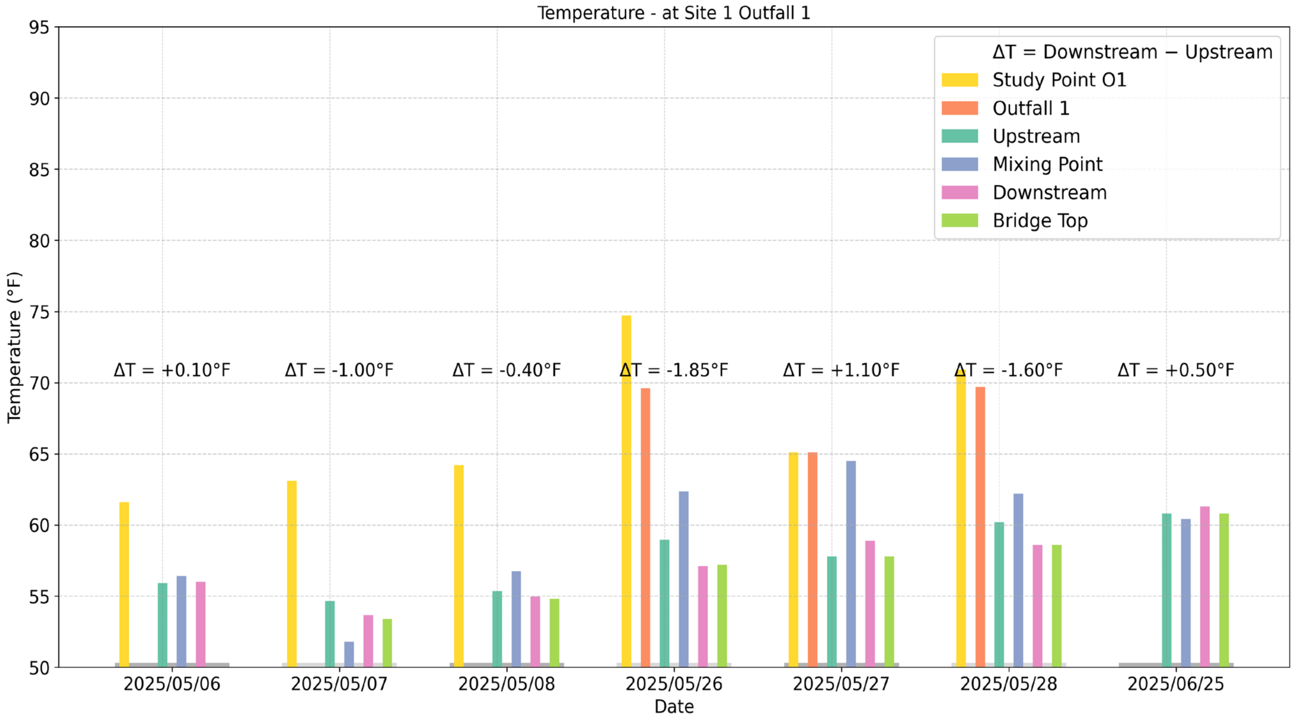


Figure 32. Chart. Temperature data collected at Site 1 Outfall 1 in 2025

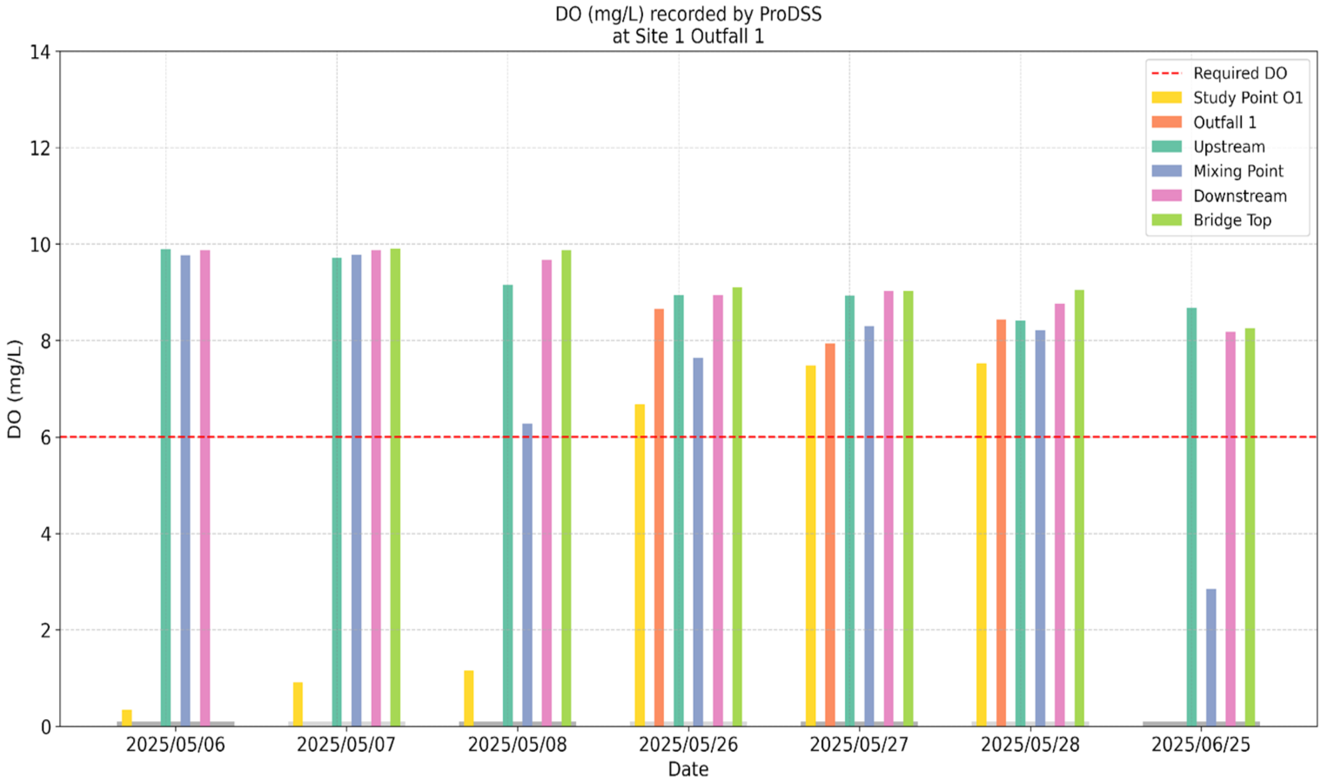


Figure 33. Chart. DO data collected at Site 1 Outfall 1 in 2025

In the graphs shown below in Figure 34 and Figure 35, the Temperature and DO log from 2025 is presented for Site 1 Outfall 2 and adjacent Study Points. As the Study Points were inaccessible most of the monitoring days, only the Outfall data are shown in the plot along with the baseline bridge top data. On 5/6/2025 and 5/7/2025, it's clearly visible from the data that Study Point 1 had higher temperature than Study Point 2, which indicates cooling effect along the flow path to Study Point 2. Data recorded on 6/25/2025 showed higher temperature at Study Point 2 than Study Point 1, which was taken on a hot, dry-day indicating temperature accumulation along the flow path through a residential area. Nevertheless, DO levels at all Study Points were higher than the regulatory minimum daily average of 6.0 mg/L and regulatory minimum 5.0 mg/L.

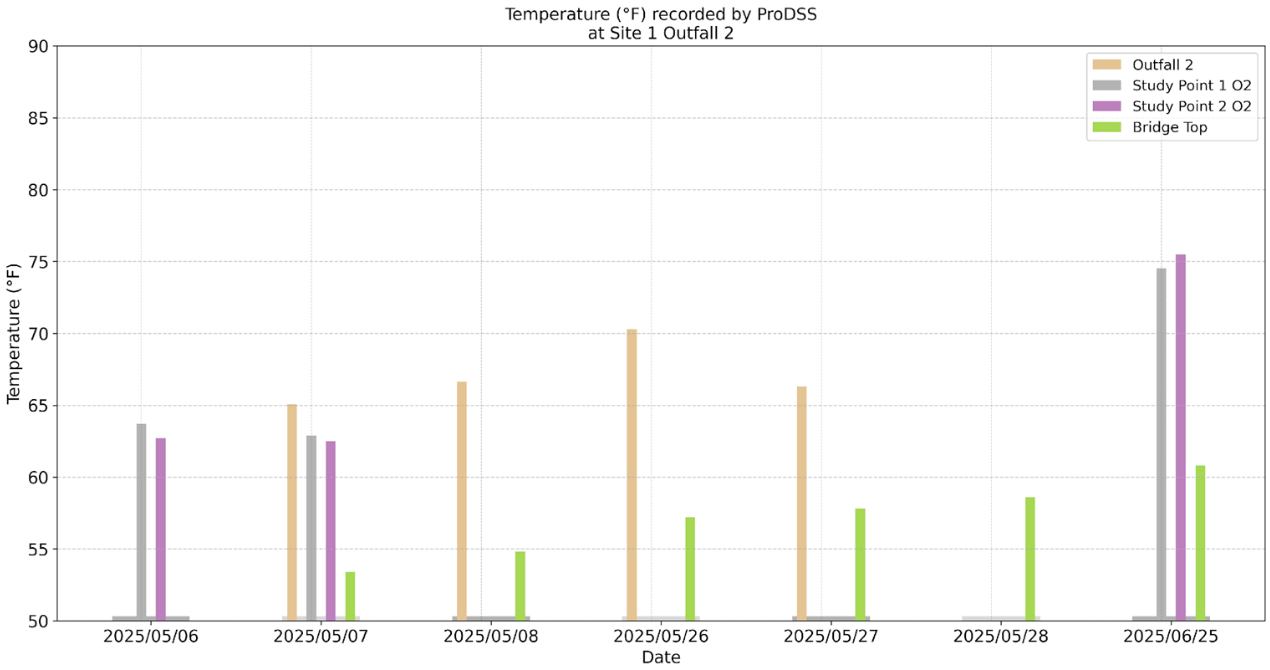


Figure 34. Chart. Temperature data collected at Site 1 Outfall 2 in 2025

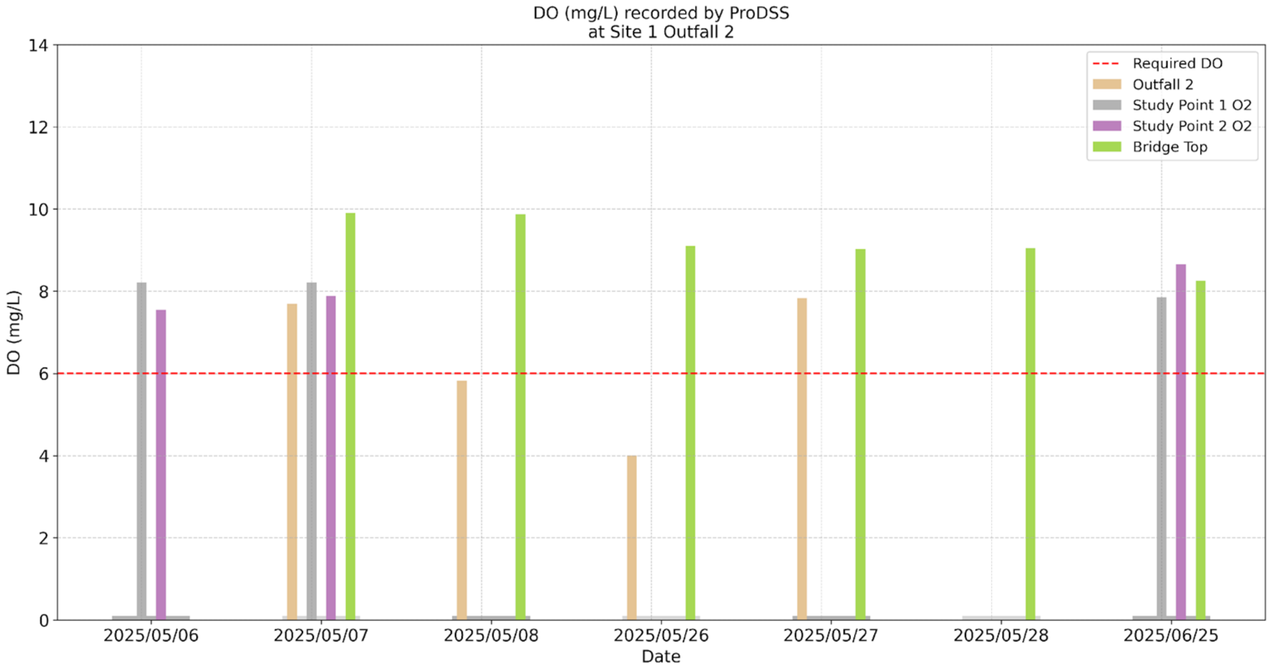


Figure 35. Chart. DO data collected at Site 1 Outfall 2 in 2025

YSI® ProDSS recorded data at Site 2

At Site 2, located along GA State Route 120 at Powder Springs Creek in Cobb County, the GSU Research Team initially designated three (3) monitoring points: an upstream reference, a roadway outfall, and a downstream impact station, to assess the temperature and DO effects of roadway runoff entering this mid-sized suburban trout stream. Upon detailed field inspection, however, it became evident that the primary outfall, Outfall 1, did not have a clearly defined discharge pipe or channel. Instead, roadway runoff was dispersed across a wide vegetated shoulder and entered the creek from multiple diffuse directions, creating a shallow overland sheet flow rather than a concentrated outfall jet. Additionally, during several moderate to heavy rainfall events, the entire floodplain adjacent to the roadway became inundated, merging the flow pathways into a single flooded mixing area rather than distinct point inflows. Because of these conditions, the GSU Research Team determined that Outfall 1 could not be treated as a conventional outfall discharge point. As a result, the site was reclassified and monitored as a single instream outfall–mixing zone, capturing the composite effect of roadway runoff entering the stream through diffuse flow during precipitation events.

The 2024 ProDSS grab-sample dataset for Site 2 doesn’t have any captured data during rainfall conditions, and the Outfalls were inaccessible or were dry. However, in 2025 during rainfall events, especially when sheet flow from the roadway surface was active, decreases in temperature were consistently observed. For example, at Outfall 1 (see Table 16) data collected on May 7th, 8th, 26th, 27th, 28th, during or after the rainfall events, the monitored temperature range was 65.2-69.6°F, which is a decrease of 4.46-8.8°F than the dry-day average temperature of 74°F. Outfall 2 (see Table 17) remained dry during dry-days, and on wet days had a temperature range of 65-70°F. Outfall 2 Study Point (see

Table 18) had a temperature decrease of 4.2-15.2°F compared to dry-day average of 83°F. Outfall 3 (see Table 19) had a temperature decrease of 3.6-7.5°F compared to the dry-day average of 68°F. Outfall 3 Study Point (showed in Table 20) had a temperature decrease of 3.8-8.65°F compared to dry-day average of 70.86°F.

While these ProDSS observations failed to confirm that roadway runoff produced brief, measurable warming at Site 2, they highlighted the challenge of capturing full event dynamics using only manual sampling. Because rainfall often occurred outside scheduled fieldwork windows, the GSU Research Team was unable to consistently capture peak runoff arrival or post-event recovery at all locations. The variable hydrology and diffuse drainage pattern further limited the precision of spatial comparisons between upstream and outfall points. In response, beginning in 2025, the Team deployed one (1) HOBO® continuous logger sensor to obtain high-frequency temperature and DO data at the same instream mixing zone at Outfall 1 at Site 2. This transition allowed for continuous observation during storm events, yielding a much clearer depiction of roadway-runoff temperature impacts under real-time conditions.

Table 16. ProDSS grab sample data collected from Instream Point of Outfall 1 at Site 2

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						Bushy, inaccessible
6/16/2024	Before rainfall						Not Visited
7/5/2024	Before rainfall						Bushy, inaccessible
8/10/2024	Before rainfall	79.1	7.365	121.2	6.84	3.375	
9/26/2024	During rainfall						Flooded area, inaccessible.
5/6/2025	Before Rainfall	65.7	8.43	87.6	7.09	5.64	
5/7/2025	During Rainfall	65.2	8.465	82.3	6.91	7.83	
5/8/2025	After Rainfall	67.6	8.2	88	6.93	8.05	
5/26/2025	After Rainfall	69.57	8.27	73.7	7.11	5.33	
5/27/2025	During Rainfall	67.9	8.44	65.77	6.75	5.11	
5/28/2025	After Rainfall	68.7	8.44	82.7	7.05	10.84	
6/25/2025	Before Rainfall	77.3	7.64	100.6	7.14	6.29	

Table 17. ProDSS grab sample data collected from Outfall 2 at Site 2

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						Dry
6/16/2024	Before rainfall						Dry
7/5/2024	Before rainfall						Dry
8/10/2024	Before rainfall						Dry
9/26/2024	During rainfall	72.8	7.915	48.25	7.27	0.885	
5/6/2025	Before rainfall						Dry
5/7/2025	During Rainfall	64.9	8.59	213.05	7.755	22.02	
5/8/2025	After Rainfall	66	8.68	284.65	7.885	34.39	
5/26/2025	After Rainfall	70.6	8.35	104.75	7.71	7.455	
5/27/2025	During Rainfall	70.2	8.61	59.6	7.43	3.98	
5/28/2025	After Rainfall	70.5	8.51	169.6	7.51	9.33	

Table 18. ProDSS grab sample data collected from Study Point of Outfall 2 at Site 2

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	79.2	9.58	123.6	8.19	1.51	
6/16/2024	Before rainfall						Dry
7/5/2024	Before rainfall	90.8	7.72	143.9	7.905	1.98	
8/10/2024	Before rainfall	86.95	7.4	99.25	7.275	2.51	
9/26/2024	During rainfall	73.2	7.005	88.15	7.395	3.085	
5/6/2025	Before rainfall	75.4	11.835	107.05	8.145	5.435	
5/7/2025	During Rainfall	70.8	11.41	98.55	8.24	7.105	
5/8/2025	After Rainfall	78.8	12.135	113.5	8.63	6.785	
5/26/2025	After Rainfall	75.2	9.79	96.3	7.675	7.67	
5/27/2025	During Rainfall	67.8	8.1	69.7	7.04	5.46	
5/28/2025	After Rainfall	76.7	9.09	95.4	7.25	6.5	
6/25/2025	Before rainfall	92.5	9.01	121.7	7.68	5.56	

Table 19. ProDSS grab sample data collected from Outfall 3 at Site 2

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						Bushy, inaccessible
6/16/2024	Before rainfall						Bushy, inaccessible
7/5/2024	Before rainfall						Bushy, inaccessible
8/10/2024	Before rainfall	72.05	7.545	134.2	6.895	7.41	
9/26/2024	During rainfall	71	7.525	45	7.01	1.935	
5/6/2025	Before rainfall	62.5	8.4	111.4	6.87	10.165	
5/7/2025	During Rainfall	61.2	8.645	104.65	6.805	11.705	
5/8/2025	After Rainfall	63.25	7.69	117.75	6.3	12.115	
5/26/2025	After Rainfall	64.5	8.215	102.85	6.84	10.82	
5/27/2025	During Rainfall	65.1	8.02	72.3	6.6	6.1	
5/28/2025	After Rainfall	64.2	8.4	107.7	6.8	11.75	
6/25/2025	Before rainfall	69.5	5.69	141.9	6.06	16.09	

Table 20. ProDSS grab sample data collected from Study Point of Outfall 3 at Site 2

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	69	7.45	100.8	7.12	1.65	
6/16/2024	Before rainfall						Dry
7/5/2024	Before rainfall	75.85	7.225	111.9	7.19	2.02	
8/10/2024	Before rainfall	74.9	7.72	112.55	7.31	3.555	
9/26/2024	After rainfall	69.7	7.9	35.75	6.975	1.27	
5/6/2025	Before rainfall	61.7	8.91	91.3	7	8.83	
5/7/2025	During Rainfall	62.2	8.57	75.7	6.89	7.29	
5/8/2025	After Rainfall	65.7	8.32	93.5	6.9	8.01	
5/26/2025	After Rainfall	67	8.4	56.25	7.08	5.4	
5/27/2025	During Rainfall	66.1	8.61	56.3	6.86	4.93	
5/28/2025	After Rainfall	65.7	8.53	83.5	6.89	10.47	
6/25/2025	Before rainfall	74	8.06	115	7.21	10.12	

YSI® ProDSS Data Bar Plots for Site 2

From the ProDSS data bar of Site 2 showed in Figure 36 and Figure 38 for year 2024 and 2025, it can be seen that in every instance, the Outfall temperatures were lower than the Outfall adjacent Study Points, which indicates the study points were carrying higher temperature influx from runoff from adjacent areas. But it was not possible to answer GDOT's question regarding the temperature increase of 2°F during the rainfall events from recorded ProDSS data. This strengthened the idea of deploying a HOBO® continuous data logger at Site 2 Outfall 1 to capture the full event dynamics. The DO data for 2024 and 2025 presented in Figure 37 and Figure 39 shows that DO was always over the regulatory limit.

