Work in the Wet Versus Work in the Dry for Stream Restoration

Final Report

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Prepared for:

Chesapeake Bay Trust
Empowering people. Restoring nature.

Prepared by:

Center for Watershed Protection

Ecosystem Planning & Restoration

Ecosystem Services

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1. Executive Summary

Stream restoration is a widely used practice in the Chesapeake Bay watershed aimed at reducing erosion, improving water quality, and restoring aquatic ecosystems. During the construction of restoration, in-stream construction activities can take place either in the Wet (with active stream flow) or in the Dry (with the stream temporarily diverted or dewatered). This study investigates the effects of these two construction methods on turbidity and total suspended solids (TSS) loading in three stream restoration sites in Maryland.

The primary objectives of the study were to:

1. Assess the impact of Wet vs. Dry construction on turbidity levels during active restoration work.
2. Compare the total suspended sediment loads generated by each method.
3. Evaluate the sediment load from construction activities relative to a 1.25-year storm event.

<u>Key Findings</u>

- **Turbidity Levels**: Construction in the Wet consistently resulted in higher turbidity levels compared to working in the Dry. The average turbidity levels during Wet construction were significantly higher at all study sites, with exceedances of Maryland's 150 NTU standard occurring more frequently.
- **Sediment Load**: Total suspended sediment loads were substantially higher for Wet construction compared to Dry construction, indicating a meaningful difference in sediment release.
- **Comparison to sediment load from Storm Events**: Despite increased turbidity and sediment load from Wet construction, the total sediment released during restoration activities at two of the sites was considerably less than what would be generated by a 1.25-year storm event. However, the third site produced more sediment load than a 1.25-year storm. This difference may be explained by key characteristics that set the third site apart: it had a smaller drainage area, lower baseflow, and a steeper stream gradient.

<u>Implications for Future Research</u>

- **Regulatory Considerations**: Current Maryland regulations stipulate Dry construction methods based on the assumption that they minimize sediment discharge and more easily assure compliance with Maryland Water Quality Standards. This study provides empirical evidence that may support that approach while also identifying watershed and site considerations that could influence the decision making for where Wet construction may still be viable or where differences in turbidity and sediment load may be more significant depending on construction methods.
- **Construction Efficiency vs. Environmental Impact**: This study found that although Wet construction is often assumed to be more efficient, field data showed only modest differences in production rates, ranging from 9% to 15%, between Wet and Dry construction methods. However, to match the lower turbidity levels (NTU/day) observed during Dry

construction methods, Wet methods would need to proceed 3 to 23 times faster. Moreover, Wet construction generated substantially more sediment, with one foot of work under Wet construction producing the same load as 11 to 21 feet under Dry construction.

- **Site-Specific Decision-Making**: Sediment transport rates depend on stream and watershed conditions. Although this study minimized variability in these conditions, future research could explore if there is a correlation between Wet or Dry Construction methods, and factors such as drainage area size or stream water surface slope. This may help determine whether any site-specific characteristic could inform regulatory decisions about when each method is environmentally appropriate.

This research contributes to the growing body of knowledge on best practices for stream restoration and provides valuable insights for project planners, regulatory agencies, and environmental professionals seeking to balance efficiency with ecological impact. Further studies with expanded datasets across diverse stream conditions will help refine guidelines for in-stream construction practices

2. Introduction

Stream bank erosion is a leading cause of increased sediment loads during high flow events (McCarney-Castle et al., 2017; Cashman et al., 2019; Lammers and Bledsoe, 2019). Suspended sediment increases turbidity and harms aquatic life, increases the cost of drinking water treatment, decreases aesthetics and recreation appeal, and destroys aquatic habitat (Schubel, 1968; Kemp et al., 1983; Orth et al., 2017). Nitrogen and phosphorus can also be bound to sediment particles, and the presence of high turbidity can indicate that an increased amount of nutrients, bacteria, and heavy metals are present within the water column. Stream restoration, a practice undertaken to assist in the recovery and rehabilitation of aquatic ecosystems, has been identified as a method to reduce stream bank erosion and encourage pollutant reduction processes such as denitrification (Schueler & Stack, 2014). In Maryland's Phase III Watershed Implementation Plan (WIP) the State proposes over 31-miles of urban and non-urban stream restoration to occur by 2025, adding to over 20-miles of verified restoration that has taken place over the last decade (MDE, 2019). Other Chesapeake Bay jurisdictions have planned similar levels of stream restoration implementation as part of their plan to reduce nitrogen, phosphorus, and sediment from entering the Chesapeake Bay. During stream restoration construction, the use of heavy equipment within a channel's wetted perimeter, grading, and the installation of in-stream structures can temporarily release suspended sediment concentrations over 12 times higher on average than background levels when working in the Dry (Eason, 2011). Because of the assumption that potential for suspended sediment release would be increased if construction is active within the flowing channel (i.e., working in the Wet), streams in restoration construction sites in Maryland are required to be diverted and dewatered, unless special permission is granted (MDE 2000). However, there is limited research available to determine if, and under what circumstances, working in the Dry is preferable to Wet in terms of effects to water quality and downstream sediment load. Given the ongoing and proposed implementation of stream restoration in the Chesapeake Bay, understanding the impacts of different methods of construction is increasingly urgent.

Although there is a wealth of research supporting most regulations that protect aquatic ecosystems from the impacts of construction projects and land disturbance adjacent to streams (e.g., Gray and Sotir, 1996; Allen and Leech, 1997), guidelines for construction within the wetted-perimeter of stream channels are primarily based on unquantified observations, because relevant data are not available to inform in-stream construction methods (Clinton et al., 2004; Straughan Environmental, 2019). Many state regulations that currently require in-stream work to be completed in the Dry are based on the unproven guiding principle that diverting water out of the channel during construction will impact water quality and aquatic biota less than working in the Wet.

Straughan Environmental (2019) conducted one of the first studies to determine differences between stream restoration in the Wet and in the Dry with funding from the Chesapeake Bay Trust. This research has informed our approach and potential improvements to the experimental design and site selection to limit confounding variables and address challenges with sample collection that they encountered.

2.1. Hypotheses

This study tests hypotheses comparing the two methods of construction, “working in the Wet” and “working in the Dry”, for Turbidity (H1) and Sediment Load (H2) at the selected sites. Further, it compares the sediment load resulting from each method to the sediment load equivalent to a