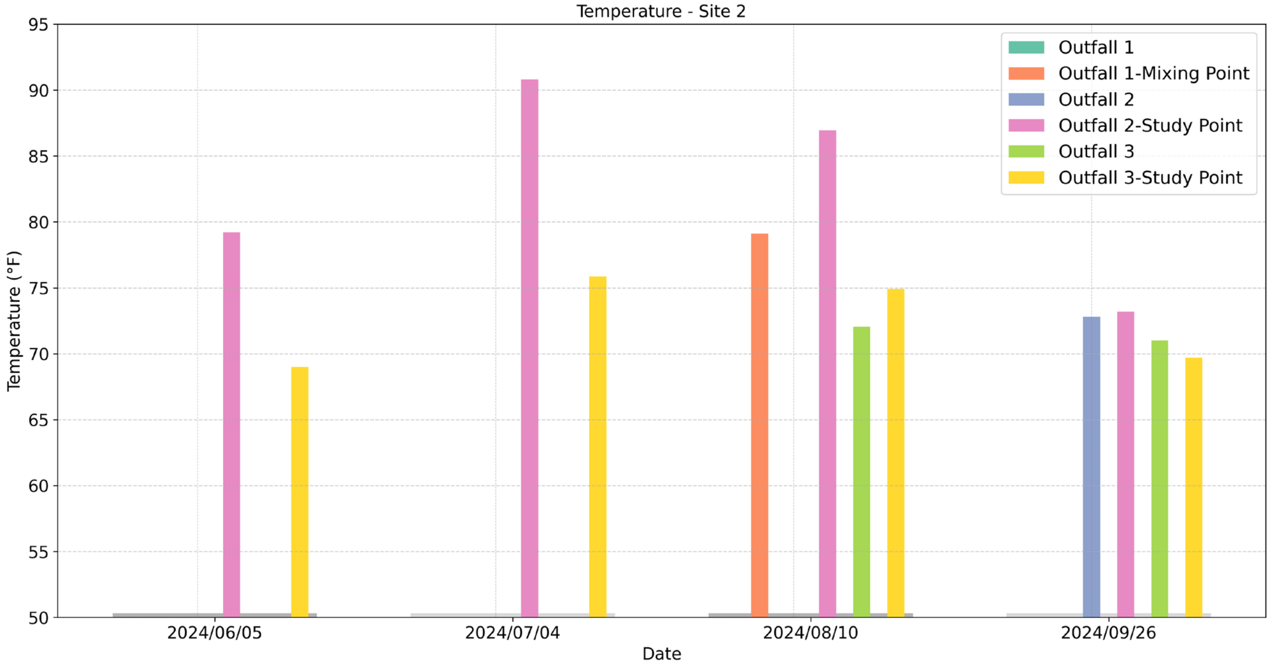


Figure 36. Chart. Temperature data collected at Site 2 in 2024

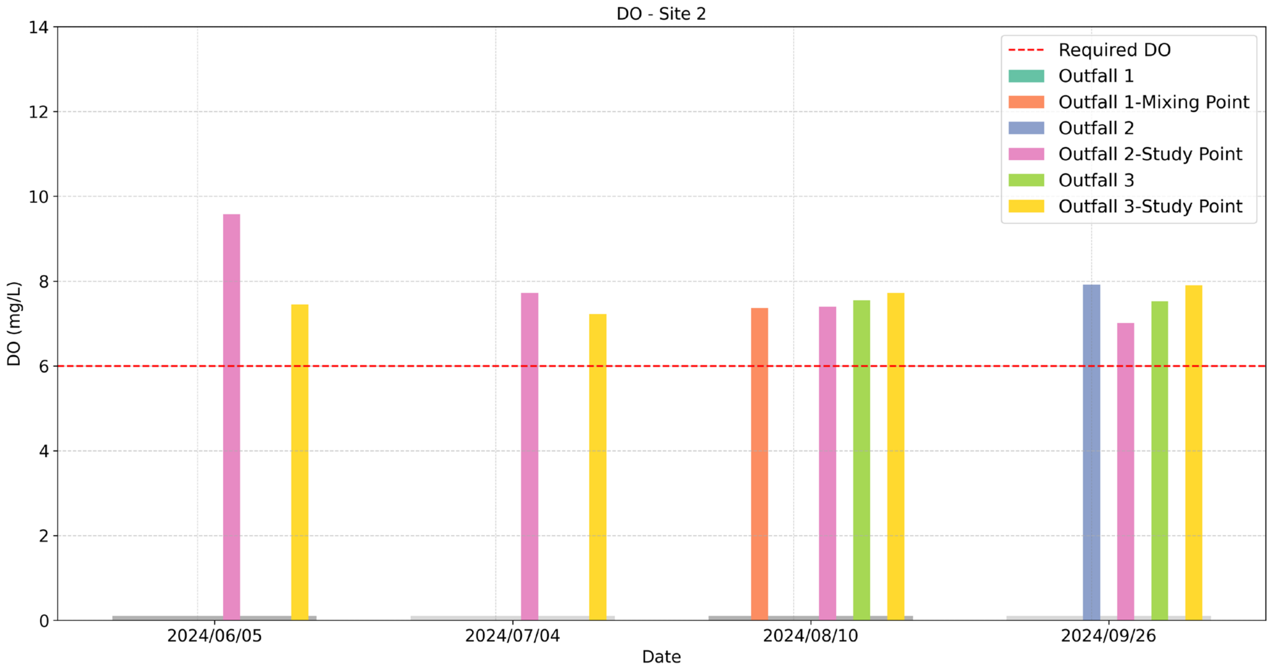


Figure 37. Chart. DO data collected at Site 2 in 2024

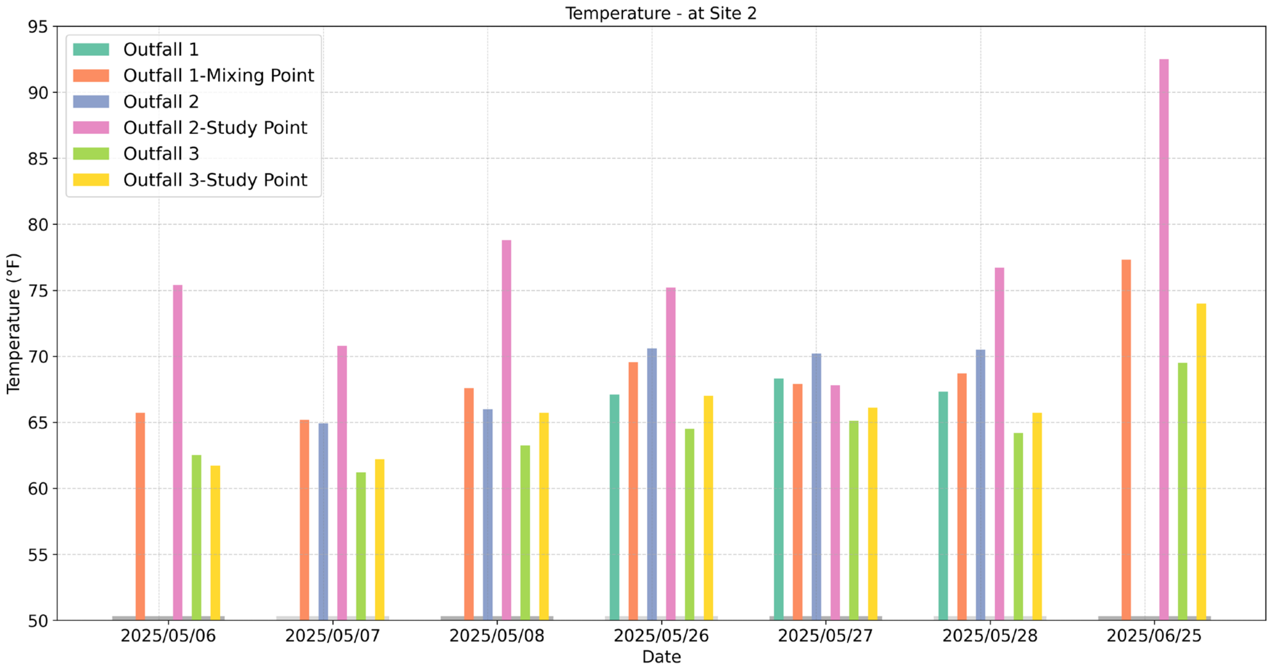


Figure 38. Chart. Temperature data collected at Site 2 in 2025

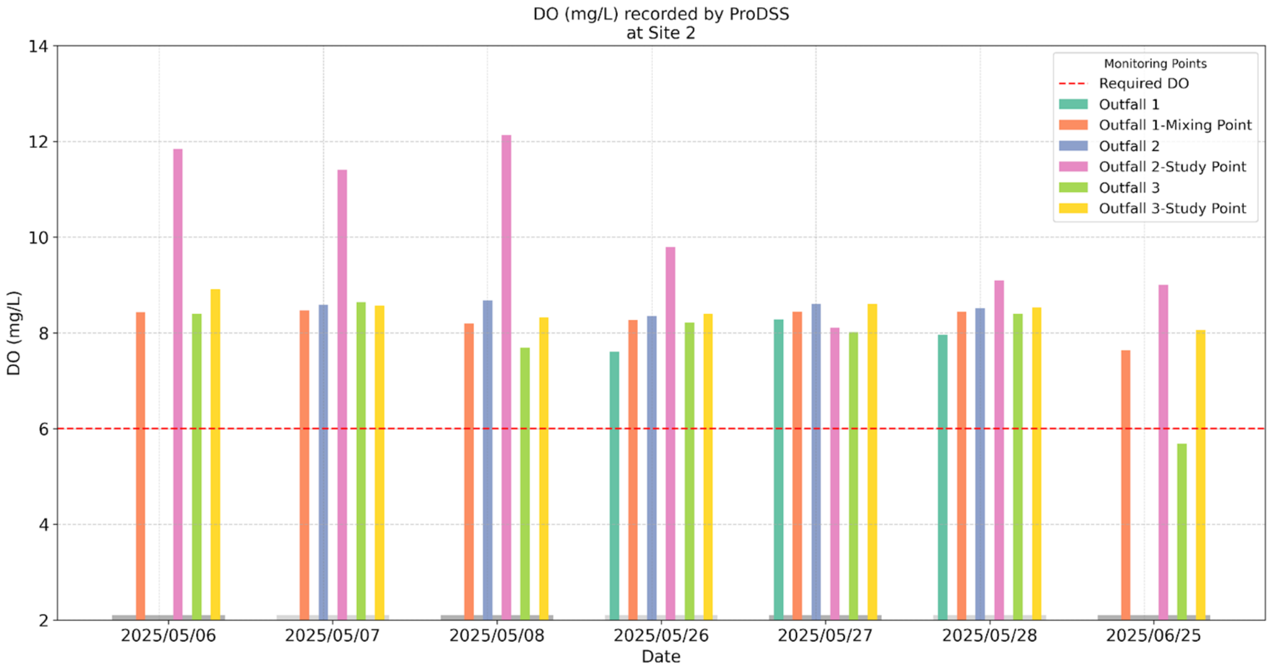


Figure 39. Chart. DO data collected at Site 2 in 2025

YSI® ProDSS recorded data at Site 3

At Site 3, located along GA State Route 293 near Kingston Highway in Bartow County, ProDSS grab sample monitoring was conducted during the 2024 field season to evaluate roadway runoff impacts on a small, high-gradient trout stream characterized by dense riparian canopy and limited baseflow. Two roadway outfalls were identified within one (1) mile upstream of the stream crossing; however, each discharge entered the floodplain through vegetated channels and drainage swales before ultimately reaching the creek. During field visits and rainfall observations, the GSU Research Team noted that these outfalls were located at considerable distances from the Instream Sampling Point and that the intervening flow paths were heavily shaded and lined with grass, shrubs, and leaf litter, creating an effective natural buffer that moderated runoff temperature before it entered the stream.

At the Site 3, Outfall 3, discharges and the runoff water flow get carried to the Outfall 2 discharge, then these two (2) streams get carried to the creek. In theory, creek water was supposed to be warmer because of all the accumulated water. However, from the ProDSS data collected in 2024 and 2025 at Instream Sampling Point (see Table 21) it can be seen that the recorded stream temperature on wet day at Instream Sampling Point was slightly lower than the baseline dry weather temperature average in range of 1-10.7°F on several occasions, indicating that the vegetated flow path from Outfall 2 and 3 provided substantial cooling through shade and surface–subsurface exchange before the runoff reached the main channel. Outfall 2 data (see

Table 22) had higher temperature readings, as it had no vegetation coverage and also because of the fact that Outfall 2 covered a 9 times larger drainage area compared to the Outfall 3 (see Table 23).

DO concentrations in Site 3 remained stable and well within trout stream standards in all conditions. No DO depletion below 5.0 mg/L was observed between the monitoring points except in two (2) events in late May of 2025 at Outfall 3, which could be coming from a stagnant puddle of water at that monitoring point. These results suggest that the small volume of roadway discharge, combined with effective vegetative filtration and the creek's rapid reaeration capacity, prevented any measurable DO depression.

The overall ProDSS dataset for Site 3 indicates that roadway runoff influence on stream temperature and DO was negligible. The combination of long vegetated drainage paths, dense canopy cover, and a narrow but shaded stream channel effectively buffered the system against temperature and DO disturbance.

Table 21. ProDSS grab sample data collected from Point 1 Instream Sampling at Site 3

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall	73.8	7.32	273.1	7.91	0.84	
7/4/2024	Before rainfall	79.7	6.965	315.7	7.955	1.265	
8/10/2024	Before rainfall	78.5	7.565	314.3	8.045	1.95	
9/27/2024	After rainfall	69.3	6.39	67.85	6.99	1.59	
5/6/2025	Before rainfall	63.15	9.08	199.7	7.75	2.59	
5/7/2025	During Rainfall	64.1	8.475	213.8	7.745	4.765	
5/8/2025	After Rainfall	69.3	7.975	230.8	7.755	4.21	
5/26/2025	After Rainfall	68.5	7.955	186.3	7.535	4.835	
5/27/2025	During Rainfall	67.3	8.29	216	7.72	5.08	
5/28/2025	After Rainfall	65.7	8.495	214.35	7.675	5.875	
6/26/2025	Before Rainfall	78	7.66	312	7.87	4.66	
9/25/2025	During Rainfall	72.50	6.61	296.50	9.03	23.81	

Table 22. ProDSS grab sample data collected from Outfall 2 at Site 3

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						Dry
7/4/2024	Before rainfall						Dry
8/10/2024	After rainfall						Dry
9/27/2024	Before rainfall	71.5	5.605	148.1	7.15	1.755	
5/6/2025	During Rainfall						Dry
5/7/2025	After Rainfall						Dry
5/8/2025	After Rainfall						Dry
5/26/2025	During Rainfall						Dry
5/27/2025	After Rainfall	69.6	8.18	165	7.66	5.14	
5/28/2025	Before Rainfall	75.2	8.81	268.6	7.72	6.89	
9/25/2025	During Rainfall	77.40	6.85	128.90	8.17	15.77	

Table 23. ProDSS grab sample data collected from Outfall 3 at Site 3

Date	Event	Avg. Temp (°F)	Avg. DO (mg/L)	Avg. Conductivity (µS/cm)	Avg. pH	Avg. Chloride (mg/L)	Note
6/5/2024	After rainfall						Dry
7/4/2024	Before rainfall						Dry
8/10/2024	After rainfall						Dry
9/27/2024	Before rainfall	70.95	6.735	40.75	6.52	0.94	
5/6/2025	During Rainfall	64.65	10.105	65.45	7.235	2.51	
5/7/2025	After Rainfall	65.8	5.755	70.65	6.42	3.865	
5/8/2025	After Rainfall	68.75	9.785	79.2	7.205	5.865	
5/26/2025	During Rainfall	67.4	1.11	78.75	5.675	7.44	
5/27/2025	After Rainfall	70.7	7.96	42.1	7.25	2.43	
5/28/2025	Before Rainfall	67.9	1.47	74.5	5.72	7.1	
9/25/2025	During Rainfall	78.00	6.08	71.00	8.17	24.14	

YSI® ProDSS Data Bar Plots for Site 3

In Figure 40 and Figure 42 for temperature data recorded in 2024 and 2025 it is clear that the Instream Sampling Point had lower temperature than Outfall 2 and 3. And from Figure 41 and Figure 43 it can be seen that the DO level at the creek was always higher than the regulatory limits.

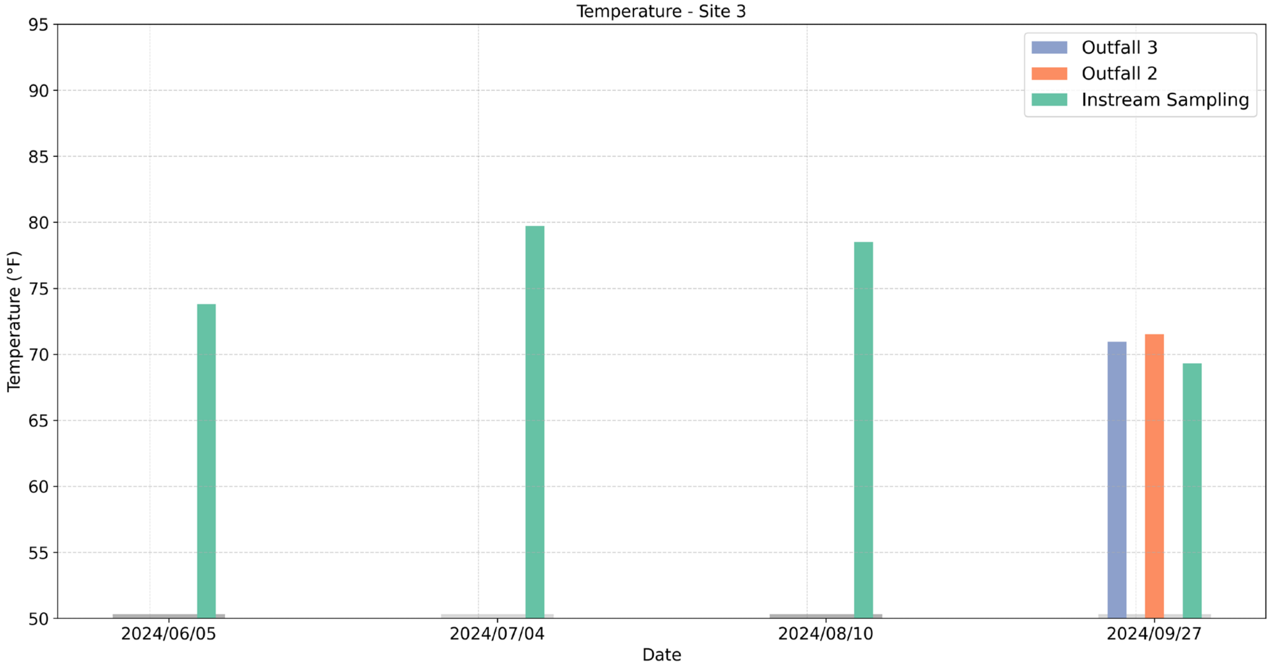


Figure 40. Chart. Temperature data collected at Site 3 in 2024

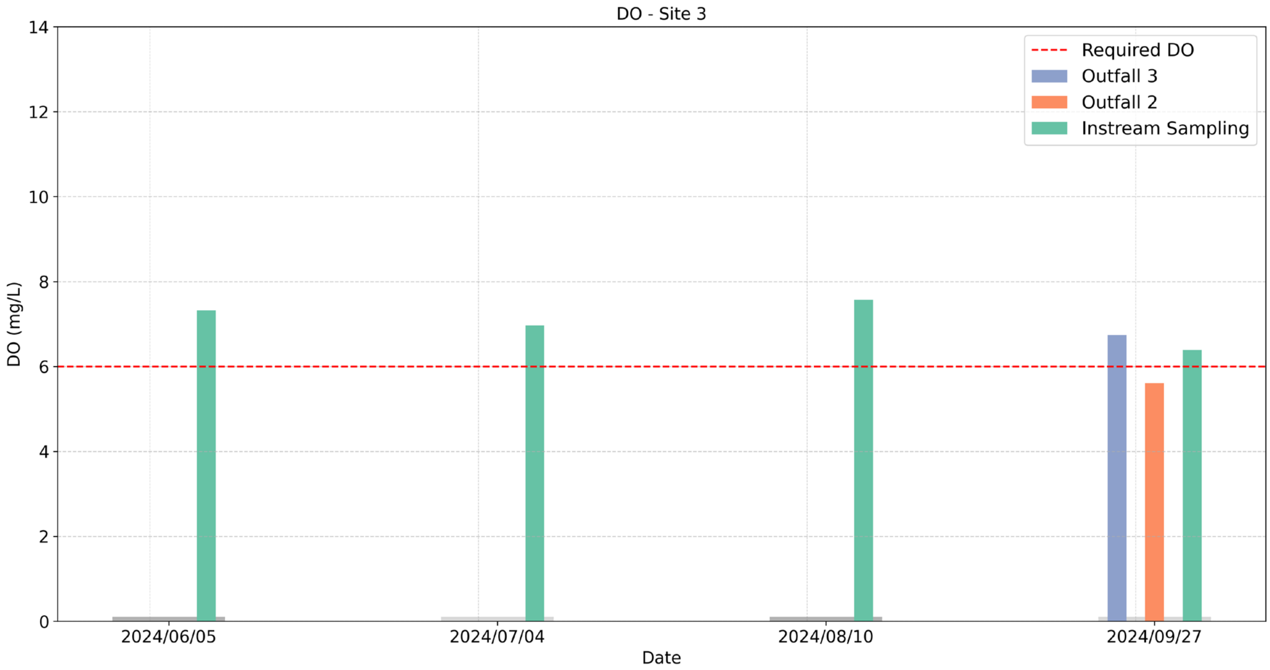


Figure 41. Chart. DO data collected at Site 3 in 2024

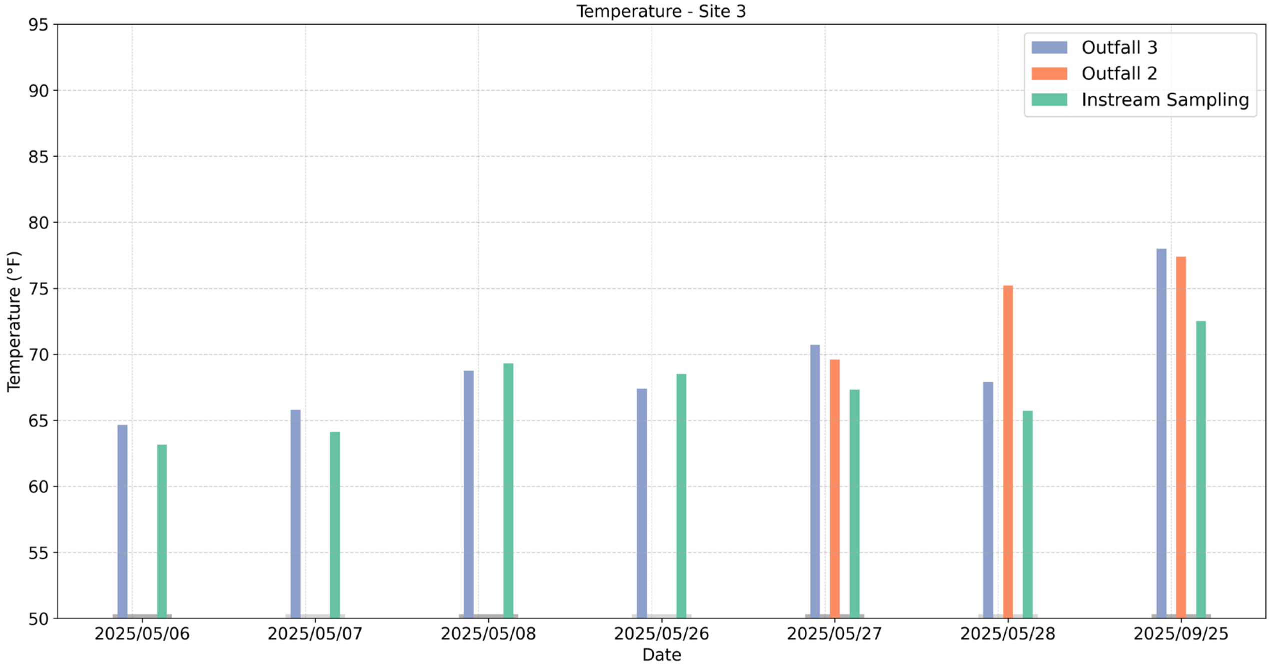


Figure 42. Chart. Temperature data collected at Site 3 in 2025

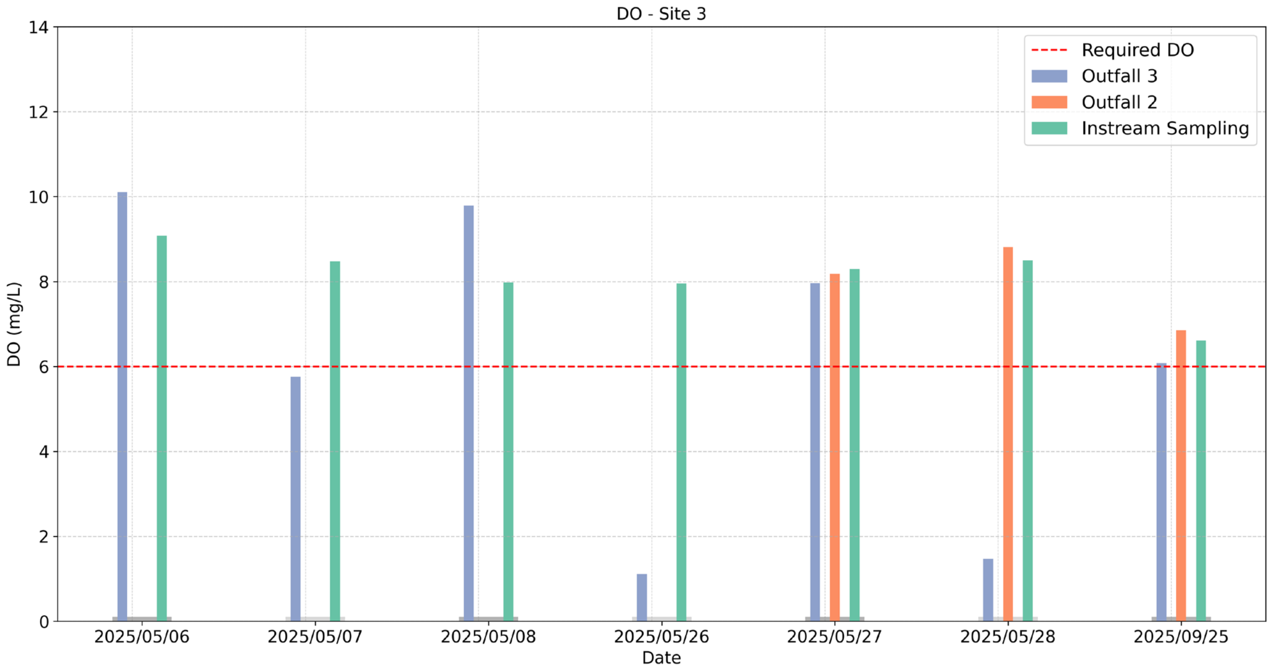


Figure 43. Chart. DO data collected at Site 3 in 2025

Remote Sensor Rainfall-Event Monitoring Results

The rainfall plots recorded by the ESP32-based remote sensor systems from May through September 2025 illustrate distinct hydrologic and temperature response patterns across the three (3) monitored trout stream sites, reflecting how watershed scale, canopy cover, and roadway configuration influenced runoff dynamics. At Outfall 2 of Site 1 on 5/7/2025 (see Figure 44), the rainfall response data from ESP32 showed clear, well-defined temperature pulses from precipitation induced roadway runoff that corresponded to temperature fluctuations of 5-7 °F and DO drop (Figure 45) of up to 4 mg/L in the continuous logger record, confirming the warmer roadway runoff water coming in and rapid dissipation of roadway inflows. At Site 2 Outfall 2 on 6/25/2025 (in Figure 46 and Figure 47) the temperature plot didn’t show any response to rainfall through ESP32 due to very small runoff coming into the big runoff drainage pathway. At Site 3 Outfall 2 and 3 on 9/24/2025 (Figure 48 and Figure 50), the temperature plots showed a short-term but high-intensity rainfall event, yet the stream’s temperature response remained minimal within 3°F and DO drop (Figure 49 and Figure 51) of up to 1 mg/L due to outlets and drainage pathways being covered with dense vegetation.

Collectively, the ESP32 data across all three (3) sites confirmed the spatial variability in roadway runoff influence under similar precipitation magnitudes: urban and semi-urban systems with exposed drainage networks (Site 1) exhibited prompt and measurable temperature and DO changes, whereas high-flow or vegetated systems (Site 2 and 3) largely buffered those impacts. These findings emphasize the importance of considering both watershed context and rainfall characteristics when assessing roadway runoff impacts on trout stream water quality and reinforce the value of high-frequency, event-based remote sensor monitoring in characterizing such transient hydrologic–temperature interactions.

Remote Sensor Data Recorded at Site 1

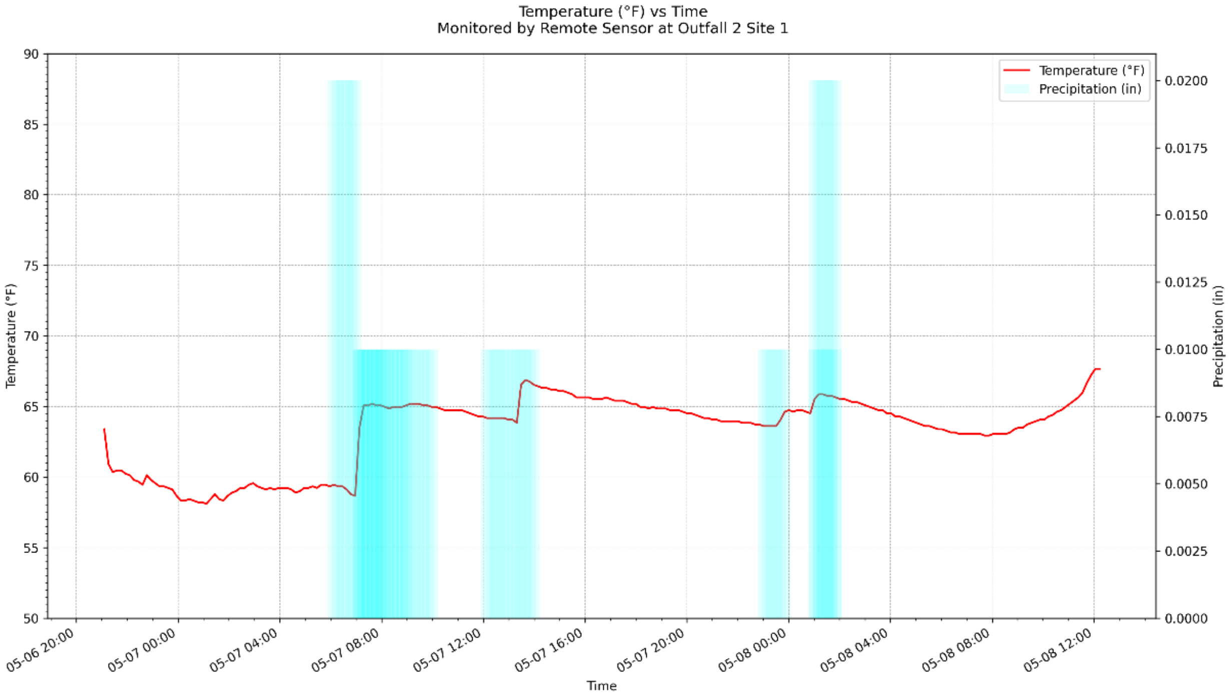


Figure 44. Chart. Temperature vs Time Plot from Remote Sensor Data from Site 1 Outfall 2 with USGS Hourly Precipitation Data from 5/8/2025

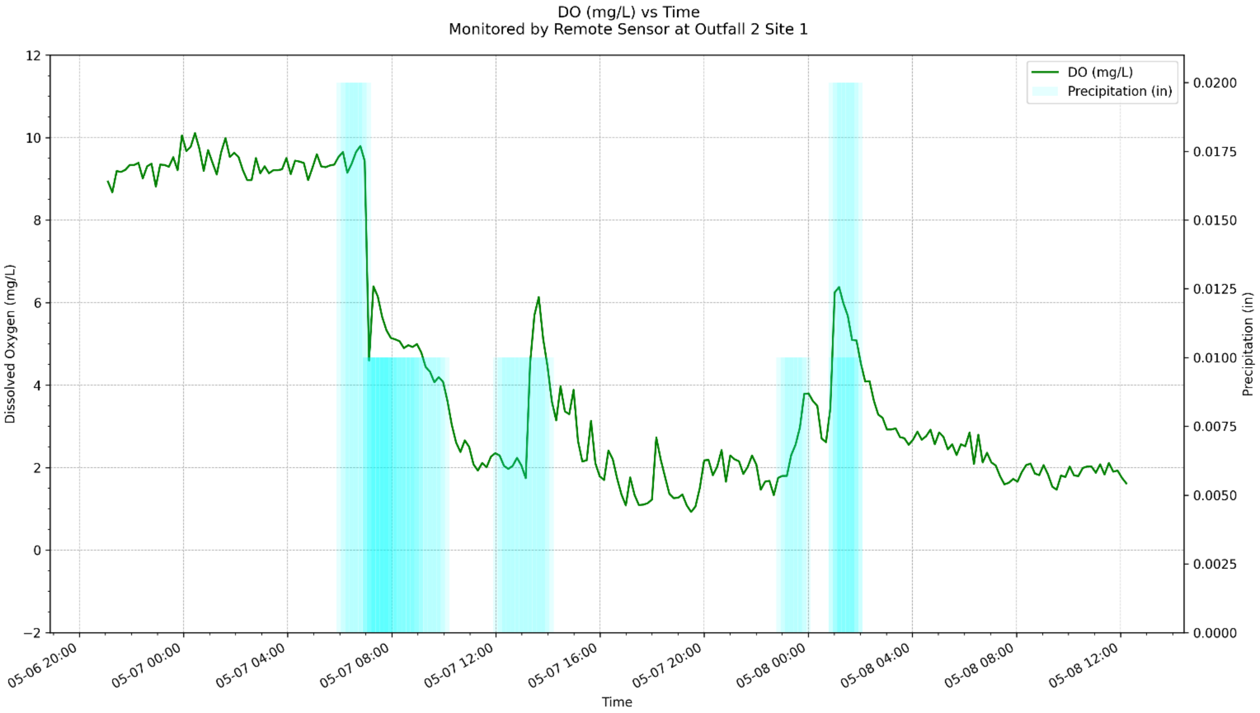


Figure 45. Chart. DO vs Time Plot from Remote Sensor Data from Site 1 Outfall 2 with USGS Hourly Precipitation Data from 5/8/2025

Remote Sensor Data Recorded at Site 2

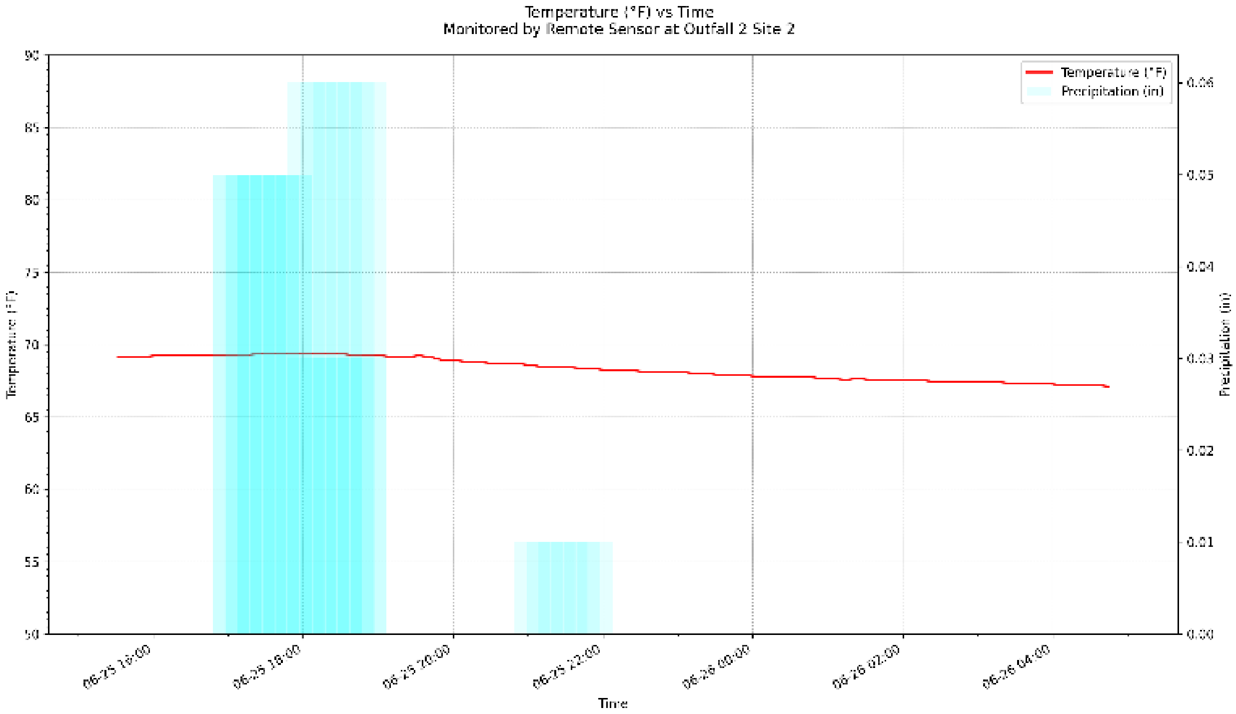


Figure 46. Chart. Temperature vs Time Plot from Remote Sensor Data from Site 2 Outfall 2 with USGS hourly precipitation data from 6/25/2025

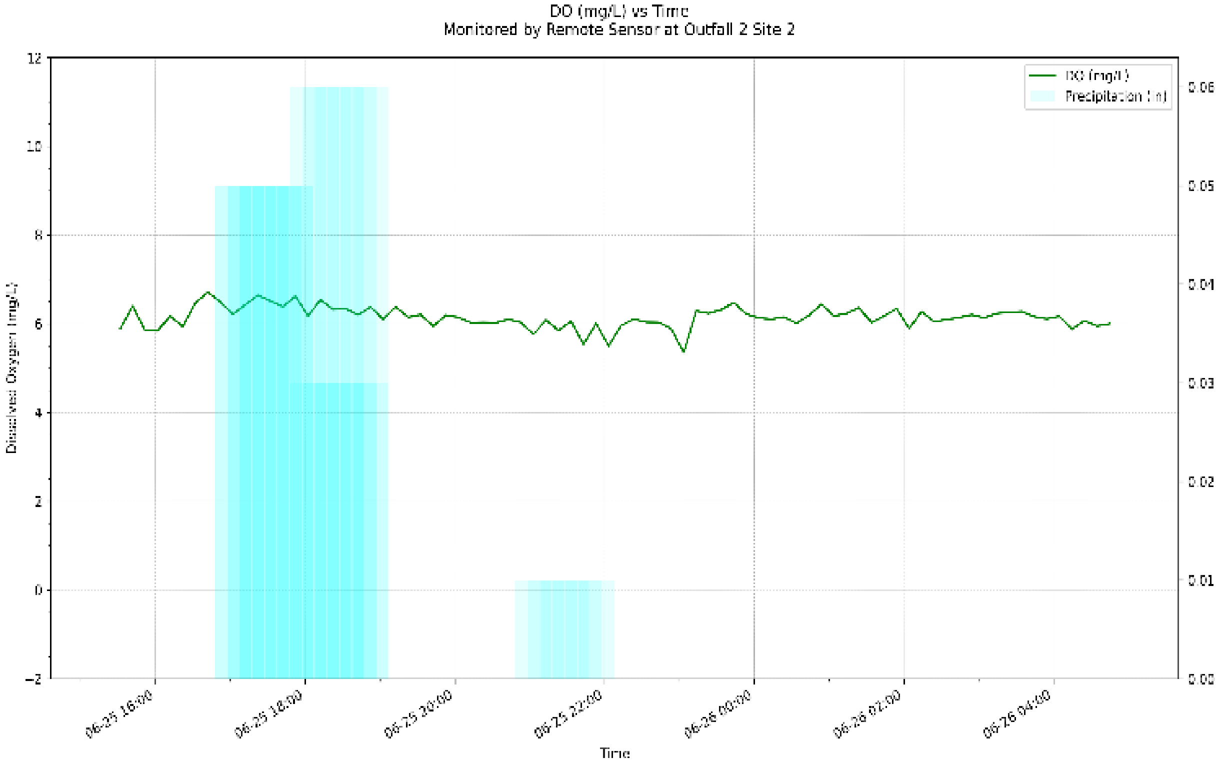


Figure 47. Chart. DO vs Time Plot from Remote Sensor Data from Site 2 Outfall 2 with USGS hourly precipitation data from 6/25/2025

Remote Sensor Data Recorded at Site 3

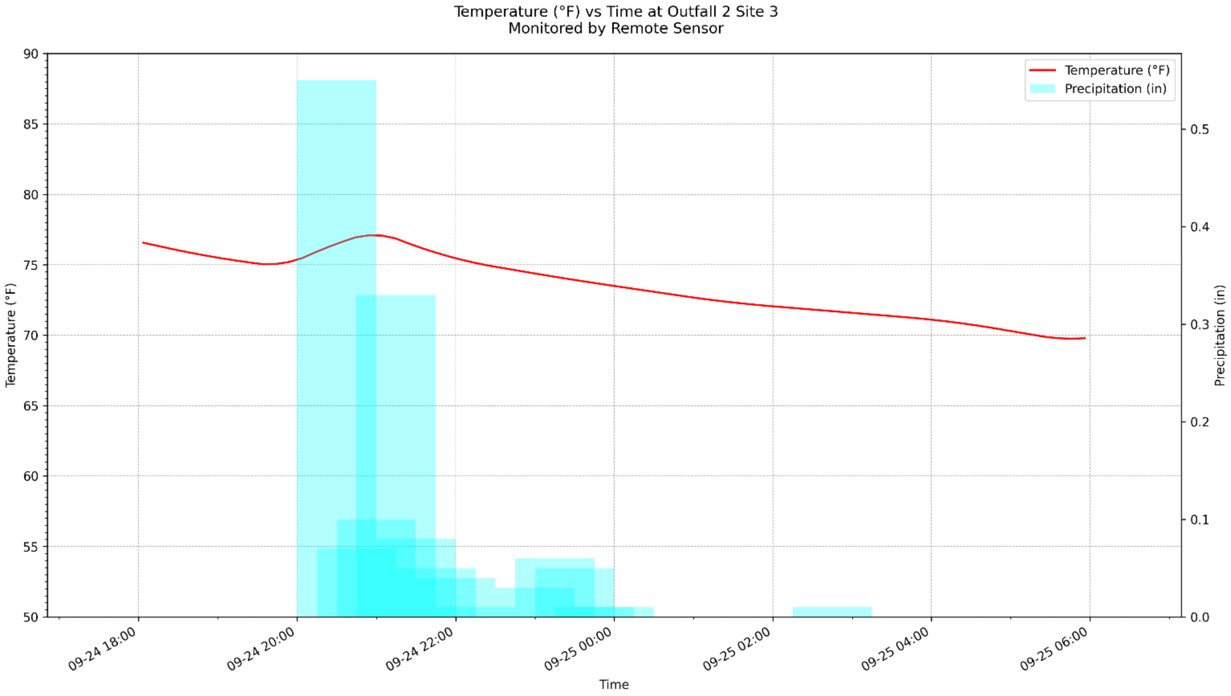


Figure 48. Chart. Temperature vs Time plot of Remote sensor data at Outfall 2 Site 3 with USGS hourly precipitation data from 9/24/2025

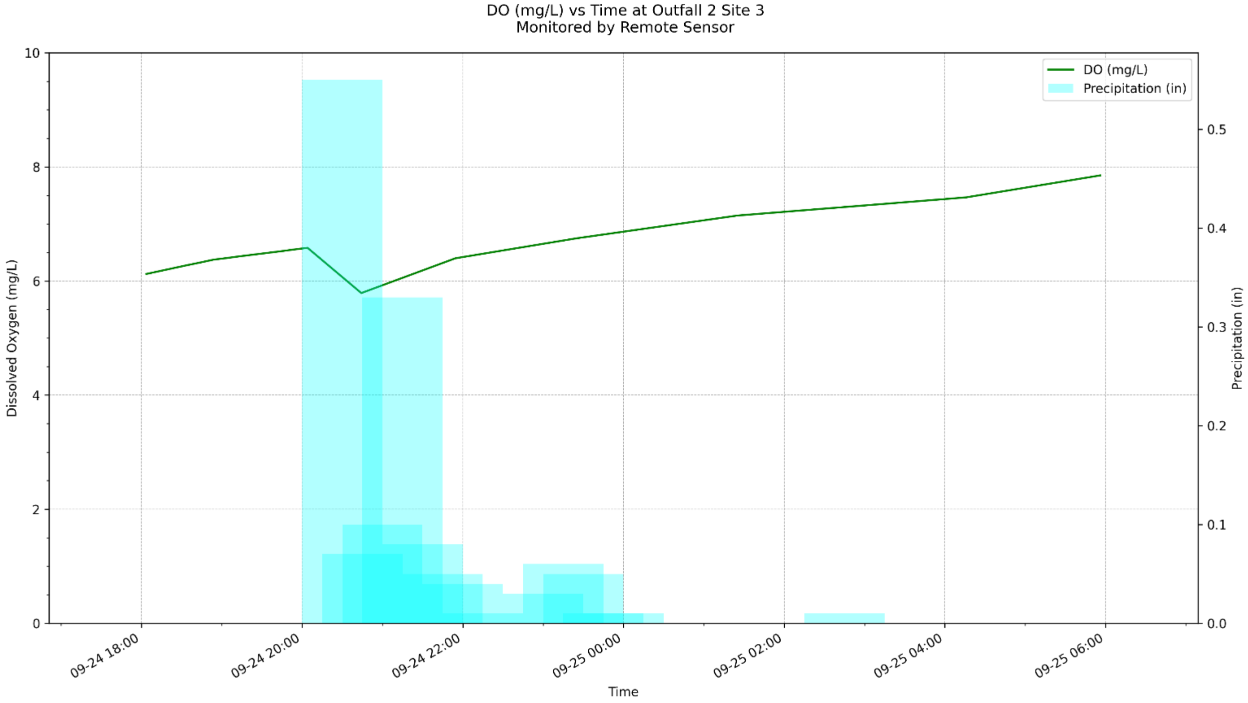


Figure 49. Chart. DO vs Time plot of Remote sensor data at Outfall 2 Site 3 with USGS hourly precipitation data from 9/24/2025

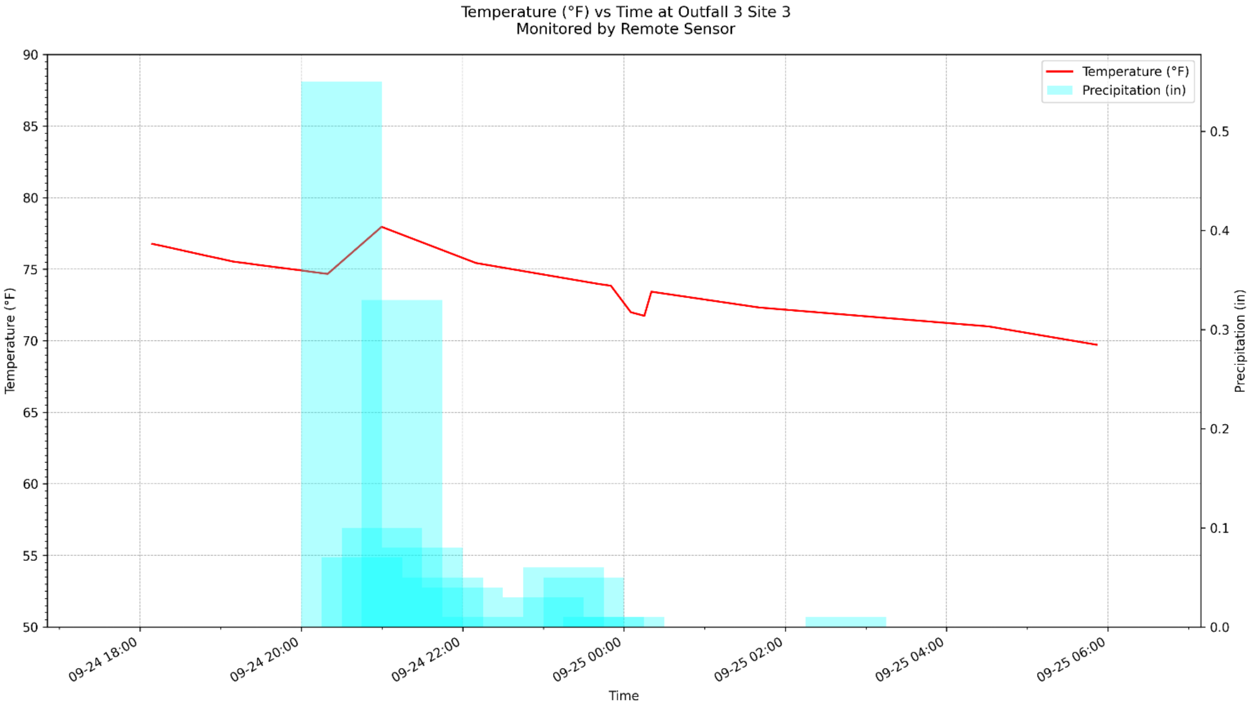


Figure 50. Chart. Temperature vs Time plot of Remote sensor data at Outfall 3 Site 3 with USGS hourly precipitation data from 9/24/2025

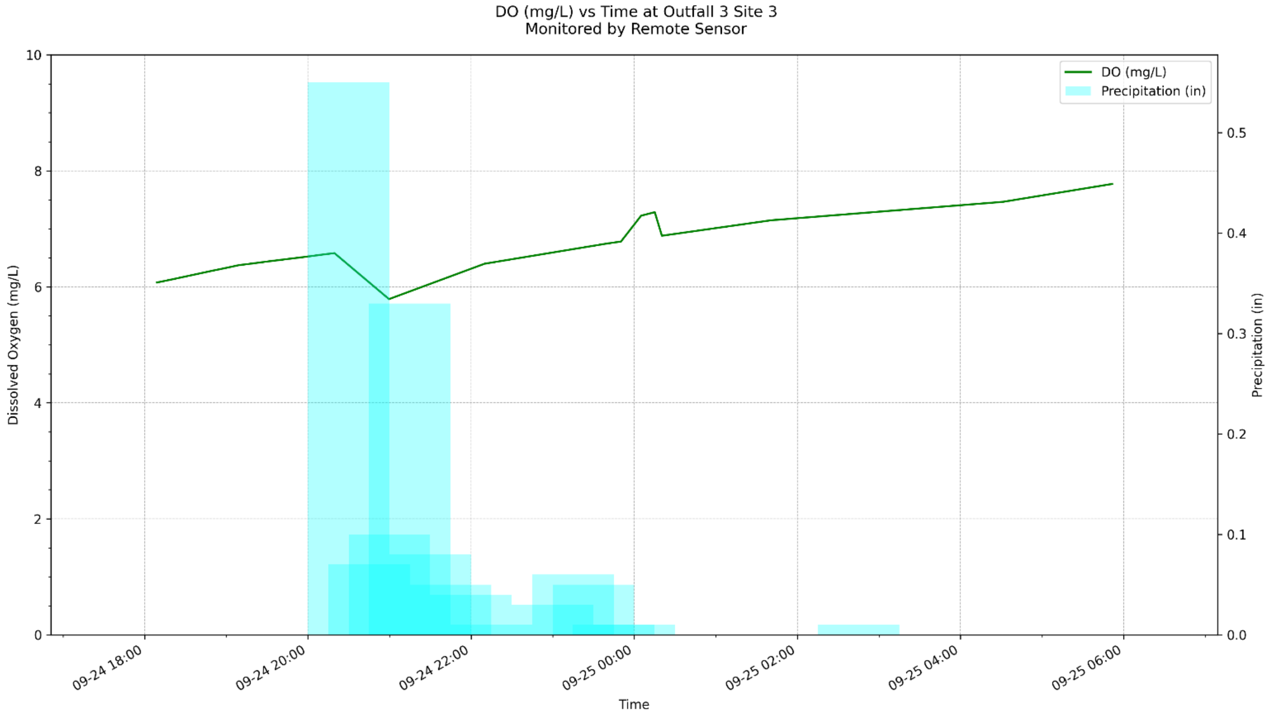


Figure 51. Chart. DO vs Time plot of Remote sensor data at Outfall 3 Site 3 with USGS hourly precipitation data from 9/24/2025

HOBO® Continuous Data Logger Results

The HOBO® continuous logger plots depict the second-year monitoring record from May 2025 through October 2025 and provide the most complete representation of roadway runoff impacts on stream temperature and DO across three (3) sites.

Site 1 Outfall 1, where upstream, mixing-zone, and downstream loggers operated simultaneously, the plots show clear rainfall-linked temperature oscillations that coincide with USGS precipitation events greater than 0.5 inch in 24 hours. At Site 2, only one (1) HOBO® logger was installed at the instream outfall-mixing point at Outfall 1 location because the floodplain conditions and diffuse drainage meant no point in deployment of multiple instruments. At Site 3 (Two-Run Creek), one (1) HOBO® logger was maintained at Point 1 Instream Sampling downstream of the vegetated drainage swales. The continuous data log record shows strong diurnal variation typical of a shaded, low-flow system but lacks clear temperature excursions linked directly to rainfall.

HOBO® Continuous Data Recorded at Site 1

Data Recorded during 2nd Quarter of 2025

At Site 1 the HOBO® datalogger data (see Figure 52, Figure 54 and Figure 56) had diurnal pattern in temperature data log ranging from 52-76°F where lowest temperature was recorded during the early morning and highest temperature was recorded in the afternoon. After each significant rainfall of ≥ 0.5” the diurnal temperature pattern had a dip in the temperature range. The DO data (see Figure 53, Figure 55, and Figure 57) showed that the daily average largely remained above 6.0 mg/L, fulfilling the regulatory limit. However, in some days the DO concentration fell below 5.0 mg/L, which is below the regulatory limit for DO at any time. The GSU research team believes that this drop in DO level was largely due to sensor fouling and sedimentation accumulation around the DO sensor cap inside the housing. Although to get a clear idea about the reason behind it, it's better to do more thorough monitoring at different depths of water and different locations.

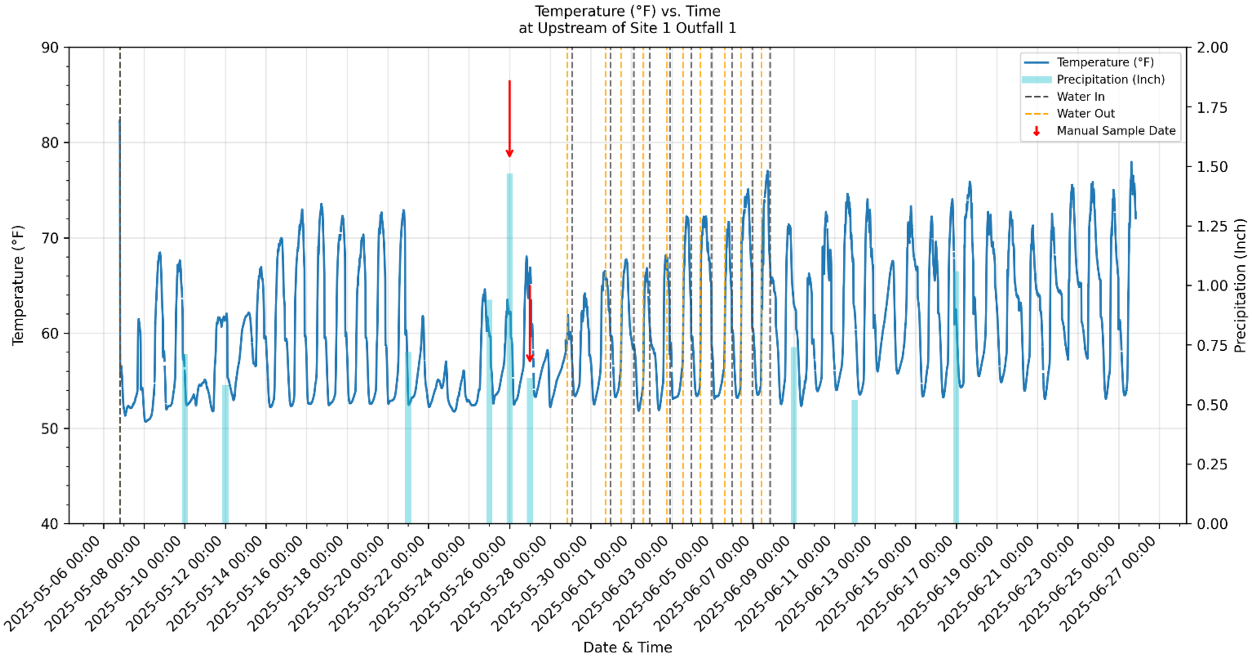


Figure 52. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Upstream point of Outfall 1 from 2nd Quarter of 2025

Figure 53. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Upstream point of Outfall 1 from 2nd Quarter of 2025

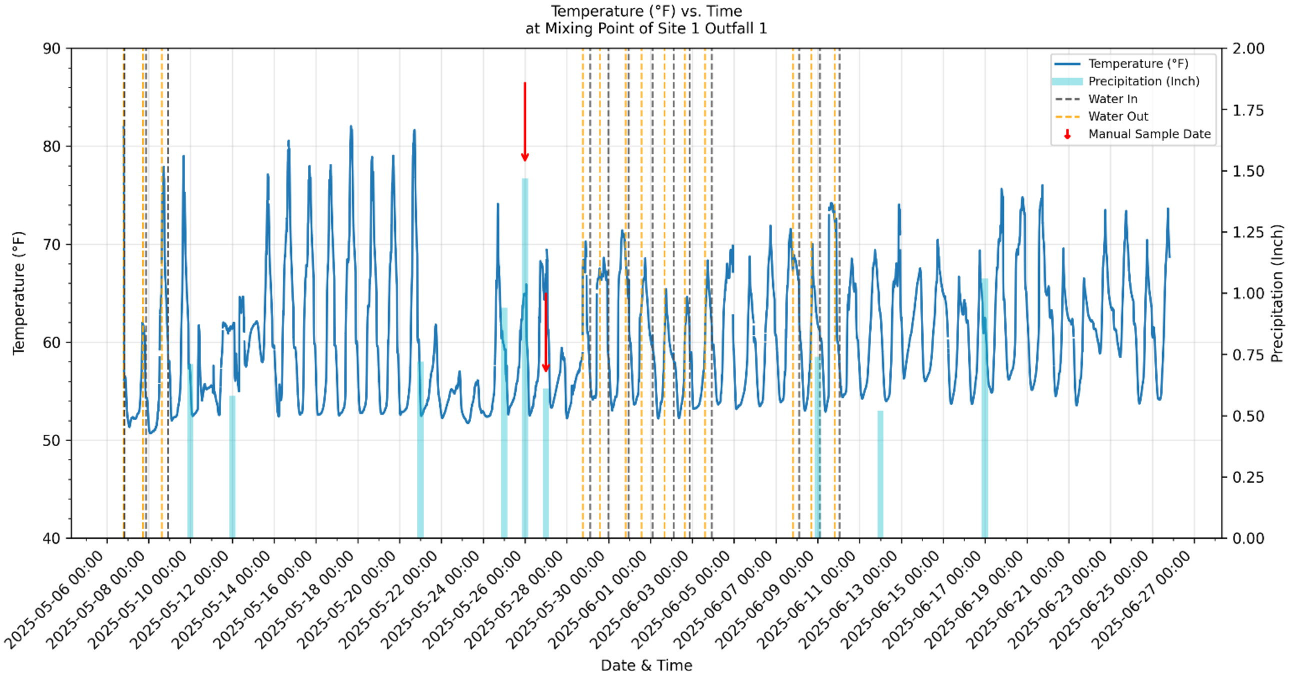


Figure 54. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Mixing point of Outfall 1 from 2nd Quarter of 2025

Figure 55. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Mixing point of Outfall 1 from 2nd Quarter of 2025

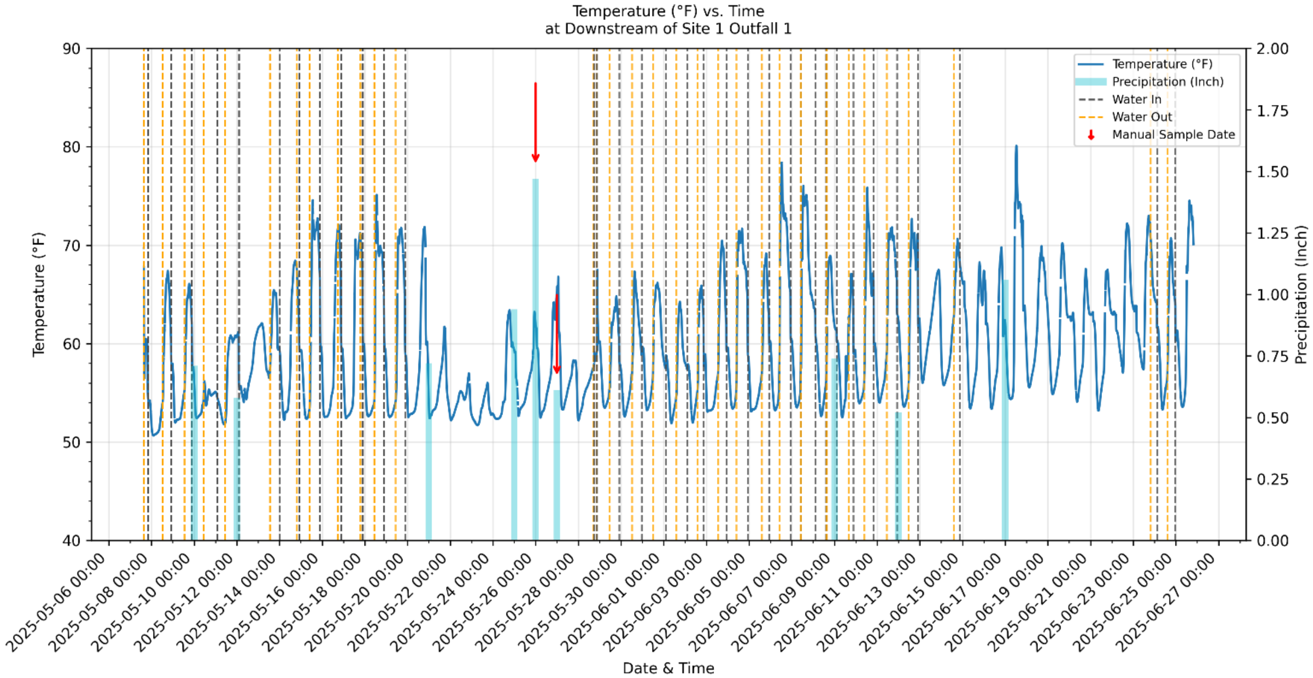


Figure 56. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Downstream point of Outfall 1 from 2nd Quarter of 2025

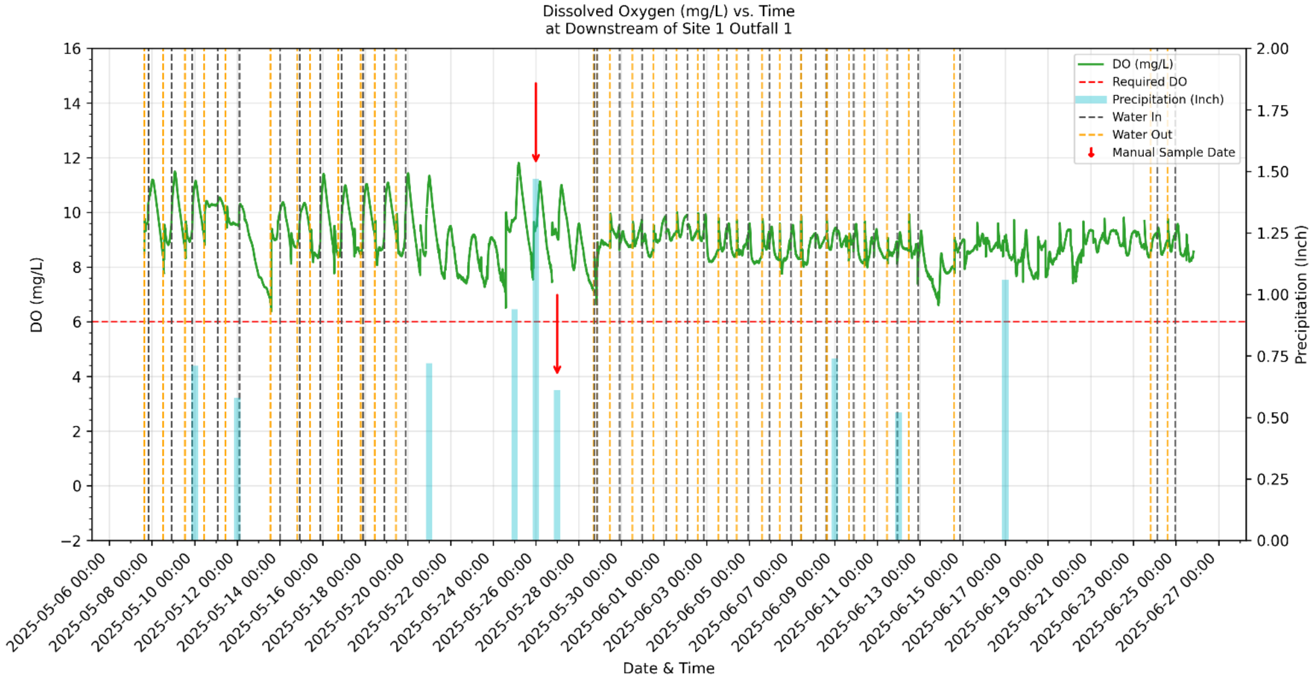


Figure 57. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Downstream point of Outfall 1 from 2nd Quarter of 2025

Data Recorded during 3rd Quarter of 2025

At Site 1 the HOBO® datalogger data (see Figure 58, Figure 60 and Figure 62) had diurnal pattern in temperature data log ranging from 52-82°F where lowest temperature was recorded during the early morning and highest temperature was recorded in the afternoon. After each significant rainfall of ≥ 0.5" the diurnal temperature pattern had a dip in the temperature range. The DO data (see Figure 59, Figure 61, and Figure 63) showed that the daily average largely remained above 6.0 mg/L, fulfilling the regulatory limit. However, in some days the DO concentration fell below 5.0 mg/L, which is below the regulatory limit for DO at any time. The GSU research team believes that this drop in DO level was largely due to sensor fouling and sedimentation accumulation around the DO sensor cap inside the housing. Although to get a clear idea about the reason behind it, it's better to do more thorough monitoring at different depths of water and different locations.

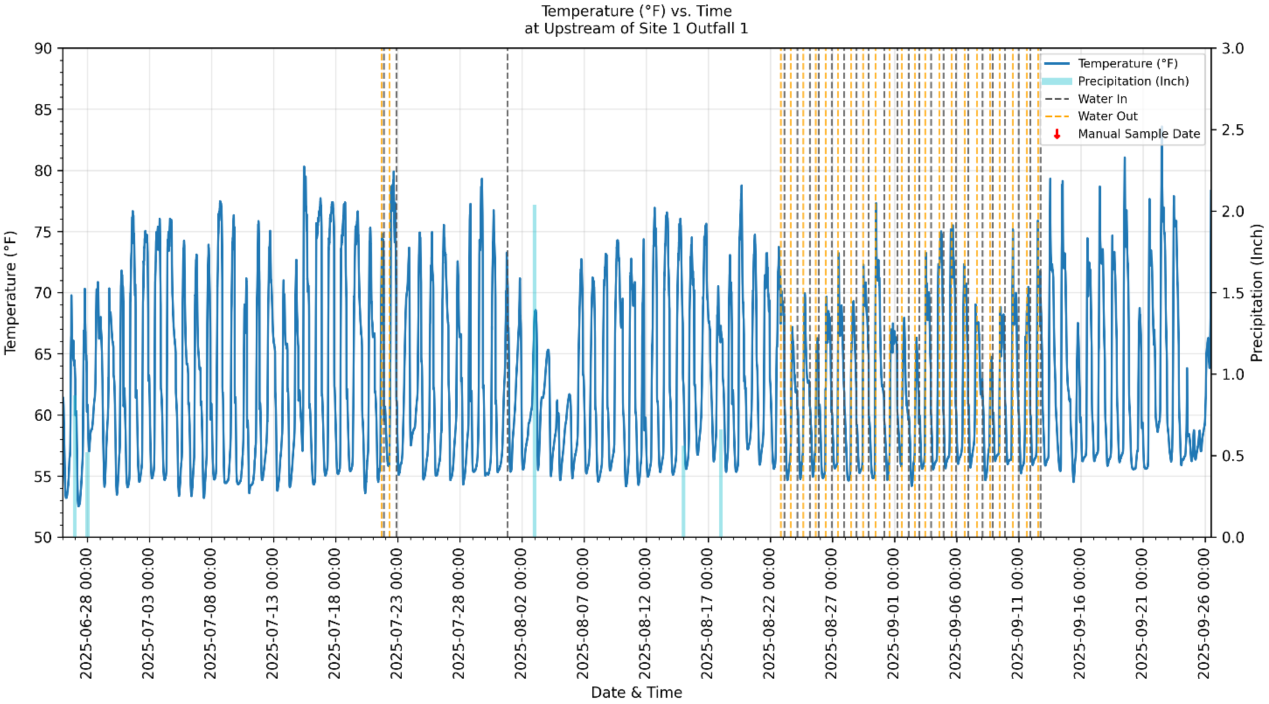


Figure 58. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Upstream point of Outfall 1 from 3rd Quarter of 2025

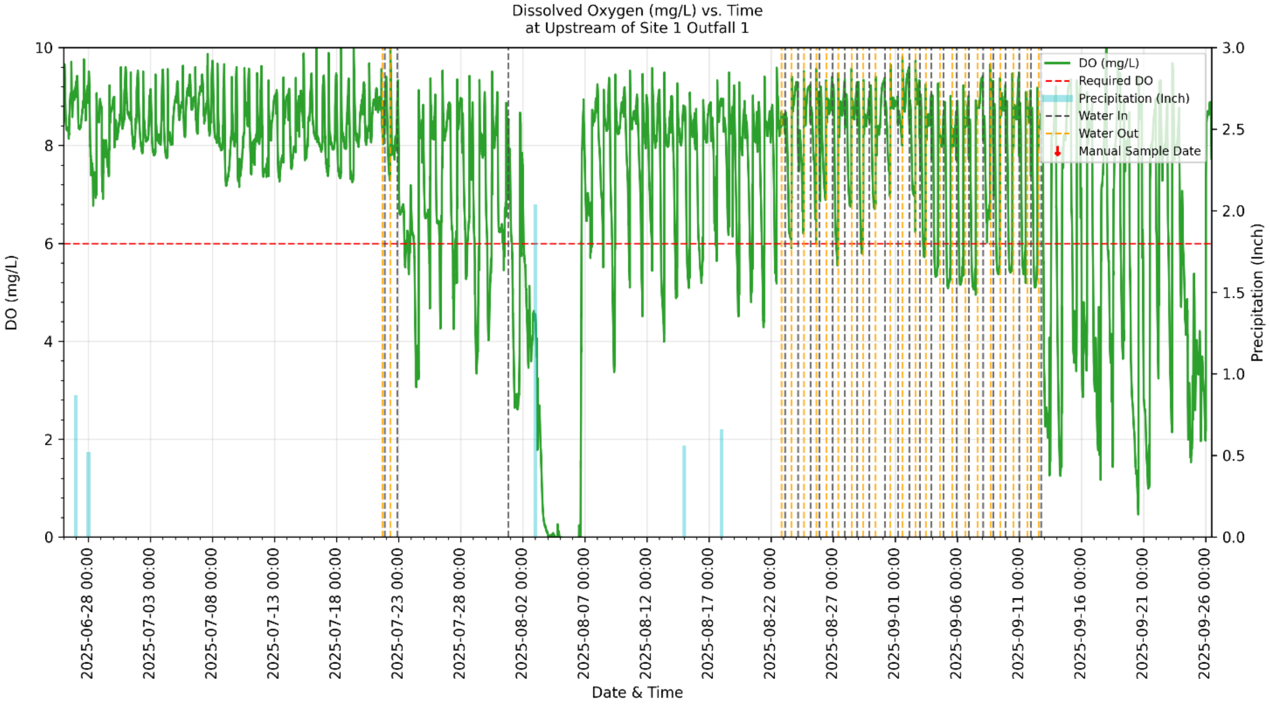


Figure 59. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Upstream point of Outfall 1 from 3rd Quarter of 2025

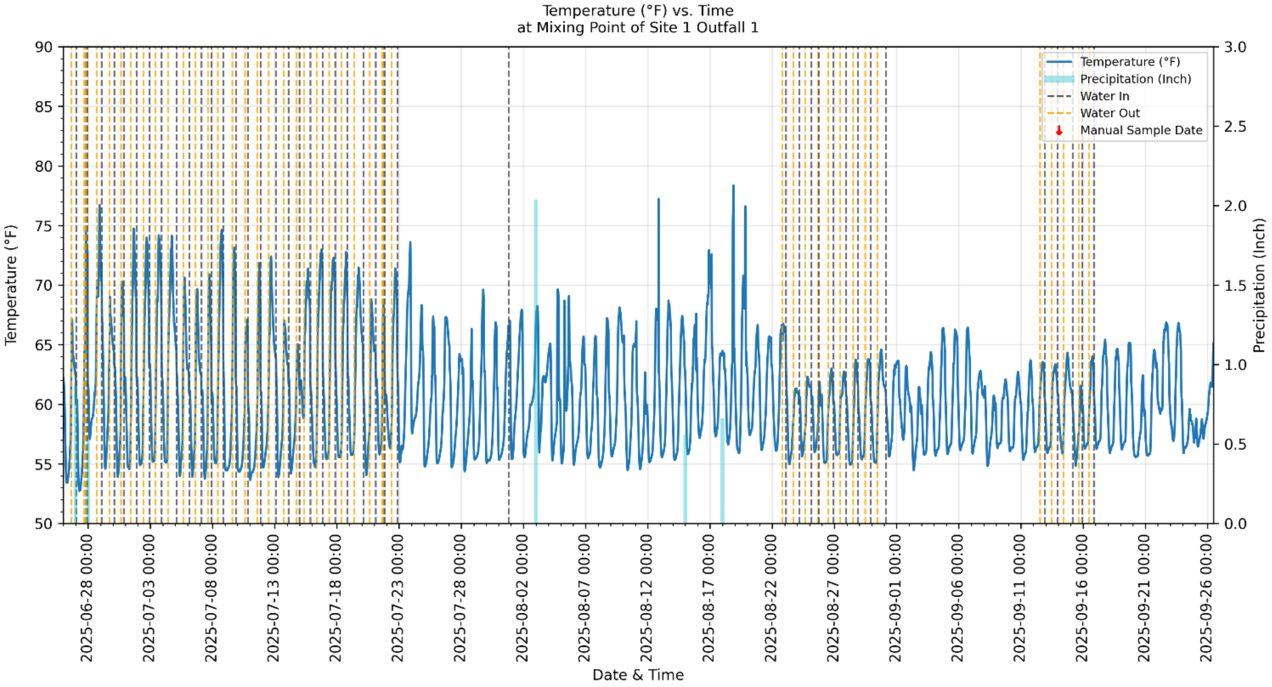


Figure 60. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Mixing point of Outfall 1 from 3rd Quarter of 2025

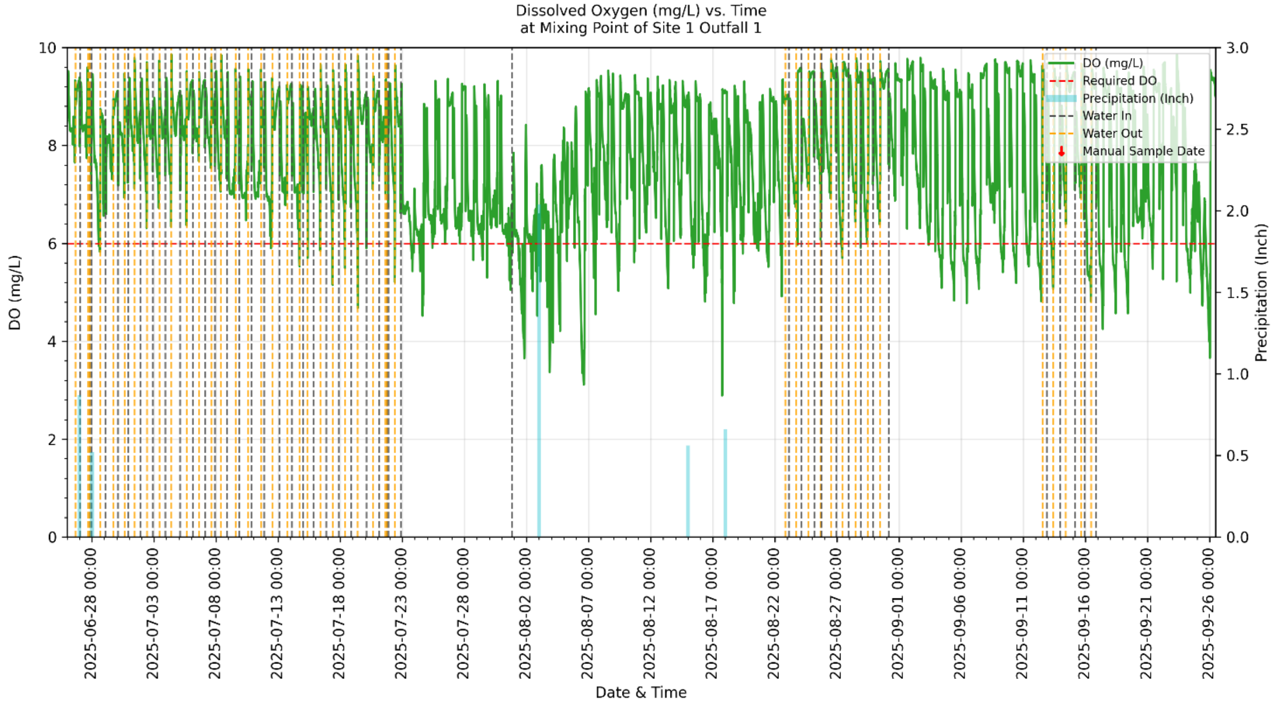


Figure 61. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Mixing point of Outfall 1 from 3rd Quarter of 2025

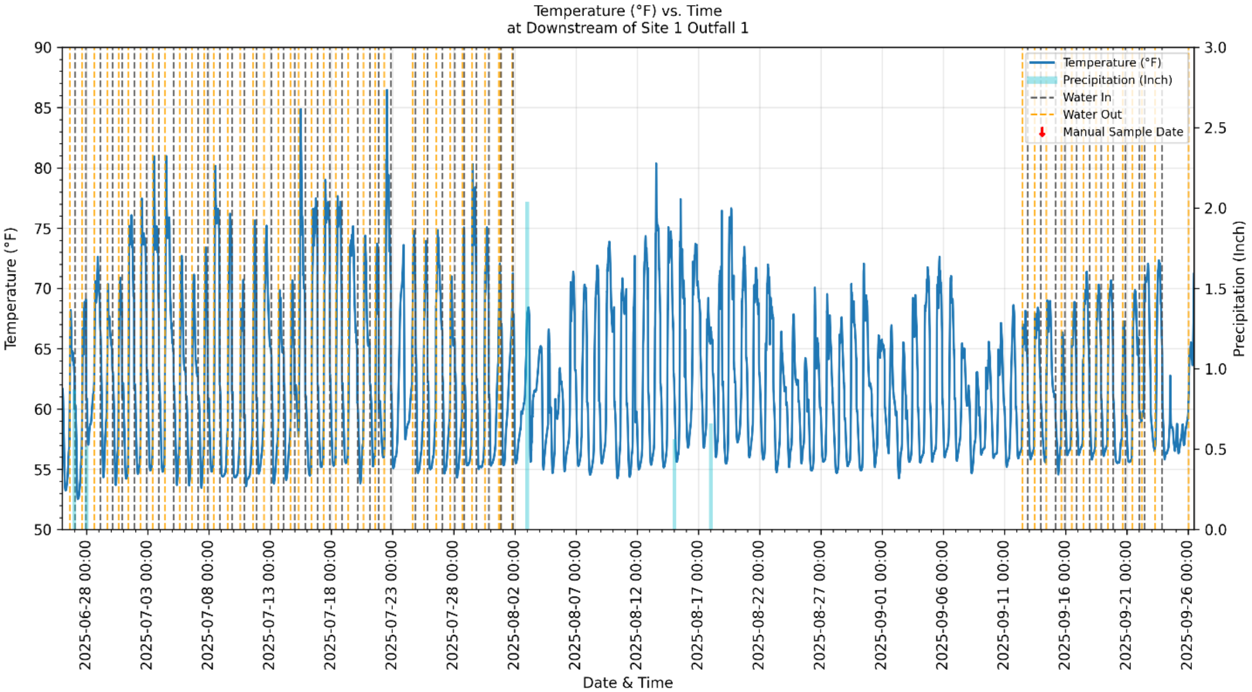


Figure 62. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Downstream point of Outfall 1 from 3rd Quarter of 2025

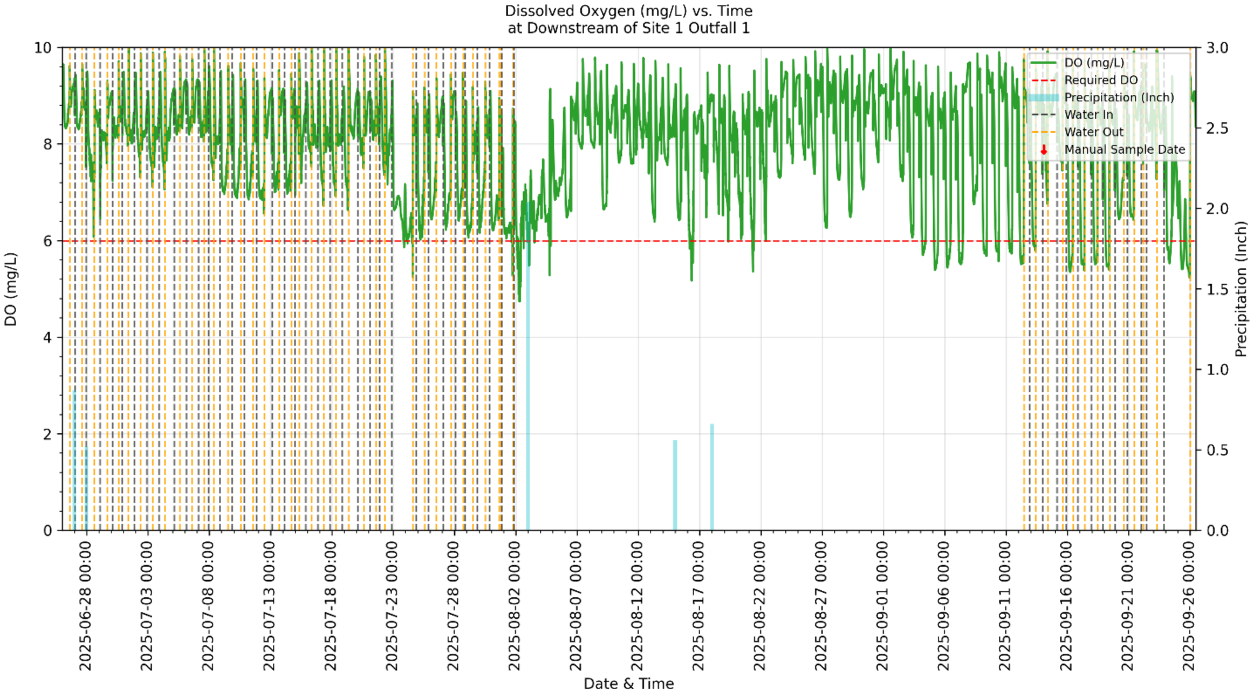


Figure 63. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Downstream point of Outfall 1 from 3rd Quarter of 2025

HOBO® Continuous Data Recorded at Site 2

At Site 2 the HOBO® datalogger data (see Figure 64 and Figure 66) had a diurnal pattern in temperature data log variation of 4°F where lowest temperature was recorded during the early morning and highest temperature was recorded in the afternoon. After each significant rainfall of ≥ 0.5" the diurnal temperature pattern had no visible dip in the temperature pattern in the quarterly data plot. The DO data (see Figure 65, and Figure 67) showed that the daily average largely remained above 6.0 mg/L fulfilling regulatory limit. However, in some days the DO concentration fell below 5.0 mg/L which is below regulatory limit for DO at any time. GSU research team believes that at this site, this drop in DO level was largely due to sensor fouling and biofilm forming around the DO sensor cap inside the housing.

Data Recorded in 2nd Quarter of 2025

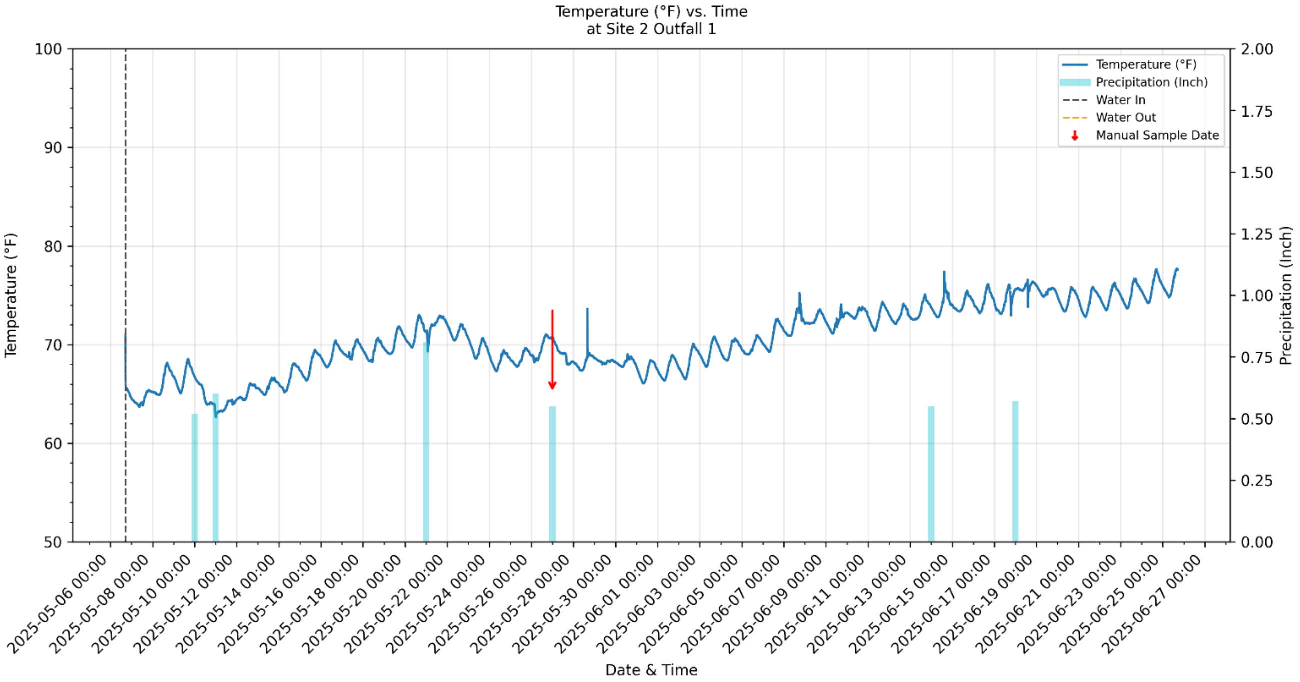


Figure 64. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Outfall 1 from 2nd Quarter of 2025

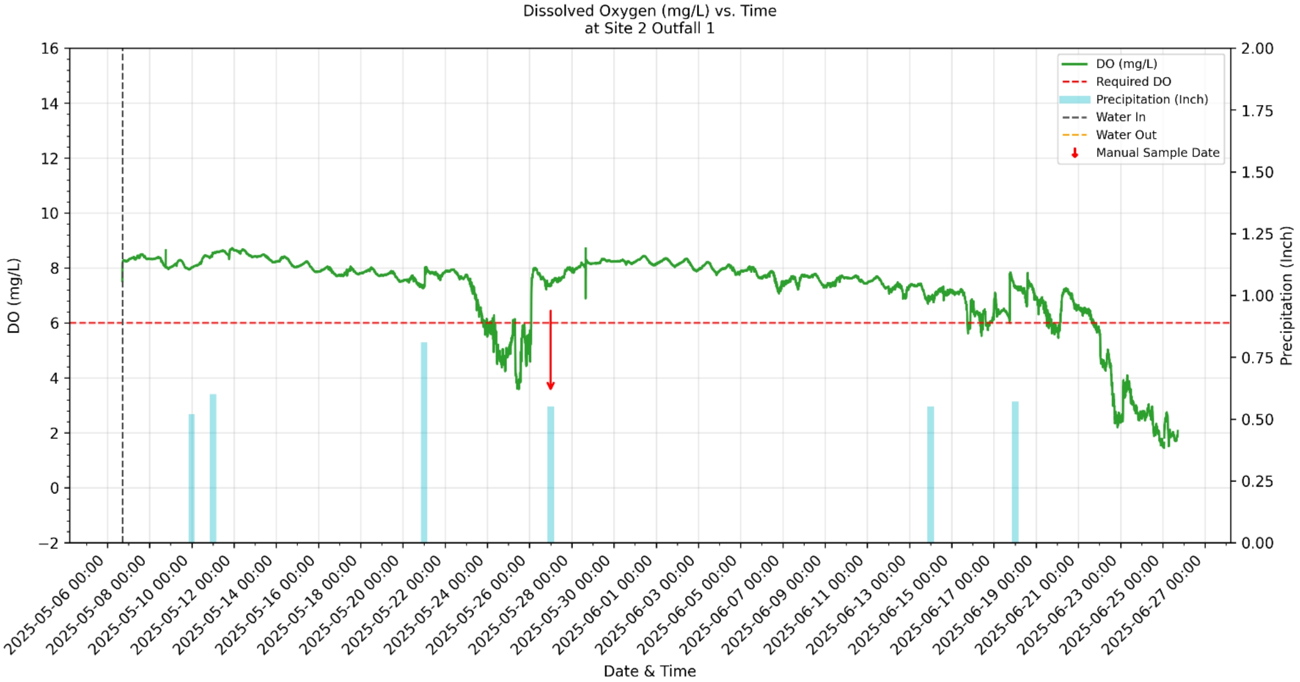


Figure 65. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Outfall 1 from 2nd Quarter of 2025

Data Recorded in 3rd Quarter of 2025

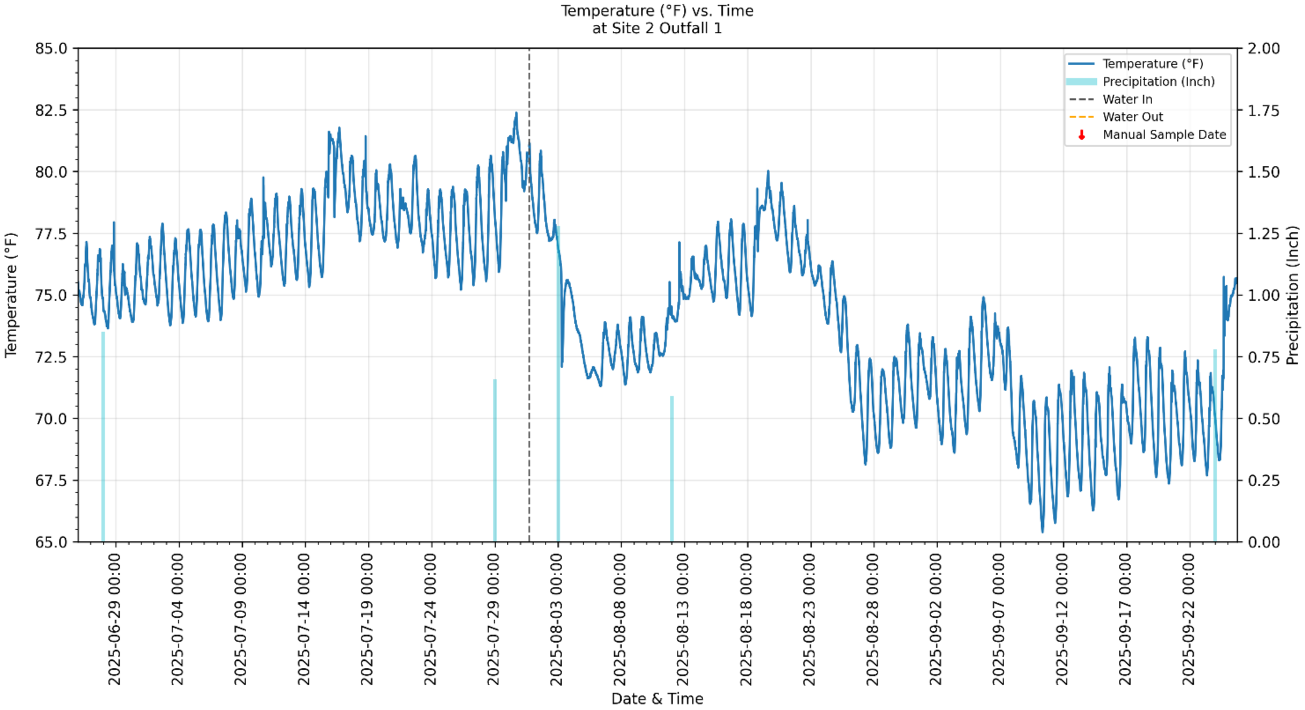


Figure 66. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Outfall 1 from 3rd Quarter of 2025

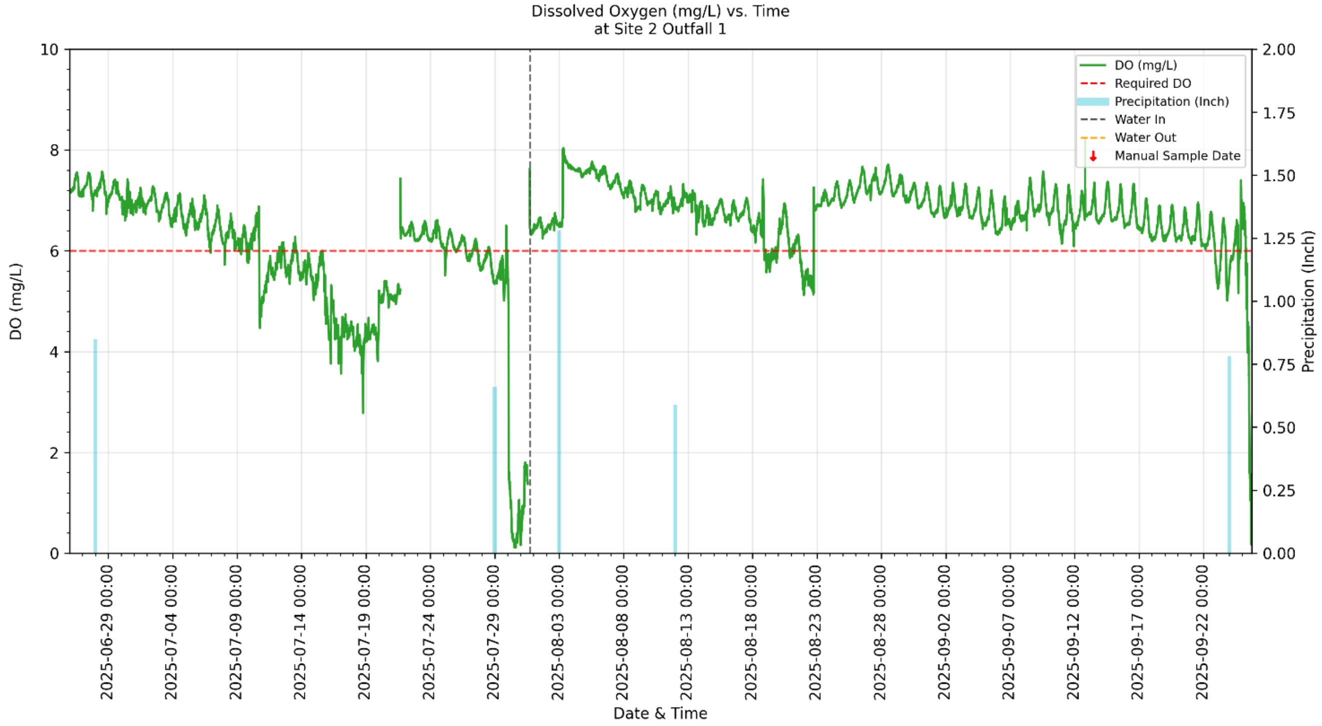


Figure 67. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Outfall 1 from 3rd Quarter of 2025

HOBO® Continuous Data Recorded at Site 3

At Site 3 the HOBO® datalogger data (see Figure 68 and Figure 70) had a diurnal pattern in temperature data log variation of 6°F where lowest temperature was recorded during the early morning and highest temperature was recorded in the afternoon. The Two-Run Creek at Site 3 is a very shallow creek during dry periods. The creek water level sometimes fell so low that the HOBO® data logger came close to the surface of water, showing sharp temperature peaks and DO drops in the plot. After each significant rainfall of ≥ 0.5" the diurnal temperature pattern had no visible dip in the temperature pattern in the quarterly data plot. The DO data (see Figure 69, and Figure 71) showed that the daily average largely remained above 6.0 mg/L, fulfilling the regulatory limit. However, in some days the DO concentration fell below 5.0 mg/L, which is below the regulatory limit for DO at any time. The GSU research team believes that at this site, this drop in DO level was largely due to sensor fouling and sediment accumulation around the DO sensor cap inside the housing. It is to be noted that this HOBO® sensor at Site 3 experienced public vandalism in the month of August, showing high temperature range and high oxygen content of air in terms of DO.

Data Recorded in 2nd Quarter of 2025

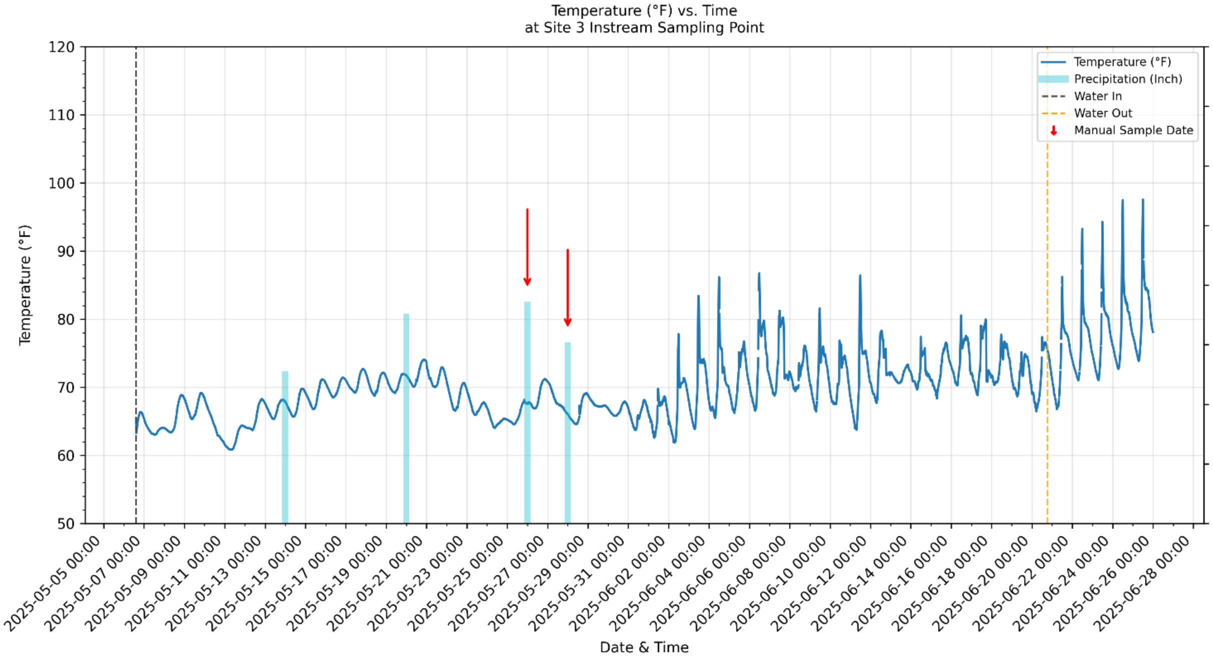


Figure 68. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Point 1 Instream Sampling from 2nd Quarter of 2025

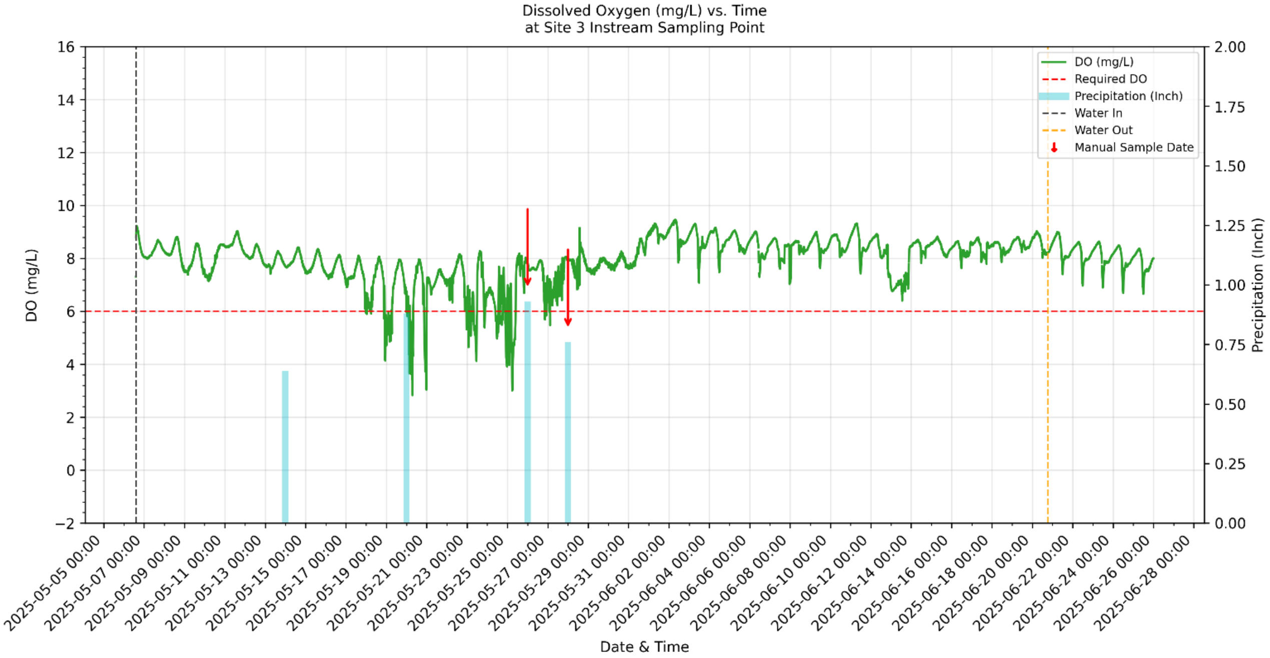


Figure 69. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Point 1 Instream Samplingfrom 2nd Quarter of 2025

Data Recorded in 3rd Quarter of 2025

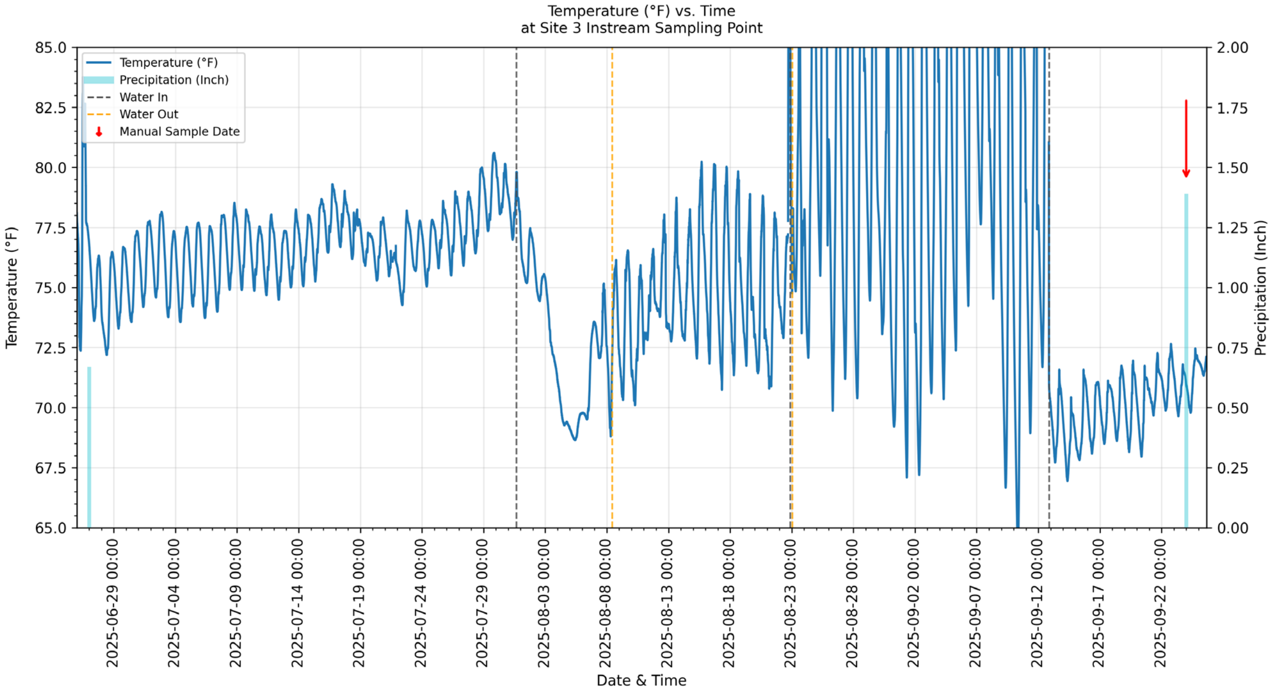


Figure 70. Chart. HOBO® Temperature vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Point 1 Instream Sampling from 3rd Quarter of 2025

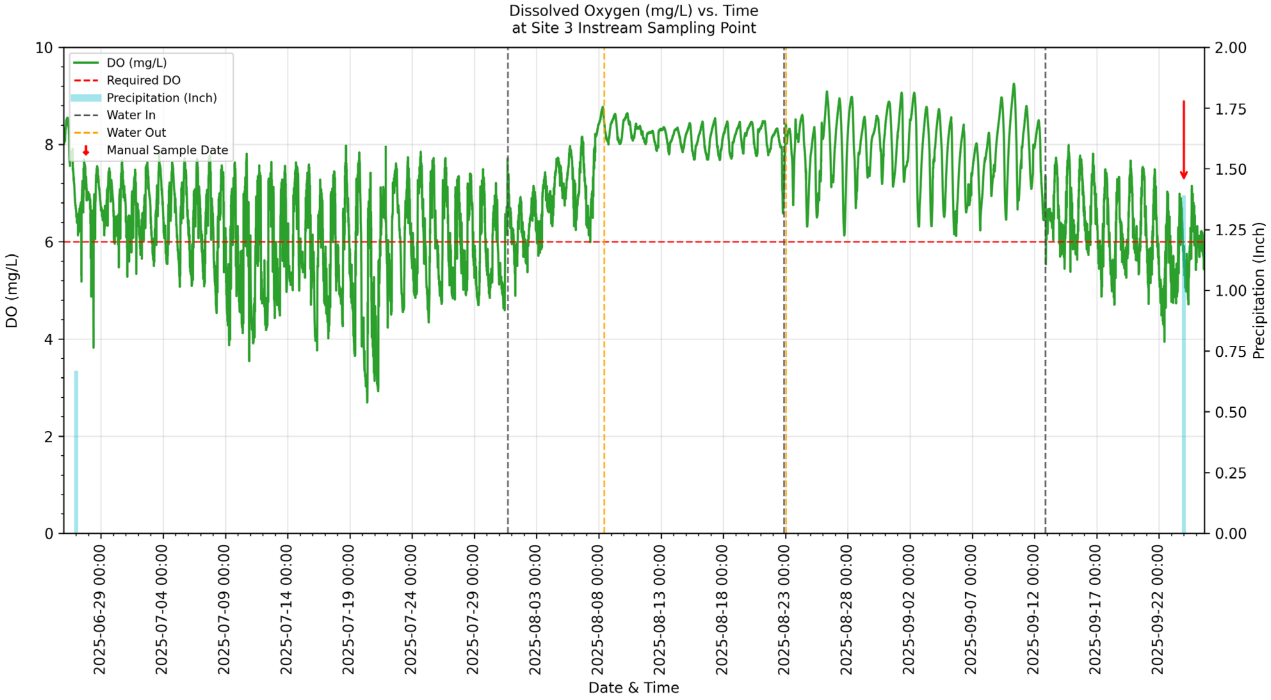


Figure 71. Chart. HOBO® DO vs Time plot with USGS daily Precipitation data (≥ 0.5 inch) at Point 1 Instream Sampling from 3rd Quarter of 2025

USGS Daily Precipitation Data Record (≥0.5”)

For Site 1

Table 24. USGS Daily total Precipitation Record (≥0.5”) for Site 1

Date	Precipitation (Inch)
5/10/2025	0.71
5/12/2025	0.58
5/21/2025	0.72
5/25/2025	0.94
5/26/2025	1.47
5/27/2025	0.61
6/9/2025	0.74
6/12/2025	0.52
6/17/2025	1.06
6/27/2025	0.87
6/28/2025	0.52
8/3/2025	2.04
8/15/2025	0.56
8/18/2025	0.66

For Site 2

Table 25. USGS Daily total Precipitation Record (≥0.5”) for Site 2

Date	Precipitation (Inch)
5/10/2025	0.52
5/11/2025	0.6
5/21/2025	0.81
5/27/2025	0.55
6/14/2025	0.55
6/18/2025	0.57
6/28/2025	0.85
7/29/2025	0.66
8/3/2025	1.28
8/12/2025	0.59
9/24/2025	0.78

For Site 3

Table 26. USGS Daily total Precipitation Record (≥0.5”) for Site 3

Date	Precipitation (Inch)
5/14/2025	0.64
5/20/2025	0.88
5/26/2025	0.93
5/28/2025	0.76
6/27/2025	0.67
9/24/2025	1.39

Event-Based Case Studies

At Site 1, during these significant rainfall events, downstream temperature rose in range of 2–15 °F (see in Figure 72 and Figure 73) above the upstream baseline within several hours of rainfall onset and then declined to equilibrium within roughly 6 to 8 hours. These short-duration excursions confirm that warm roadway runoff from bridge and pavement hot surfaces produced measurable but transient heating of the receiving reach. Although concentration of DO was found to be above 5.0 mg/L most of the time, largely consistent with trout stream regulatory expectations, corresponding DO traces show synchronous depressions at the mixing point, reflecting the inverse temperature–DO relationship and temporary dilution of cooler, DO-rich water. The continuous HOBO® data thus captured the temperature impact that the 2024 ProDSS grab sampling could only suggest, providing the first complete event-scale view of runoff-driven warming at Site 1.

At Site 2, the second-and third-quarter records reveal relatively stable diurnal temperature and DO cycles punctuated by distinct, rainfall-related disturbance. Some notable events (discussed in the event-based case studies in Chapter 4) show temperature differences of approximately 1–2 °F occurring within hours of precipitation exceeding 0.5 inch per day and brief DO reductions of 0.5–1.0 mg/L. These patterns, when aligned with USGS rainfall data, indicate that roadway runoff caused short-term temperature enrichment and DO suppression at the single monitored point, though without comparative upstream data, the full spatial extent of impact could not be resolved. Event-based analyses in later sections further quantify these transient responses.

At Site 3, event-based rainfall event case studies reveal that during and after precipitation events, the logger recorded smooth temperature trends and only minor DO fluctuations. These data corroborate field observations that the long, vegetated flow paths and dense canopy effectively dissipated roadway runoff heat before it entered the creek.

Site 1 Events

The HOBO® temperature plots for Site 1 (Figure 72 and Figure 73) show that roadway runoff driven warming was closely tied to periods of recurring significant rainfall of ≥ 0.5” precipitation in May, June and August 2025 (see Table 24). During the monitoring period, a series of moderate-intensity rainfall produced several distinct Δ temperature (downstream – upstream temperature) peaks, each following rainfall onset by roughly 30 to 60 minutes. Rainfall events with long duration such as happened on 8/3/25 (see Figure 73) produced ΔT below 2 °F indicating that substantial runoff accumulation within a short period of time and pre-storm surface heating were necessary to generate observable Δ Temperature signals at this high-baseflow trout stream reach. Each temperature peak beyond 2 °F had a duration of 0.2 to 3 hours (see

Table 27). Having Buford dam at the upstream, there was a distinct pattern on days which had warmer temperature and also significant rainfall events happened after the day ended. On 6/27/2025 and 8/18/2025, which had the largest temperature differentials, the large differentials occurred right when the wave of discharge from Buford dam hit the monitoring points, causing the stream flow to increase significantly and the upstream temp to decrease significantly. Having warmer runoff water coming from the highways, the resultant temperature delta created very high peaks.

Table 27. Peak ΔTemperature and Event Duration Comparison with Precipitation for Site 1

Date	Precipitation (Inch)	Peak ΔTemperature (°F)	> 2°F Event Duration (hours)
5/10/2025	0.71	3	1.5
5/27/2025	0.61	6.8	1
6/9/2025	0.74	3.8	0.25
6/12/2025	0.52	4.7	0.4
6/17/2025	1.06	5.6	0.25
6/27/2025	0.87	8.2	3
6/28/2025	0.52	5.9	3
8/3/2025	2.04	1.9	0
8/15/2025	0.56	4.1	0.5
8/18/2025	0.66	15.2	2

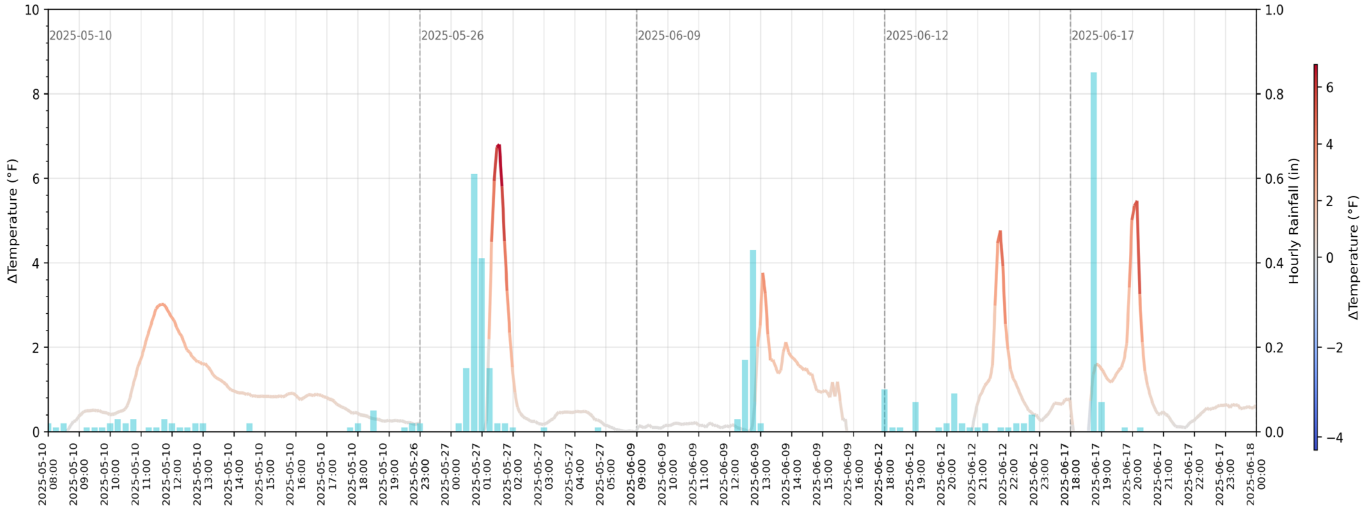


Figure 72. Chart. Selected Events from 1st Quarter of 2025 to show ΔTemperature at Site 1

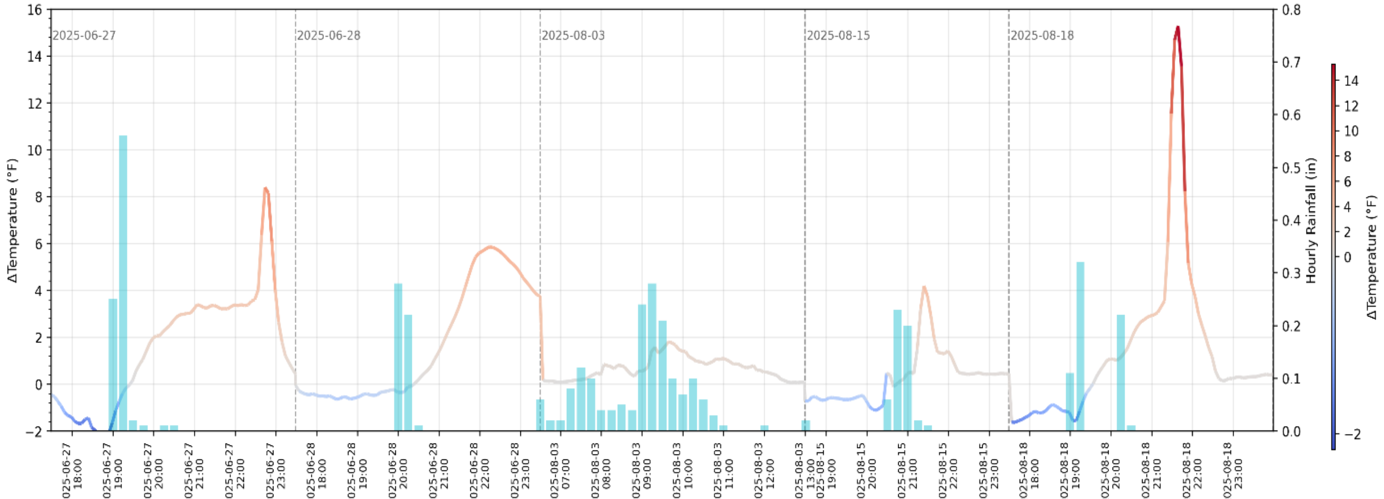


Figure 73. Chart. Selected Events from 2nd Quarter of 2025 to show ΔTemperature at Site 1

In the Figure 74, Figure 76, Figure 78, Figure 80, and Figure 82 below, the selected rainfall events with higher than 0.5” precipitation are shown in a zoomed-in manner to show the runoff interaction to the temperature change in all three (3) HOBO® sensors. In the Figure 75, Figure 77, Figure 79, Figure 81, and Figure 83 below, the same precipitation events are shown in a zoomed-in manner to show the runoff interaction to the DO change in three (3) HOBO® sensors. Table 28 below shows the comparison side by side of the five (5) rainfall events shown in the above-mentioned figures.

Table 28. Temperature and DO Change Comparison Table for Selected Events for Site 1

Date	Precipitation (Inch)	Peak ΔTemperature (°F)	Peak DO Change (mg/L)	> 2°F Event Duration (hours)
6/27/2025	0.87	8.2	0.2	3
6/28/2025	0.52	5.9	0.4	3
8/3/2025	2.04	1.9	N.A.	0
8/15/2025	0.56	4.1	0.1	0.5
8/18/2025	0.66	15.2	0.2	2

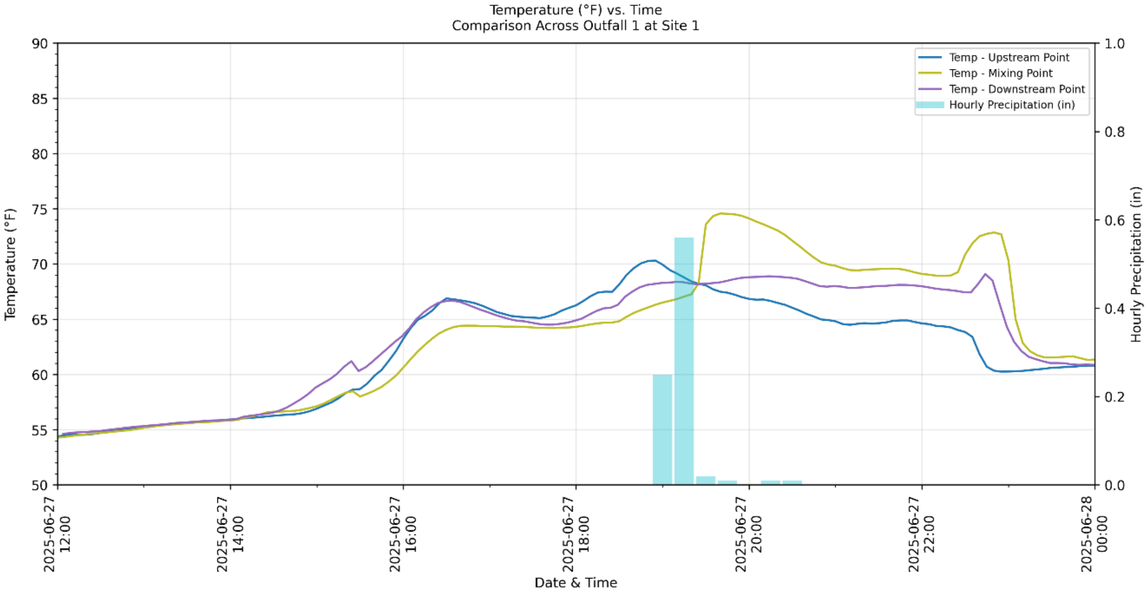


Figure 74. Chart. HOBO® Temperature change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 6/27/2025.

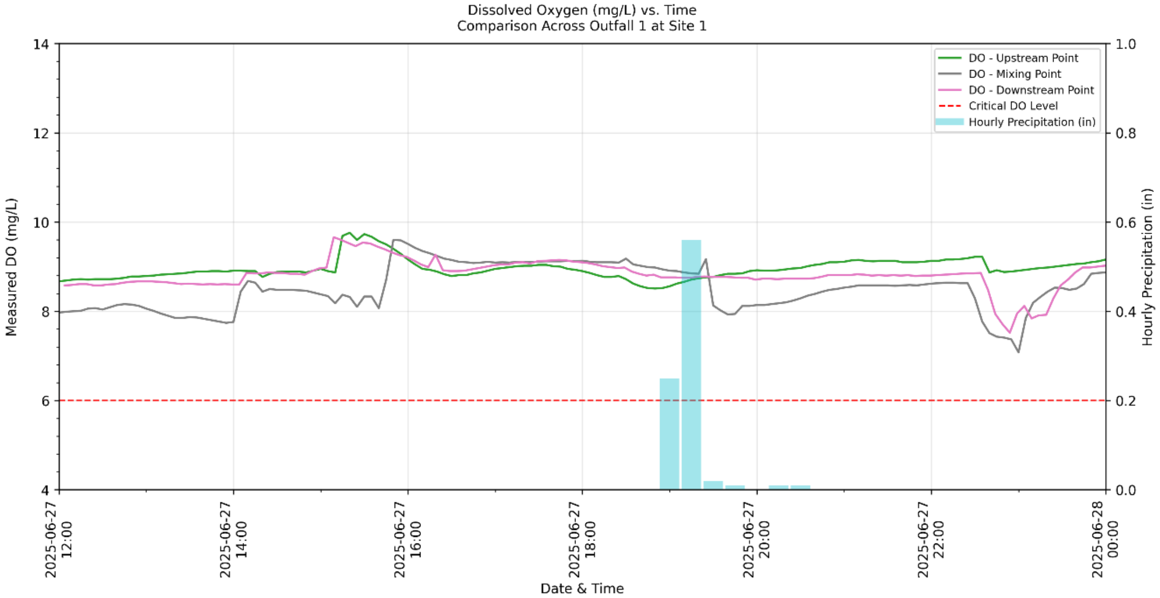


Figure 75. Chart. HOBO® DO change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 6/27/2025

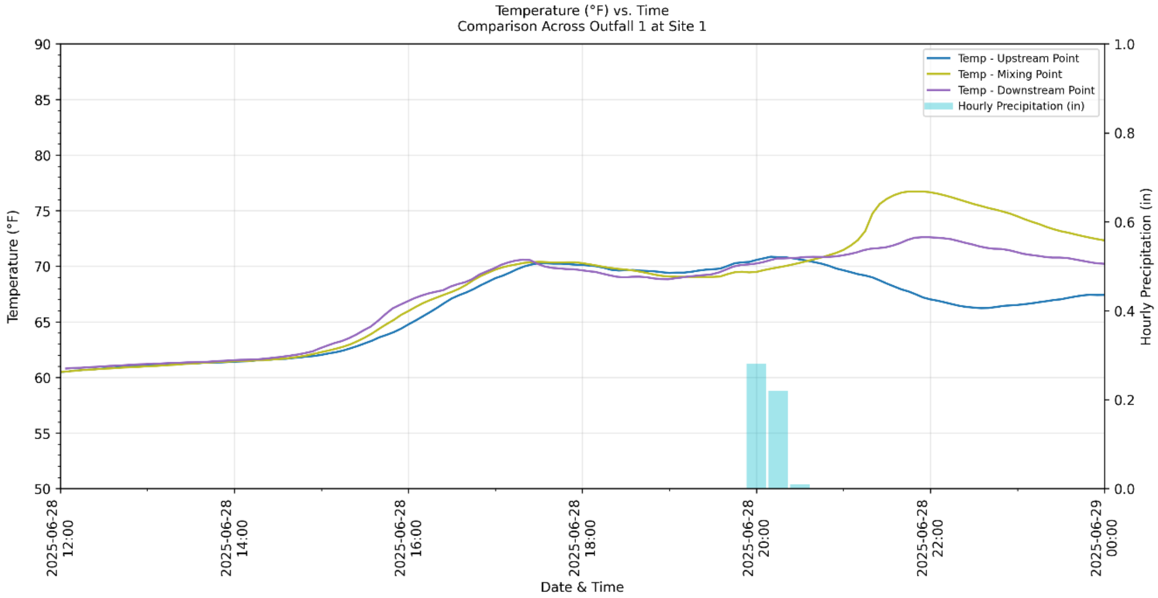


Figure 76. Chart. HOBO® Temperature change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 6/28/2025

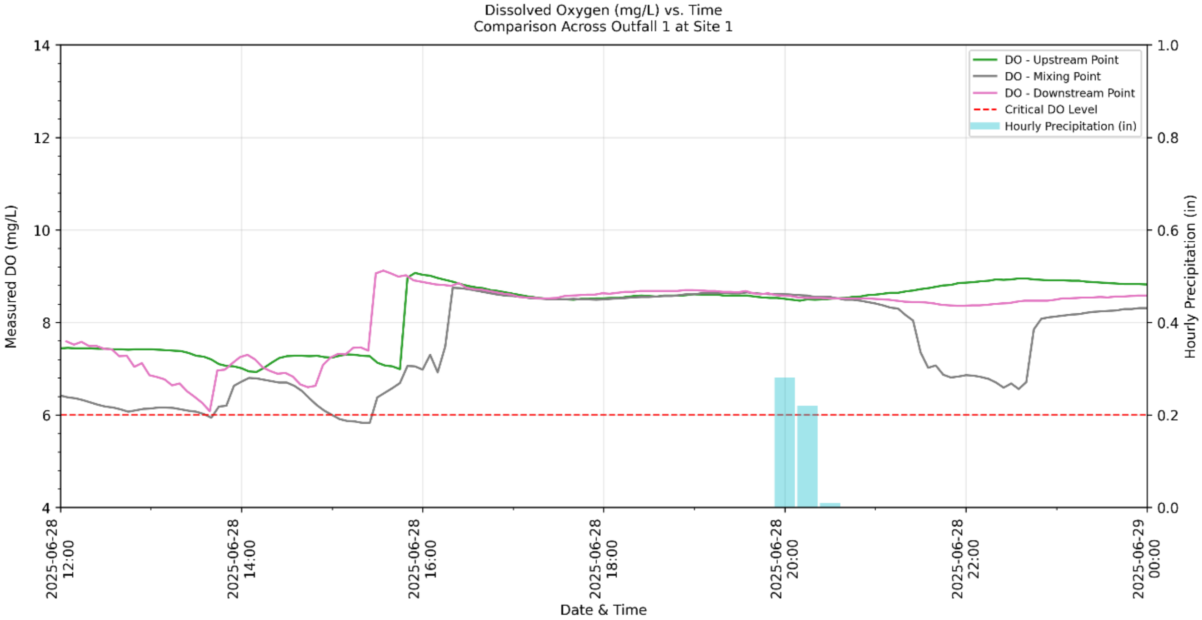


Figure 77. Chart. HOBO® DO change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 6/28/2025

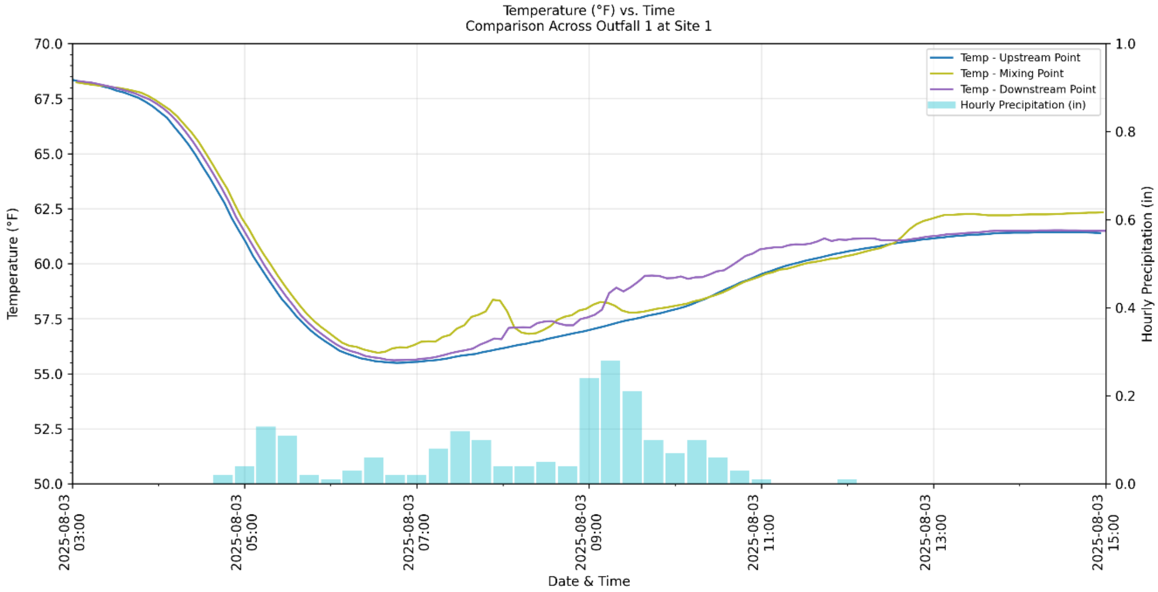


Figure 78. Chart. HOBO® Temperature change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 8/3/2025

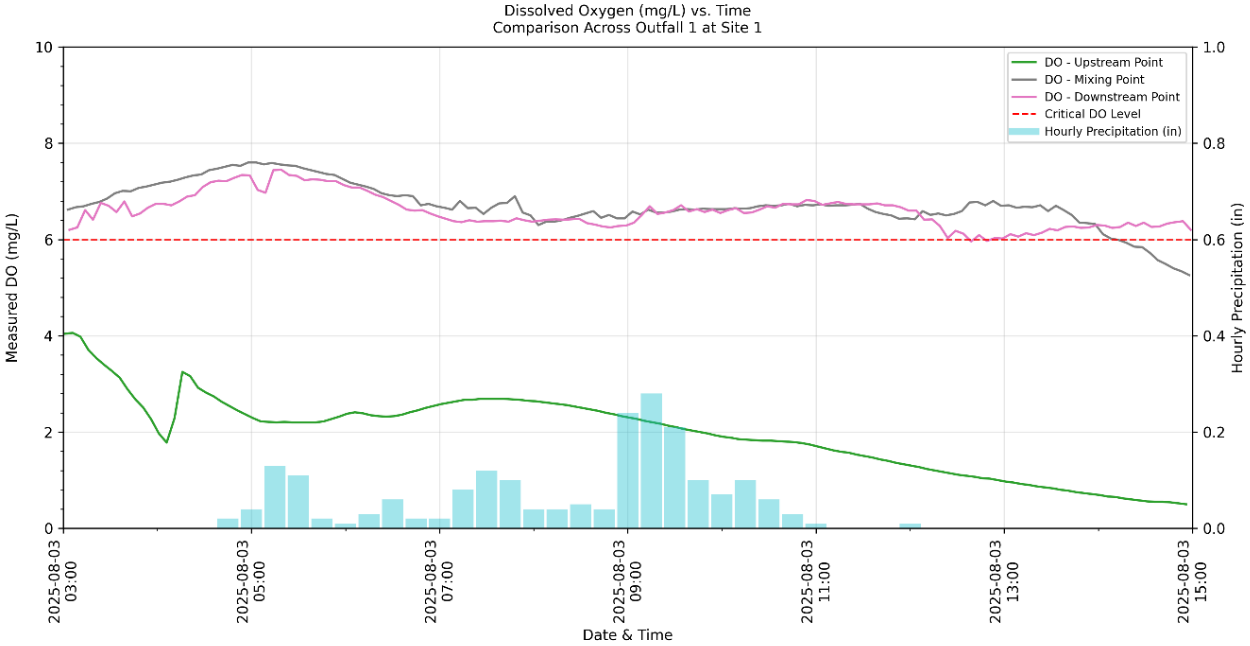


Figure 79. Chart. HOBO® DO change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 8/3/2025

In the Figure 79 above, the upstream data logger showed very low DO reading. GSU research team believes the low DO reading is largely due to the sediment accumulation around the DO sensor cap inside the sensor housing. However, to confirm this theory it is necessary to monitor DO change at different depths of water and at different points in the site.

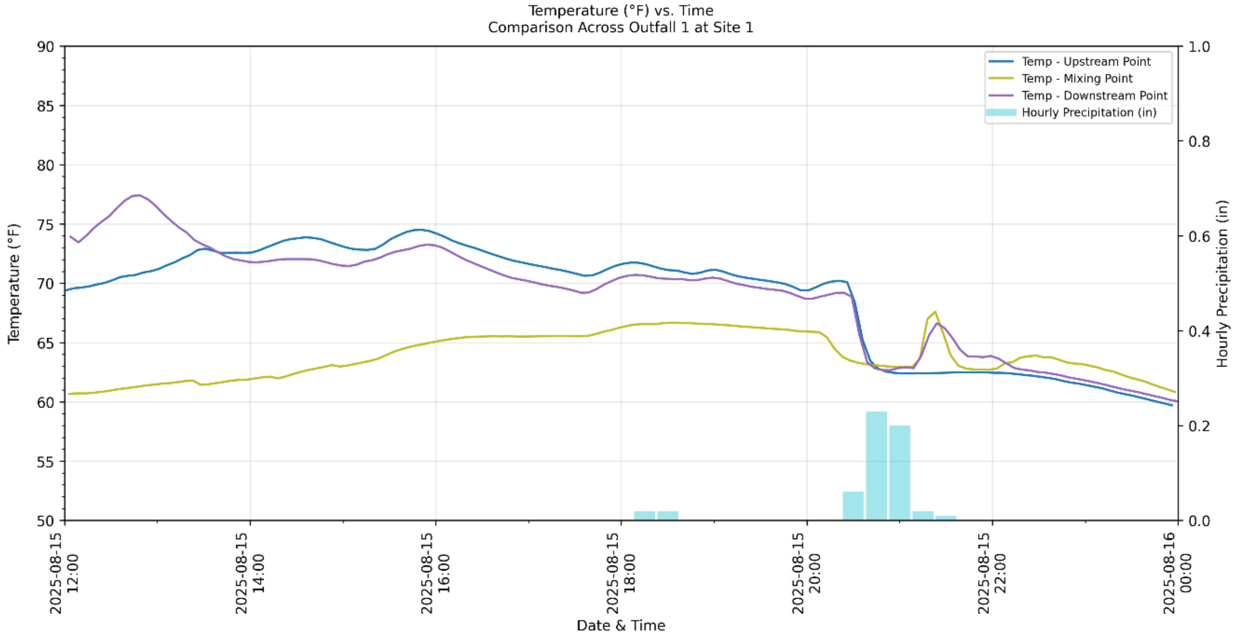


Figure 80. Chart. HOBO® Temperature change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 8/15/2025

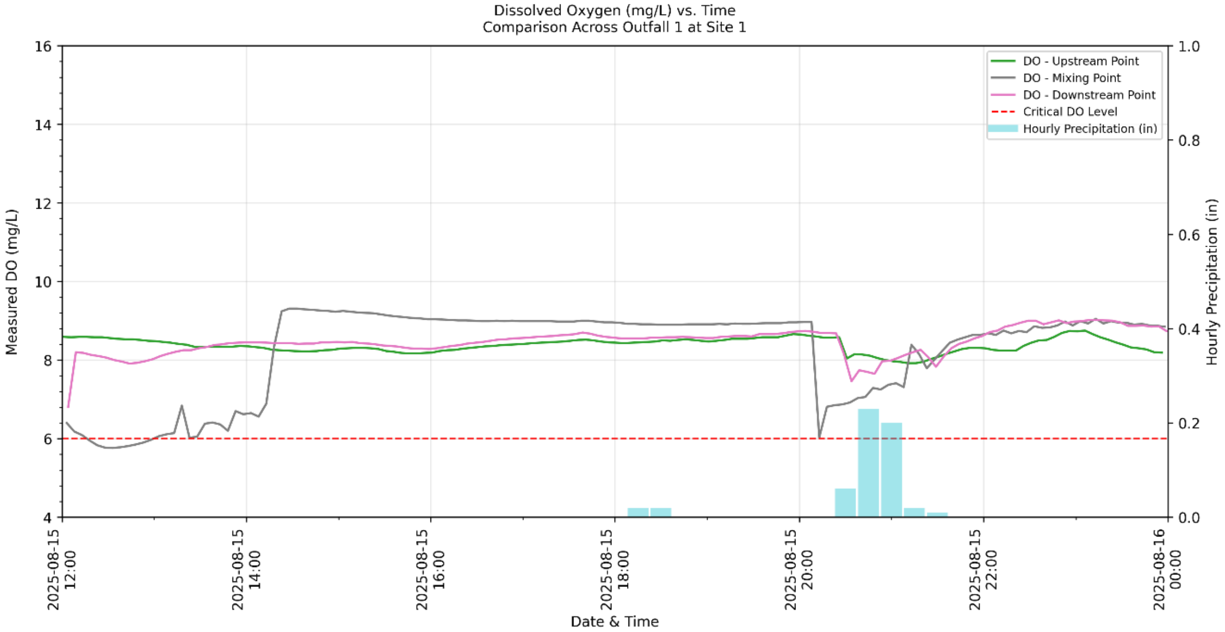


Figure 81. Chart. HOBO® DO change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 8/15/2025

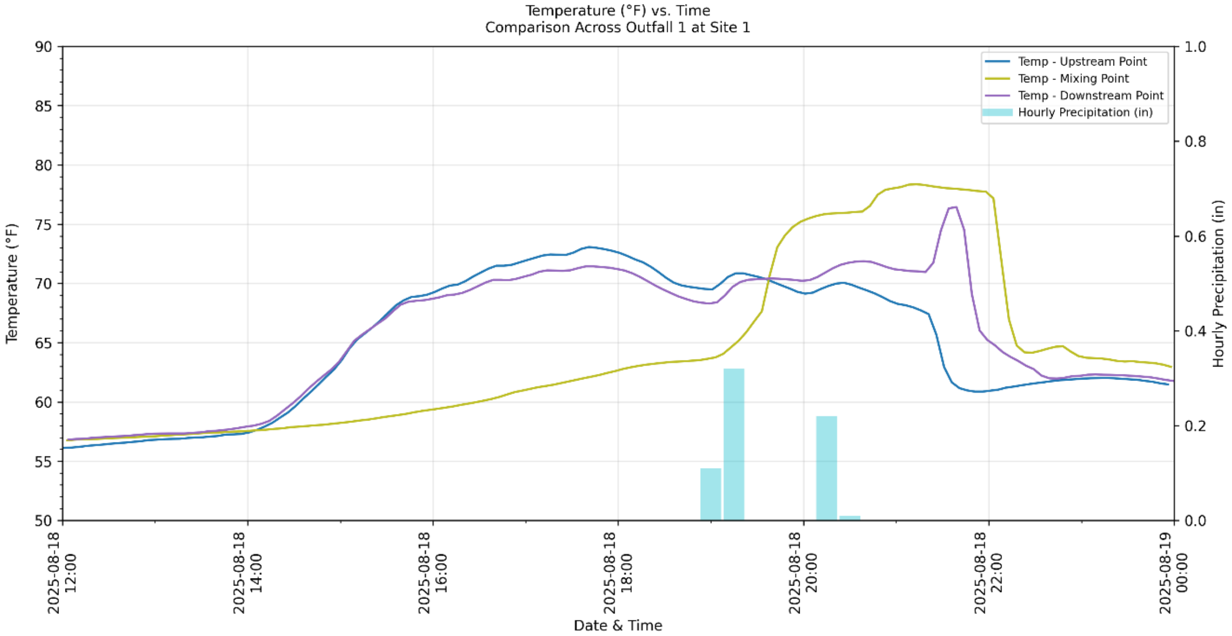


Figure 82. Chart. HOBO® Temperature change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 8/18/2025

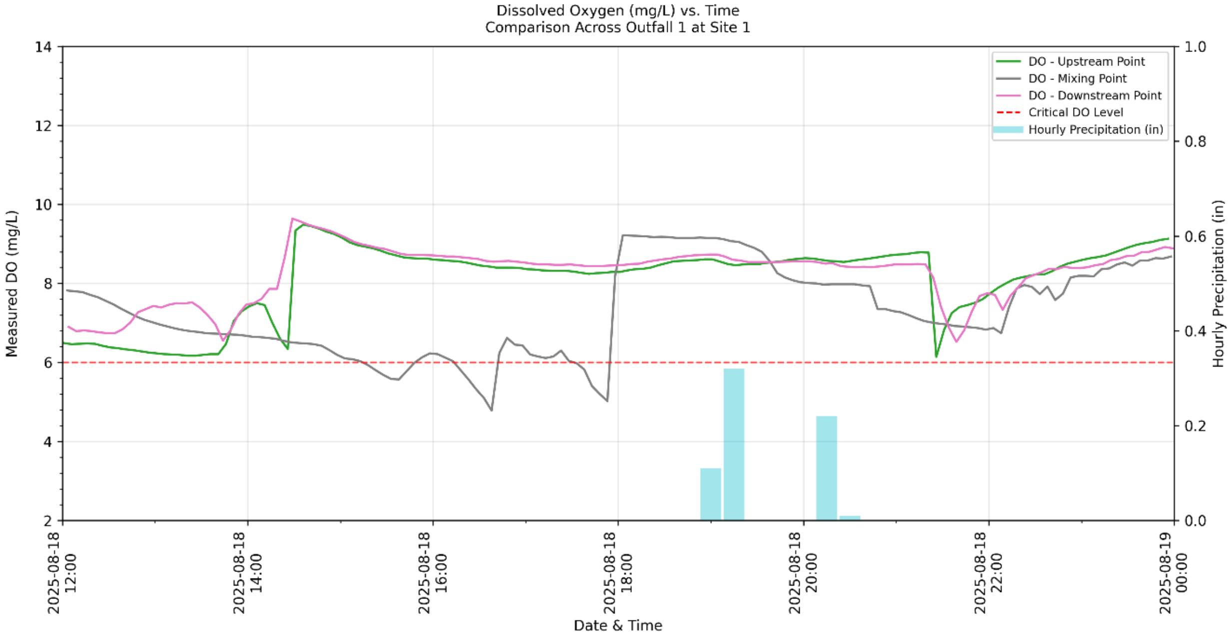


Figure 83. Chart. HOBO® DO change plot for comparison between Upstream-Mixing-Downstream points with USGS hourly precipitation data at Site 1 Outfall 1 for rainfall event from 8/18/2025

Site 2 Events

The HOBO® temperature and DO plots for Site 2 (Figure 84 through Figure 87) show that roadway runoff driven warming was closely tied to periods of recurring significant rainfall of ≥ 0.5" precipitation (see Table 29). A temperature decrease of 2.5 °F from early morning precipitation was also recorded on 8/3/2025 which also resulted 1.8 mg/L DO increase. Although at Site 2 there's only one (1) HOBO® logger deployed without any upstream or downstream reference, during the monitoring period, a series of moderate-intensity rainfall events produced several distinct temperature peaks and DO drops in the data plots.

Table 29. Temperature and DO Change with Precipitation for Site 2

Date	Precipitation (Inch)	Approx. Temperature Increase (°F)	Approx. DO Change (mg/L)
7/29/2025	0.66	1	0.8
8/3/2025	1.28	-2.5	1.8
8/12/2025	0.59	2.5	0.2
9/24/2025	0.78	3.5	1.1

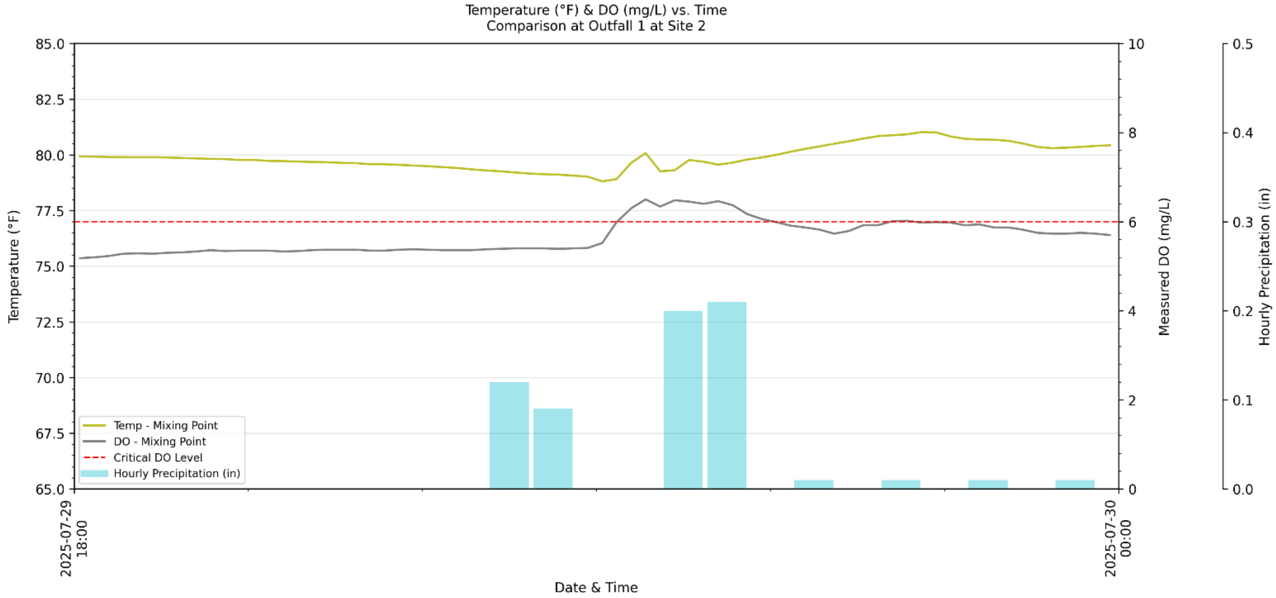


Figure 84. Chart. HOBO® Temperature and DO change plot for comparison with USGS hourly precipitation data at Site 2 Outfall 1 for rainfall event of 7/29/2025

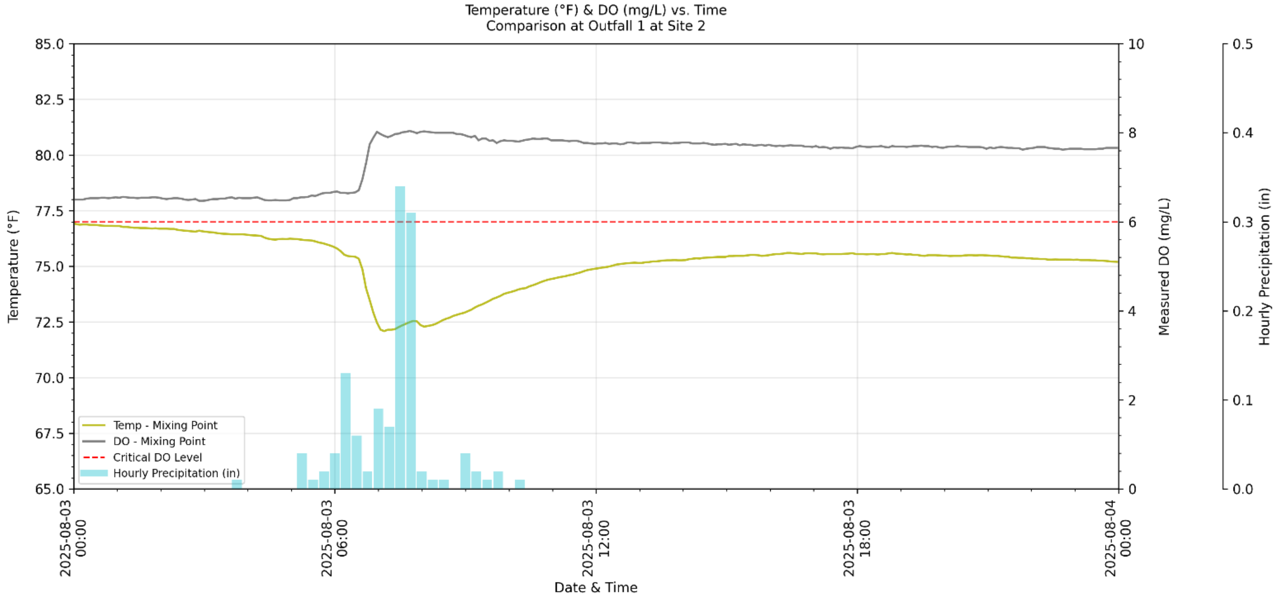


Figure 85. Chart. HOBO® Temperature and DO change plot for comparison with USGS hourly precipitation data at Site 2 Outfall 1 for rainfall event of 8/03/2025

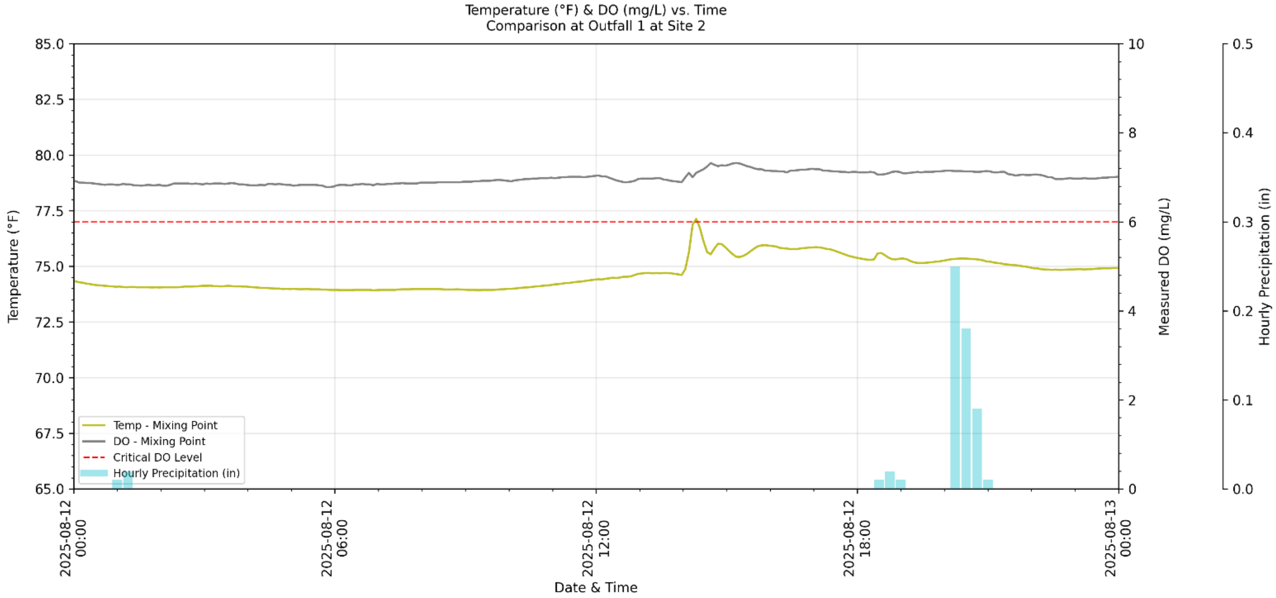


Figure 86. Chart. HOBO® Temperature and DO change plot for comparison with USGS hourly precipitation data at Site 2 Outfall 1 for rainfall event of 8/12/2025

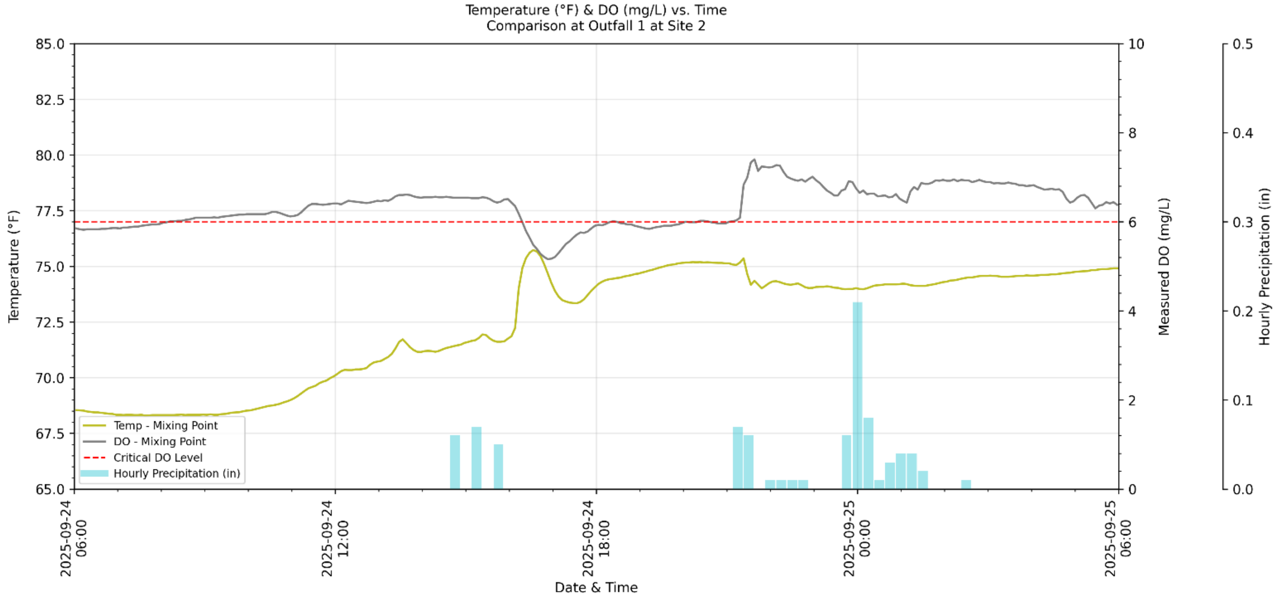


Figure 87. Chart. HOBO® Temperature and DO change plot for comparison with USGS hourly precipitation data at Site 2 Outfall 1 for rainfall event of 9/24/2025

The Site 2 event figures show that the HOBO® temperature data and corresponding DO curves exhibit synchronized fluctuations, where DO concentrations decline during temperature peaks and recover as temperatures fall, forming mirrored waveforms indicative of temperature-driven solubility effects. The temporal alignment between these temperature–DO oscillations and recorded rainfall events confirms that the logger successfully captured direct roadway runoff influences at the mixed instream location, despite the absence of a nearby upstream reference site for comparison.

Site 3 Events

The event-based plots for Site 3 display temperature and DO records from a single instream HOBO® logger beneath two rainfall sequences, one (1) in late June 2025 (see Figure 88) and another in late September 2025 (see Figure 89). In both cases, rainfall bars rise sharply but the temperature line remains nearly flat, fluctuating only within the normal diurnal envelope of about 1 °F. No sudden inflection or delayed temperature crest follows the rainfall peaks. The DO curve likewise maintains smooth cyclic variation between roughly 6 and 7 mg/L with no visible downturn concurrent with precipitation. The graphical pattern therefore shows that despite measurable rainfall intensity; the instream logger did not record any immediate warming or DO depletion linked to roadway runoff; the plotted data remained stable throughout the precipitation periods. The absence of distinct post-rainfall disturbance visually supports the field observation that vegetated drainage paths and canopy shading moderate runoff before it reached the creek.

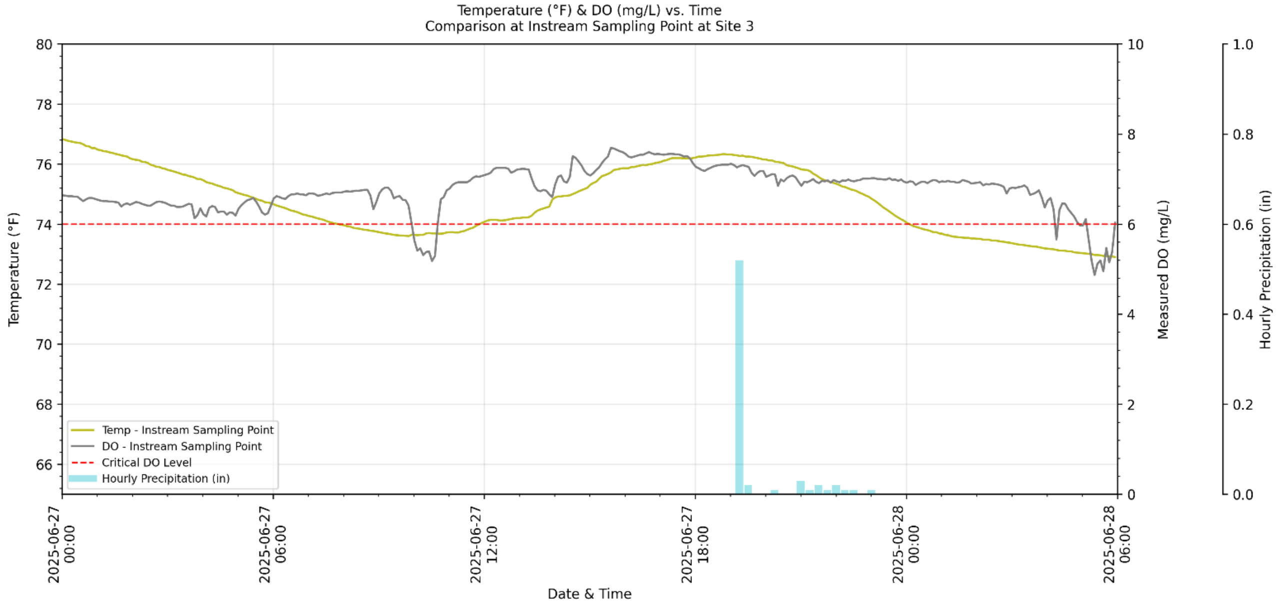


Figure 88. Chart. HOBO® Temperature and DO change plot for comparison with USGS hourly precipitation data at Site 3 Point 1 Instream Samplingfor rainfall event of 6/27/2025

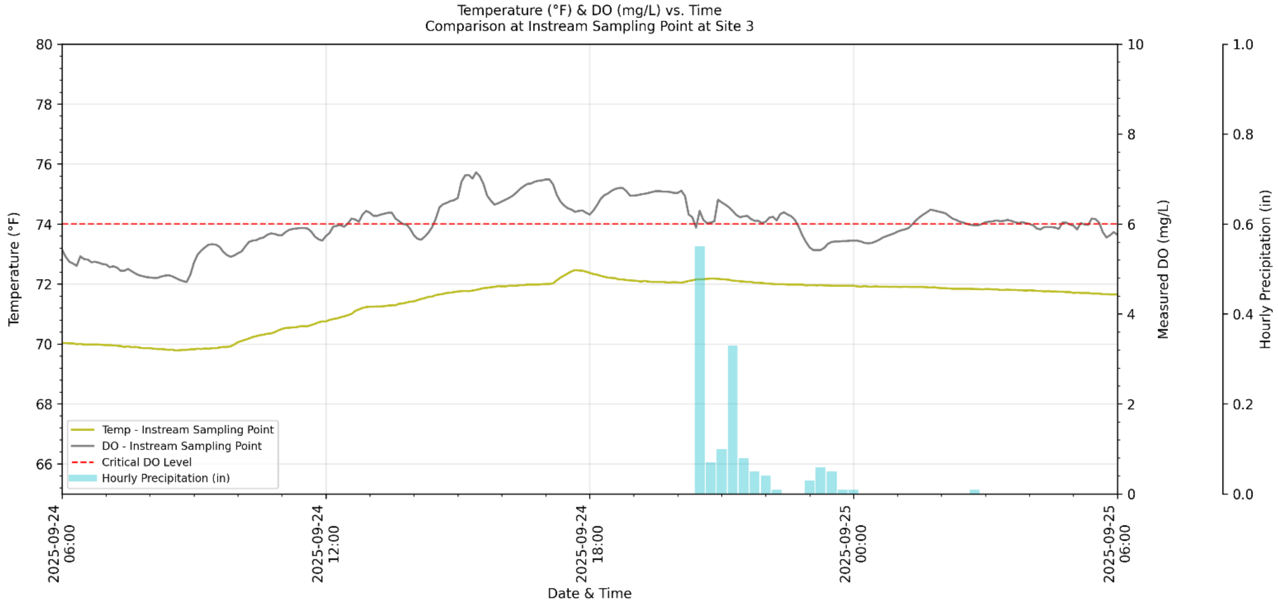


Figure 89. Chart. HOBO® Temperature and DO change plot for comparison with USGS hourly precipitation data at Site 3 Point 1 Instream Sampling for rainfall event of 9/24/2025

COMPARISON OF MONITORED AND CALCULATED STREAM TEMPERATURES

The comparison between monitored mean stream temperatures and calculated mean temperatures provides important insight into the role of site-specific hydrology, thermal regulation mechanisms, and watershed characteristics that are not fully captured by generalized temperature estimation equations. Across all three sites, systematic differences were observed between calculated seasonal temperature curves and measured instream conditions, highlighting the importance of field-based monitoring for trout stream compliance assessment. [27]

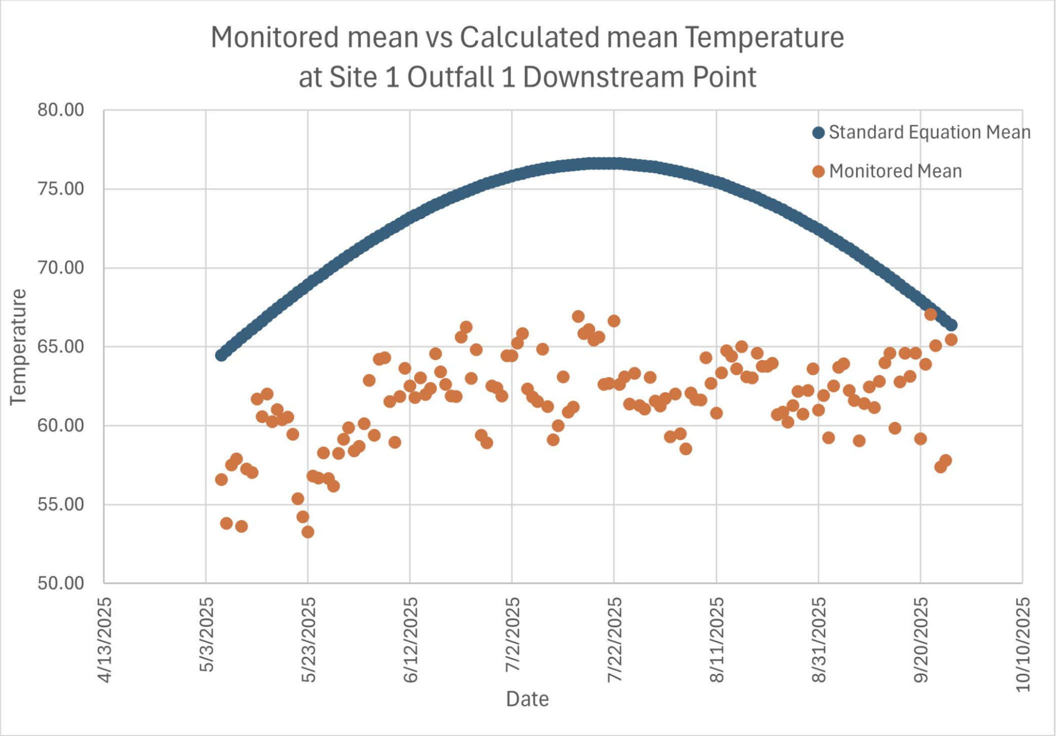


Figure 90. Chart. HOBO® Temperature and Natural Stream Temperature Mean Data Comparison at Site 1 Outfall 1 Downstream Point

At Site 1, the calculated mean temperature follows a smooth seasonal trajectory, peaking in mid-summer at approximately 76–77 °F. In contrast, monitored mean temperatures remained substantially lower, generally ranging between 58 °F and 66 °F throughout the monitoring period (see Figure 90). This persistent negative bias indicates that the standard temperature estimation equation substantially overpredicts instream temperatures at this location.

The divergence is primarily attributed to the regulatory influence of Buford Dam cold-water releases, which maintain a stable, cool thermal regime year-round. Hypolimnetic releases from Lake Lanier, combined with a short travel time of approximately 2.5–3 hours to Site 1, preserve the cold-water signal and suppress seasonal warming. As a result, the monitored data reflect a regulated river system with limited diurnal and seasonal variability, conditions that are not represented in the generalized air temperature–based calculation. These findings demonstrate that calculated temperature models are poorly suited for regulated river systems without explicit incorporation of dam-release effects.

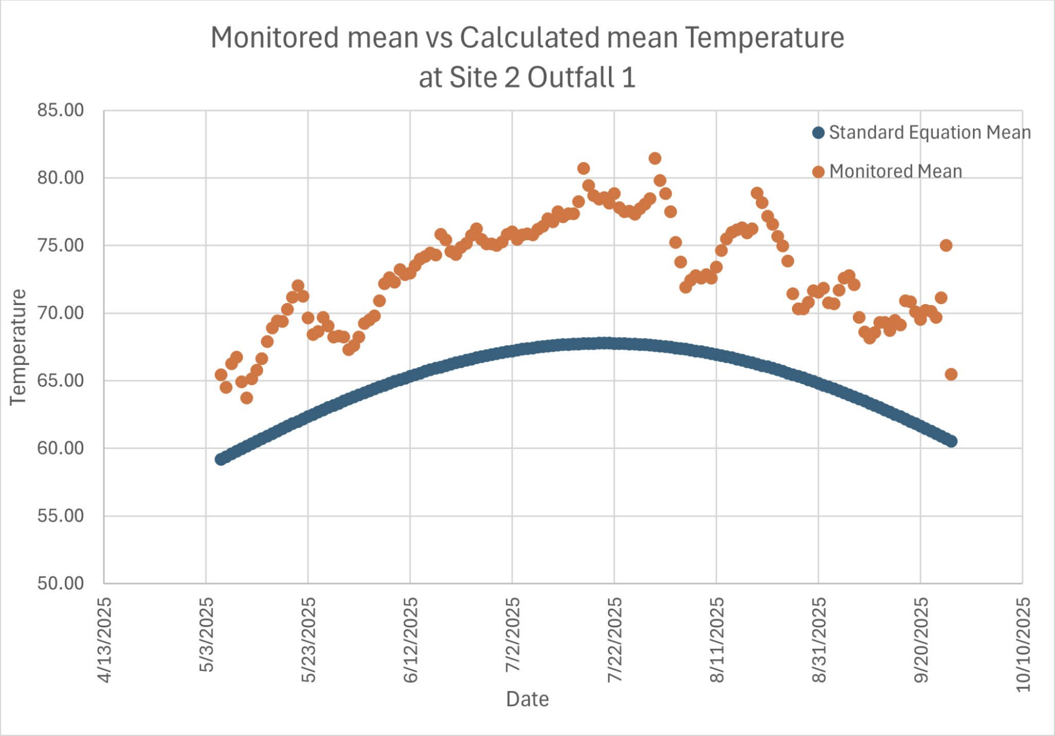


Figure 91. Chart. HOBO® Temperature and Natural Stream Temperature Mean Data Comparison at Site 2 Outfall 1

At Site 2, the relationship between monitored and calculated temperatures differed markedly from Site 1. Monitored mean temperatures consistently exceeded calculated values by approximately 6–15 °F during the summer months, with observed temperatures frequently reaching 75–80 °F during peak summer (see Figure 91). The calculated curve, which peaks near 68 °F, substantially underestimates actual stream temperatures at this site.

This positive bias reflects the small to moderate watershed size, limited baseflow, reduced riparian shading, and strong atmospheric coupling characteristic of Powder Springs Creek. Unlike Site 1, this unregulated system responds rapidly to ambient air temperature and solar radiation. Shallow depths, lower discharge, and direct exposure amplify heat exchange, producing warmer instream conditions than predicted by generalized equations calibrated for larger or more shaded systems. These results indicate that standard calculation methods may underrepresent thermal stress potential in smaller, urbanized trout streams.

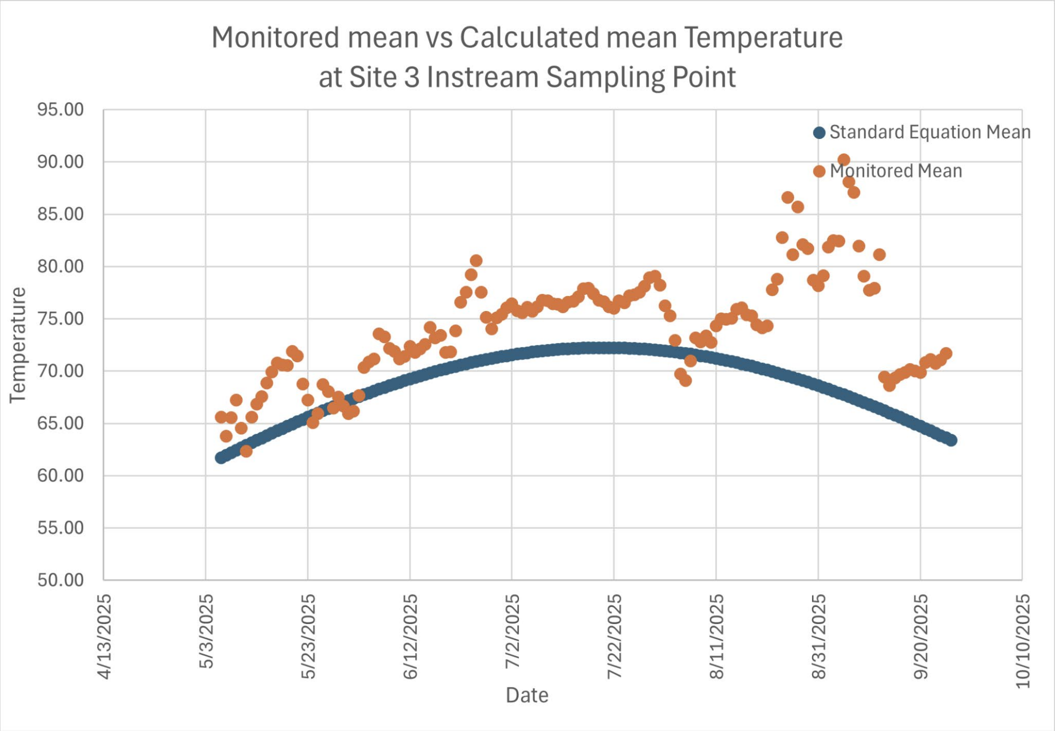


Figure 92. Chart. HOBO® Temperature and Natural Stream Temperature Mean Data Comparison at Site 3 Instream Sampling Point

At Site 3, monitored and calculated mean temperatures showed the closest agreement among the three sites, particularly during early summer. While monitored temperatures occasionally exceeded calculated values by 2-6 °F during peak summer periods, the overall seasonal pattern and magnitude were comparable (see Figure 92).

This alignment reflects the strong moderating influence of dense riparian canopy and long vegetated drainage pathways at Site 3. These factors dampen atmospheric heating and constrain thermal variability, producing a stream temperature regime that more closely approximates regional background expectations. The modest divergence observed during late summer likely reflects localized warming during low-flow conditions but does not indicate sustained thermal amplification.

Implications for Model Application and Compliance Assessment

Collectively, these comparisons demonstrate that calculated mean stream temperature equations provide only a coarse approximation of instream conditions and can either overestimate or underestimate true thermal regimes depending on site context. Regulated large-sized rivers such as Site 1 require explicit consideration of dam-release dynamics, while mid-sized smaller urban streams such as Site 2 demand localized calibration that accounts for shading, depth, and impervious-area heat loading. Site 3 of small-sized rural stream illustrates conditions under which generalized models may be reasonably applicable.

SUMMARY OF OBSERVED TRENDS

Roadway runoff produced measurable but transient temperature and DO responses across the three (3) monitored trout stream systems. The magnitude, spatial footprint, and persistence of these responses were governed by rainfall depth and duration, watershed scale, riparian shading, and the hydraulic connectivity of GDOT roadway runoff outfall infrastructure. Across all monitored events, the stream demonstrated rapid recovery, returning to near-baseline temperature and DO conditions within hours, underscoring the buffering role of natural mixing, dilution, and vegetated floodplain pathways.

Temperature responses were strongly event-driven and site-specific.

- Site 1 – Chattahoochee River (Large, high-baseflow, urban setup)

Continuous HOBO® data showed clear rainfall-linked warming at the downstream logger relative to the upstream reference during storms ≥ 0.5 inch in 24 hours. Peak temperature increase of ΔT ranged from 3 °F to 15.2 °F, with exceedances of the 2 °F threshold occurring during multiple moderate to large storms, particularly on 5/10/25, 5/27/25, 6/27/25, 6/28/25, 8/15/25, and 8/18/25. Each excursion persisted for only 0.2–3 hours, confirming that the warming was brief and tightly tied to storm-driven inflows from heated pavement and bridge surfaces

- Site 2 – Powder Springs Creek (Moderate-flow, suburban, diffuse outfall)

  The HOBO® logger at the mixed outfall–instream location showed small temperature increases of 1–3.5 °F during rainfall events, but no multi-hour excursions above 2 °F comparable to Site 1. The diffuse nature of the drainage flow path and partial canopy cover reduced the temperature signature relative to the bridge-scupper plume observed at Site 1. Temperature peaks were more muted, short-lived, and typically embedded within the natural diurnal cycle

- Site 3 – Two Run Creek (Small, shaded headwater, rural setup).

  Neither HOBO® nor ProDSS data showed measurable temperature excursions linked to rainfall. Temperature remained within the normal diurnal range (approximately 63–79 °F), and rainfall events up to 1.39 in/day of precipitation produced no discernible ΔT signal. Dense riparian shading, long vegetated flow paths, and low runoff volumes provided strong natural temperature buffering

DO fluctuations tracked temperature inversely, consistent with solubility controls.

- Across Sites 1 and 2, DO minima typically occurred concurrently with or within 1 hour of temperature peaks, forming mirrored time-series curves
- At Site 1, DO depressions during large rainfall events were typically 0.1–0.4 mg/L, with the most prominent dips occurring during the high-intensity June–August storms

- At Site 2, rainfall events produced 0.2–1.8 mg/L decreases in DO
- At Site 3, DO remained stable (generally 6–7 mg/L) with no event-linked depressions
- Isolated DO values below 5.0 mg/L in the HOBO® record were attributed to sensor fouling, sediment intrusion, or low-depth exposure, not environmental depletion

Recovery to baseline conditions was rapid across all events.

- Temperature and DO returned to pre-storm values within 6–8 hours at Site 1 and within 1–3 hours at Sites 2 and 3
- No sustained warming or DO suppression was observed, reinforcing that roadway runoff effects were short-duration and event-dependent, not chronic

Instrumentation performance corroborated the observed patterns.

- HOBO® loggers reliably captured diurnal cycles and storm-event excursions, with stable inter-sensor calibration across deployments
- Low-cost remote ESP32 sensors effectively recorded high-frequency temperature responses during precipitation events, confirming the arrival timing of runoff pulses
- YSI® ProDSS grab samples provided essential calibration checks and verified that long-term DO remained within acceptable limits despite localized short-term perturbations

Site characteristics strongly influenced resilience to warming and DO changes.

- Large, high-baseflow, well-mixed systems (Site 1) showed the clearest, most quantifiable temperature increase (ΔT) responses due to direct hydraulic connectivity and substantial pavement drainage

- Moderate-flow, semi-urban systems (Site 2) exhibited muted but detectable temperature responses driven by diffuse sheet flow and shallow floodplain mixing
- Small, shaded headwater systems (Site 3) displayed strong natural temperature stability, with negligible influence from roadway runoff even during high-rainfall events

Comparison to Georgia Rule 391-3-6-.03(6) Temperature and DO Standards

Georgia's trout stream criteria require:

- Secondary trout waters: No > 2 °F increase above natural background
- Primary trout waters: No human-induced temperature increase at all
- All trout waters: DO ≥ 6.0 mg/L daily average and not below 5.0 mg/L at any time

Temperature Compliance Perspective

- Site 1:

  Several storm events produced short duration ΔT > 2 °F, with maximum up to 15.2 °F, indicating temporary exceedances of the allowable temperature rise immediately following rainfall. However, excursions were brief (≤ 3 hours) and rapidly attenuated, and the river returned to equilibrium conditions shortly thereafter.
- Site 2:

  ΔT occasionally approached but only rarely exceeded the 2 °F threshold. Observed peaks (≈1–3.5 °F) were similarly short duration and embedded within the natural daily temperature envelope.

- Site 3:

  No measurable warming occurred during any rainfall event; therefore, no violations of the requirement were identified.

DO Compliance Perspective

- Across all three (3) sites, field-verified DO values remained ≥ 5.0 mg/L during all validated observations
- The majority of HOBO® DO depressions below 5.0 mg/L occurred during suspected biofouling or low-depth anomalies, not environmental depletion
- Verified DO measurements via ProDSS consistently met both the daily average (≥ 6.0 mg/L) and minimum (≥ 5.0 mg/L) standards

CHALLENGES IN THE FIELD

Several practical and methodological challenges were encountered during the two-year monitoring period that affected data collection continuity and influenced interpretation of roadway runoff impacts. Although these issues did not compromise overall study objectives, they underscore the logistical complexity of long-term field monitoring in trout stream systems and highlight areas for procedural refinement in future GDOT research projects.

Sediment and Biofilm Interference

Continuous monitoring devices, particularly HOBO® and low-cost ESP32 sensors, were periodically affected by sediment deposition and biofilm growth, most notably during mid-summer low-flow periods and immediately following high-intensity rainfall events. Fine sediment transported from upstream dam, unpaved shoulders, and embankments settled around and inside sensor housings, partially obstructing flow across optical DO caps and thermistor wells. In addition, algal and bacterial biofilms developed on the optical surfaces after two to three (3) weeks of submersion, causing minor signal drift and dampened short-term response. Routine cleaning during monthly maintenance trips effectively corrected these interferences, but the problem reduced data continuity at several intervals and required additional quality-control screening. Future monitoring programs would benefit from installing elevated housing from river/creek bed or incorporating antifouling shields in high-sediment reaches to minimize maintenance frequency.

Vandalism and Tampering

Incidents of human interference occurred primarily at the more accessible suburban sites. At Site 2 (Powder Springs Creek), the low-cost remote sensor attachment stand was dislodged during early summer of 2025, likely by recreational visitors using the stream corridor. At Site 3 (Two Run Creek), the HOBO® sensor concrete block anchor and protective housing were disturbed on several occasions, probably by human curiosity and livestock movement. Although the GSU Research Team recovered the sensor housing and re-anchored it using heavier rebar stakes and cam-lock cables, these events caused temporary data gaps at Site 3 HOBO® dataset and underscored the need for concealed or tamper-resistant installations in public or agricultural settings. Labeling sensors only with generic contact information written in muted color to the substrate reduced subsequent attention.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

ROADWAY RUNOFF IMPACTS

The integrated temperature and DO datasets collected from the YSI® ProDSS, HOBO® Data Logger, and low-cost ESP32 sensor systems demonstrate clear but short-lived roadway runoff influences during summer rainfall events across the three (3) monitored trout stream sites. Although the magnitude and timing of these responses varied with watershed scale, hydrologic connectivity, and riparian shading, all observed changes remained transient, event-driven, and rapidly dissipated following storm cessation. Comparative assessment indicates that Site 1 exhibited the greatest thermal sensitivity due to its large watershed area, extensive impervious cover, and direct hydraulic linkage between bridge and roadway runoff drainage and the receiving reach. Site 2 displayed moderate sensitivity, reflecting its smaller mid-sized watershed and more diffuse sheet-flow inflows that reduced concentrated heat loading. Site 3 showed the least sensitivity due to its small and rural watershed area, where dense canopy cover, long vegetated flow paths, and limited pavement area effectively buffered runoff heat before it reached the channel. Collectively, these differences highlight the dominant role of baseflow magnitude, shading, and flow-path attenuation in governing the intensity of roadway-runoff temperature and DO responses.

Temperature Response to Rainfall Events

Temperature records from the HOBO® Data Logger, YSI® ProDSS, and low-cost ESP32 sensor systems confirm that roadway runoff produced short duration warming in receiving waters when daily rainfall exceeded approximately 0.5 inch. The most pronounced and repeatable responses occurred at Site 1 (Chattahoochee River at Medlock Bridge Road) Outfall 1, where downstream loggers consistently registered temperature increase ΔT peaks ranging from 3 to 15.2 °F during major storm events such as those on 5/10/2025, 5/27/2025, 6/27–6/28/2025, and 8/15–8/18/2025. These increases typically persisted for 0.2 to 3 hours before declining toward equilibrium over the following evening or overnight period, reflecting the river's strong capacity for thermal dissipation despite direct bridge-scupper inflows and roadway runoff from Outfall 1.

At Site 2 (Powder Springs Creek at Charles Hardy Parkway) Outfall 1, temperature responses were present but more subdued. HOBO® data showed 1–3.5 °F increases, occurring almost immediately after rainfall pulses and tracking closely with short-duration runoff surges through the diffuse and intermittently flooded mixing zone. These thermal pulses diminished within two to three (3) hours, indicating a localized but recurring warming effect that lacked the multi-hour persistence observed at Site 1.

In contrast, Site 3 (Two Run Creek at Kingston Highway NW) Outfalls 2 and 3 exhibited no measurable rainfall-induced temperature excursions. Continuous logger records showed variations confined to the natural diurnal range, with no distinct departures following heavy storms up to 1.39 inches/day. The long-vegetated outfall pathways, dense canopy shading, and low impervious area effectively cooled and attenuated roadway drainage before it entered the creek.

Across all three (3) systems, continuous HOBO® monitoring confirmed that post-event thermal recovery was consistently completed within a single diurnal cycle, and no cumulative or sustained warming patterns were detected over the monitoring period.

DO Impacts and Anomalies

DO records across the three (3) monitored trout stream systems displayed clear inverse relationships with temperature fluctuations, consistent with expected solubility dynamics under short-term warming. At Site 1 (Chattahoochee River) Outfall 1, the largest and most consistent DO depressions occurred during major summer rainfall events. Continuous HOBO® data showed DO decreases of approximately 0.1–0.4 mg/L, with the strongest drops coinciding with the highest ΔT peaks on 6/27/2025, 6/28/2025, and 8/18/2025. These reductions were short-lived and returned to pre-event levels within several hours, reaffirming that DO depletion was a direct physical response to transient temperature elevations rather than sustained DO consumption.

At Site 2 (Powder Springs Creek) Outfall 1, rainfall-driven DO changes were smaller but clearly detectable. During key events such as 7/29/2025, 8/3/2025, 8/12/2025, and 9/24/2025, DO concentrations fell by 0.2–1.8 mg/L, closely tracking the timing of minor temperature rises. The rapid recovery typically within two (2) to three (3) hours demonstrated that the creek's reaeration capacity and moderate baseflow were sufficient to offset short-term thermal effects from roadway sheet flow entering the flood-prone mixing zone.

At Site 3 (Two Run Creek) Outfalls 2 and 3, DO levels showed no rainfall-linked depressions. Continuous data maintained a stable diurnal envelope between 6.0 and 7.0 mg/L, even during a heavy rainfall exceeding 1.39 inches/day. This stability reflects the strong moderating effect of long vegetated outfall pathways, cool shaded inflows, and rapid reaeration in the shallow high-gradient channel, which collectively prevented roadway runoff from exerting any measurable oxygen demand or thermal stress.

Across Sites 1 and 2, isolated single-point DO dips occasionally fell below 5.0 mg/L but were determined to be non-environmental artifacts arising from sensor fouling, sediment accumulation, biofilm growth, or temporary low-depth exposure within the protective housings. These anomalies were systematically removed during QAPP-compliant data screening and did not influence trend analysis. Overall, the validated DO dataset confirms that roadway-runoff impacts on DO levels were episodic, physically driven, and rapidly reversible, with no evidence of prolonged DO impairment at any monitoring location.

The summary of matrix of rainfall events approaching regulatory temperature or DO minimum thresholds across all three (3) sites is given in Table 30 below.

Table 30. Summary Matrix of Rainfall Events Approaching Regulatory Temperature or DO Minimum Thresholds across all Three Sites

Site	Date	Rainfall (in/day)	ΔTemperature (Downstream – Upstream or Local Instream Spike) (°F)	Exceeded / Approached 2 °F Limit?	Observed DO Change (mg/L)	Approached DO Minimum?	> 2°F Event Duration (hours)
Site 1	5/10/2025	0.71	3.0	Exceeded	0.8	No	1.5
	5/27/2025	0.61	6.8	Exceeded	1.0	No	1
	6/9/2025	0.74	3.8	Exceeded	0.4	No	0.25
	6/12/2025	0.52	4.7	Exceeded	0.4	No	0.4
	6/17/2025	1.06	5.6	Exceeded	0.3	No	0.25
	6/27/2025	0.87	8.2	Exceeded	0.2	No	3
	6/28/2025	0.52	5.9	Exceeded	0.4	No	3
	8/3/2025	2.04	1.9	Approached	N.A.	Possible sensor artifact	0
	8/15/2025	0.56	4.1	Exceeded	0.1	No	0.5
	8/18/2025	0.66	15.2	Exceeded	0.2	No	2
Site 2	7/29/2025	0.66	~1	Below limit	0.8	No	1
	8/3/2025	1.28	~2.5	Approached	1.8	No	0.75
	8/12/2025	0.59	~2.5	Approached	0.2	No	0.5
	9/24/2025	0.78	~3.5	Approached	1.1	No	1.5
Site 3	6/27/2025	0.67	No ΔT	No	~0	No	N/A
	9/24/2025	1.39	No ΔT	No	<1 mg/L	No	

Key Regulatory Interpretation for GDOT

- Only Site 1 exhibited repeated, short-term exceedances of the 2 °F allowable increase for secondary trout waters
- Site 2 produced localized, brief warming that intermittently approached but seldom exceeded the threshold
- Site 3 showed no threshold exceedances, confirming full thermal buffering by natural vegetation and long flow paths

- All three (3) sites mostly met DO standards after QAPP-compliant artifact removal, with no DO < 5.0 mg/L picked up by YSI® ProDSS in the streams and daily average DO in the streams was above 6.0 mg/L monitored by HOBO® dataloggers

COMPARISON OF SENSOR SYSTEMS

The RP 23-11 Project utilized three complementary water-quality monitoring platforms–YSI® ProDSS Multi-parameter handheld instruments, HOBO® continuous dataloggers, and low-cost ESP32-based remote sensor systems–to evaluate roadway runoff impacts on trout stream temperature and DO. Each system contributed distinct advantages in accuracy, temporal coverage, and cost efficiency. Their comparative performance under field conditions informs recommendations for future GDOT MS4 monitoring and stream-protection programs.

Reliability and Data Quality

The **YSI® ProDSS** instruments demonstrated the highest measurement accuracy and served as the calibration reference for all other systems. Field checks showed that ProDSS readings maintained consistency within ±0.2 °F for temperature and ±0.3 mg/L for DO over the entire two-year period. However, their use was limited by manual sampling frequency and the need for on-site personnel during rainfall events, which restricted their temporal resolution.

The **HOBO® MX-801** series loggers provided highly reliable continuous datasets at 5-minute intervals with minimal drift. Long-term field performance was stable, and only minor interruptions occurred due to sediment fouling or temporary submergence loss. HOBO® sensors proved robust in extended deployments (3–4 weeks per cycle), maintaining stable calibration and producing high-fidelity time-series data suitable for both baseline and event-scale analyses. They also required less maintenance and power management than portable probes, making them the most dependable tool for extended unattended operation.

The **low-cost ESP32-based remote sensor systems**, though less precise than commercial instruments, successfully captured the rapid temperature responses associated with rainfall events. Their sub-minute logging capability revealed short-term temperature peaks that were not observable by the ProDSS instrument sensor. While the low-cost DFRobot® temperature sensors occasionally experienced drift (up to ±0.4 °F) and intermittent signal dropouts due to humidity or power fluctuations, the DFRobot® DO sensor was found to be unreliable for long-term (> 8 hours) field deployment. Extended usage revealed significant drift and inconsistent readings, particularly under fluctuating temperature and moisture conditions. The sensor's housing and sensor cap membrane were also prone to degradation and fouling (see Figure 93 below), indicating poor resistance to environmental stress in harsh outdoor settings. Consequently, the DO sensor probe proved unsuitable for continuous water-quality monitoring applications in the field for longer deployment. Overall, the low-cost temperature sensor performance was strong for event detection and real-time communication. Their modular, inexpensive design made them a practical supplement to higher-end systems for capturing transient hydrologic temperature responses.

Figure 93. Photo. DFRobot® DO Sensor Cap Degraded by Fouling.

Strengths and Limitations in MS4 Monitoring Applications

For GDOT's MS4 compliance monitoring, each sensor type offers unique operational strengths. The ProDSS provides the most reliable point-in-time measurements for regulatory verification and QA/QC validation. It remains essential for calibration, field checks, and targeted sampling during rainfall events when staff are available. The HOBO® loggers represent the optimal backbone for long-term baseline monitoring, capturing diurnal variability and post-storm recovery trends while requiring limited field labor. They are well-suited for permanent or semi-permanent deployment at high-priority outfalls or trout stream crossings.

The low-cost ESP32 remote sensor systems extend monitoring capability to previously unmonitored or resource-limited locations. Their affordability allows broad spatial coverage, and their short-interval logging provides valuable insight into the immediate timing of roadway-runoff inflows. However, their susceptibility to biofilm interference, humidity ingress, and power interruption requires regular maintenance and field validation. In an MS4 context, these units are most effective as supplementary "storm-event sentinels" integrated with periodic ProDSS verification and co-located HOBO® loggers for continuous monitoring.

In summary, the three (3) systems together form a tiered monitoring framework:

- ProDSS – calibration standard and high-accuracy reference
- HOBO® – reliable long-term monitoring for trend and compliance evaluation
- ESP32 – cost-effective, high-frequency event detection network

This multi-sensor approach proved essential for characterizing roadway runoff impacts on trout stream temperature and DO within GDOT's MS4 Program. It provides a scalable model for future deployments where precision, coverage, and cost must be balanced to achieve both scientific rigor and operational efficiency.

INTEGRATION WITH LITERATURE

The results of this study align closely with established research on the temperature and DO impacts of roadway runoff on receiving surface waters. Previous studies have demonstrated that rainfall over impervious surfaces, especially asphalt and concrete pavement, can rapidly elevate runoff temperature and contribute short-term heat loads to adjacent streams [8], [23], [24]. These temperature pulses are typically most pronounced during summer rainfall events following prolonged dry periods when pavement surfaces are pre-heated, a pattern mirrored in the RP 23-11 monitoring results. At Site 1 (Chattahoochee River) and Site 2 (Powder Springs Creek), temperature increases beyond 2 °F were recorded within hours of rainfall onset, consistent with the 1–3 °F short-term rises reported by Nelson and Booth [23] and Herb et al. [8] in urban Minnesota streams. Similarly, LeBlanc et al. [24] found in their study conducted in Southern Ontario, Canada that roadway stormwater can cause temperature plumes of limited spatial extent but high temporal intensity, a behavior also documented in our August 2025 events at both Site 1 and Site 2. These consistencies affirm that the short-duration, event-scale temperature effects observed in Georgia trout streams are comparable to those reported in northern and western U.S. watersheds despite climatic differences.

The DO dynamics observed in the RP 23-11 dataset also align with previously documented temperature–DO coupling mechanisms. The small but distinct DO depressions (≈ 0.6–1.0 mg/L) that occurred during the peak of temperature rises at Sites 1 and 2 correspond to the inverse solubility behavior described by Booth et al. [25] and summarized in the literature review. These authors emphasized that short-term DO declines following roadway-runoff inflow are typically physical rather than biochemical in origin, driven by reduced DO solubility and temporary mixing of low-DO surface runoff [25]. The rapid DO recovery observed across all monitored events in this study supports that interpretation and confirms that runoff-induced DO changes in trout streams are episodic, not sustained.

Additionally, the lack of measurable temperature or DO response at Site 3 (Two-Run Creek) corroborates findings from riparian and hydrologic studies that emphasize the importance of vegetative buffers and shaded flow paths in moderating roadway-runoff heat transfer. Research by Moore et al. [26] and Herb et al. [8] similarly reported that streams bordered by mature riparian canopy and grass-lined drainage swales experience significantly lower temperature loading than unshaded reaches [8], [26]. The long, vegetated conveyance paths at Site 3 provided effective dissipation of heat before runoff reached the creek, illustrating in practice the mitigation mechanisms identified in those earlier works.

Overall, the RP 23-11 findings are consistent with and expand upon prior national and regional studies, demonstrating that roadway runoff can cause short-duration, localized temperature and DO disturbance in trout streams but that natural hydrologic and vegetative buffers provide effective mitigation of these effects. The study contributes to the literature by offering a field-validated, sensor-based dataset from southeastern U.S. trout waters, a region with limited prior documentation of roadway runoff temperature effects. The consistency between these observations and past findings [8], [24] strengthens confidence in using continuous temperature and DO monitoring as a cost-effective, regulatory tool within GDOT's MS4 permit framework.

BMP IMPLICATIONS

The results of this study provide clear guidance on the selection and application of BMPs that can reduce roadway-runoff temperature and DO-demand impacts in trout stream watersheds. While none of the monitored sites exhibited long-term exceedances of Georgia trout stream standards, the event-based temperature differences and short-term DO depressions documented at Sites 1 and 2 confirm that localized warming can occur during intense rainfall in a hot summer. Accordingly, BMPs that attenuate, cool, or delay runoff discharge are most relevant to GDOT's ongoing MS4 compliance program.

Riparian Buffer Strips and Shading Enhancements

Vegetated buffer strips remain one of the most practical and effective temperature mitigation measures for trout streams. Field observations at Site 3 demonstrated that grass-lined and forested flow paths substantially dissipate roadway runoff heat before it enters the stream. This confirms prior findings that continuous vegetative shading and shallow overland conveyance promote both radiative cooling and infiltration, reducing the instantaneous runoff heat flux. For GDOT, maintaining and expanding riparian vegetation along roadway-adjacent channels, culvert outlets, and drainage ditches provides a low-cost, passive strategy that directly supports GA EPD's Permit for GDOT; criteria under Part 2 (Criteria for Receiving Waters).

Bioswales and Vegetated Filter Systems

Bioswales are especially suitable for GDOT right-of-way applications where space and slope allow shallow infiltration. These systems slow the velocity of roadway runoff, promote sediment deposition, and enhance heat exchange with cooler subsurface soils. In the context of RP 23-11 findings, bioswales could meaningfully reduce the temperature of discharge entering trout streams, particularly at sites similar to Powder Springs Creek where sheet flow currently reaches the stream without substantial cooling. Periodic maintenance to prevent sediment clogging is essential for sustained performance, but installation costs are moderate, and design integration with existing ditch lines is straightforward for district-level implementation.

Low-Impact Development (LID) Practices

LID strategies such as permeable shoulders, infiltration trenches, and disconnected pavement drainage could offer long-term potential to minimize direct runoff conveyance. These measures reduce peak flow and delay hydrograph timing, thereby limiting the magnitude of short-term temperature pulses. While retrofitting existing highway infrastructure poses challenges, incorporating LID features into new construction or major rehabilitation projects could substantially improve compliance with temperature and DO criteria in trout stream corridors.

Wet Ponds and Detention Systems

In certain high-drainage locations, wet detention ponds or extended dry basins may provide effective hydraulic buffering by detaining and cooling runoff prior to release. However, ponds can also stratify temperature and discharge warmer water if not properly designed. For trout stream protection, shallow, shaded ponds or multi-cell systems with vegetated forebays are preferable. A temperature modeling study could be conducted to assess the impact of wet ponds and detention systems on roadway runoff. Such systems should be evaluated on a site-specific basis considering space availability, maintenance burden, and potential mosquito or sedimentation issues.

Controlled Reservoir Releases and Flow Management

For larger regulated systems such as the Chattahoochee River, timing of the Bulford Dam reservoir releases can mitigate temperature impacts by maintaining higher baseflows and promoting mixing during storm periods. Coordinated flow management with the U.S. Army Corps of Engineers or local water authorities could enhance stream resilience to short-term roadway-runoff inputs, especially during critical summer low-flow months when trout stream temperature sensitivity is highest.

The site-specific BMP recommendations are given in Table 31 below.

Table 31. Site-Specific BMP Recommendations

Site	Most Appropriate BMP Types
Site 1 – Chattahoochee River (High-baseflow, direct outfall discharge)	1. **Hydraulic buffering measures**: Extended mixing length, plunge-pool energy dissipation, channel roughness additions.
	2. **Targeted detention/retention retrofits**: Shallow vegetated forebays at bridge outfalls (where feasible).
	3. **Monitoring-forward strategy**: Seasonal HOBO® deployment and event-triggered remote sensors.
Site 2 – Powder Springs Creek (Moderate flow, diffuse sheet-flow mixing zone)	1. **Bioswales and vegetated filter strips**: Grass-lined or forested conveyance to reestablish cooling pathway.
	2. **LID retrofits**: Infiltration trenches, permeable shoulder segments, disconnected pavement drainage.
	3. **Distributed detention**: Shallow vegetated basins or multi-cell dry ponds upstream of diffuse outfalls.
Site 3 – Two Run Creek (Small, shaded headwater stream, long vegetated outfall pathways)	1**. Riparian buffer conservation and enhancement**: Maintain and strengthen canopy and groundcover along drainage channels.
	2. **Minimal structural BMPs needed**: Existing vegetated pathways provide effective natural treatment.
	3. **Protection-oriented BMP policy**: Prevent clearing, mowing intensification, or channel straightening.

SUITABILITY FOR MS4 COMPLIANCE AND IMPLEMENTATION

From an MS4 perspective, the BMPs most applicable to GDOT are those that balance temperature performance, constructability, and maintenance feasibility. Vegetated buffers, bioswales, and shallow infiltration systems provide the best combination of temperature mitigation and practical implementation within GDOT right-of-way constraints. These measures align with MS4 permit requirements for post-construction stormwater management and support compliance with Georgia Rule 391-3-6-.03(6)(ii),(v) by reducing short-term temperature excursions and promoting DO recovery. Larger structural BMPs such as wet ponds or controlled releases are best reserved for high-flow corridors where hydrologic retention is achievable.

In summary, the BMP strategies supported by this project emphasize passive temperature attenuation through vegetation, infiltration, and detention rather than mechanical or chemical treatment. When integrated with sensor-based monitoring networks, these approaches provide a practical, cost-effective means for GDOT to manage roadway runoff temperature and DO impacts, ensuring ongoing protection of trout stream water quality and continued compliance with MS4 regulatory standards.

KNOWLEDGE GAPS & SUGGESTED FUTURE RESEARCH

While RP 23-11 study successfully quantified roadway-runoff influences on trout stream temperature and DO and demonstrated the effectiveness of sensor-based monitoring systems, several knowledge gaps remain that warrant further investigation to enhance GDOT's long-term stormwater management and trout stream protection strategies.

Temporal and spatial monitoring limitations

Although the two (2) year dataset captured representative rainfall and runoff events, the monitoring record did not encompass multiple hydrologic years when baseflow and air temperature dynamics differ substantially. Expanding monitoring duration to include multiple seasonal cycles would provide greater insight into inter-annual variability and long-term climate influences on roadway runoff behavior. Additionally, finer spatial coverage particularly at intermediate distances between outfalls and downstream points, would help quantify how quickly roadway-derived heat dissipates under varying flow regimes and geomorphic settings.

Integration of rainfall intensity and energy flux modeling

The current study employed the rational method for estimating roadway-runoff discharge, which provided useful hydrologic scaling but limited capacity to represent rapid surface-energy transfer. Future work could couple continuous rainfall intensity and solar-radiation data with heat-budget and surface-energy models (e.g., CE-QUAL-W2 or SWMM-Heat) to more accurately predict temperature loading under diverse precipitation scenarios. Incorporating site-specific pavement albedo, antecedent heat storage, and surface roughness factors would refine predictions of temperature plume magnitude and duration.

Biological response assessment

While RP 23-11 focused on physical and chemical parameters (temperature and DO), biological metrics such as macroinvertebrate assemblages, trout behavior, and metabolic stress indicators were not evaluated. Future studies could integrate biological monitoring to directly link physical changes observed during rainfall events with ecological response, thereby supporting a more comprehensive assessment of trout stream health and compliance outcomes.

Sensor technology advancement and data management

The tiered sensor framework proved successful, yet additional research should be done to optimize calibration frequency, anti-fouling design, and telemetry reliability for long-term deployment in remote areas. Future work could explore integration of machine-learning algorithms and automated event detection to process real-time data streams, identify threshold exceedances, and transmit automated alerts during critical runoff periods. Developing a centralized GDOT cloud-based data repository would further enhance accessibility and consistency of statewide MS4 monitoring data.

Evaluation of BMP temperature performance

The present study qualitatively identified vegetative buffers, bioswales, and infiltration practices as effective temperature mitigation measures. Future research could conduct controlled field experiments or modeling to quantify the temperature attenuation efficiency of specific BMP designs under Georgia climatic conditions. Such studies would allow GDOT to prioritize BMPs based on measurable cooling performance and cost-benefit outcomes.

ACKNOLEDGEMENTS

The authors gratefully acknowledge the Georgia Department of Transportation (GDOT) for its sponsorship, guidance, and sustained support throughout the RP 23-11 research project, as well as the active involvement of GDOT staff and resource-agency partners whose expertise contributed meaningfully during site selection, technical review, and project implementation. The Georgia Southern University (GSU) research team extends special appreciation to Mr. Brad McManus, P.E., Assistant State Design Policy Engineer of the Office of Design Policy and Support, for his leadership, coordination, and continued guidance in aligning the project objectives with GDOT MS4 permit requirements and environmental compliance needs. Sincere thanks are also extended to Mr. Drew Martin, P.E., State Roadway Hydraulics Engineer, Ms. Sarah Jones, P.E., Office of Design Policy and Support, Mr. Jaime Collazo, Senior Ecology Team Leader from the Office of Environmental Services, and Mr. Md Sabbir Ahmed, Project Manager from the Office of Research, for their technical advice, site selection guidance, field coordination assistance, and critical review input throughout the study. The authors further acknowledge the support of the Department of Civil Engineering and Construction at Georgia Southern University, the contributions of the Spring 2024 and Fall 2024 Civil Engineering Senior Project Teams for their involvement in equipment testing and prototype development, and Mr. Shawn Jackson, Laboratory Coordinator, for logistical support. Finally, the authors recognize the valuable technical guidance provided by collaborators within the broader water-resources research community, whose insights strengthened the monitoring framework and analytical approach applied in this project.

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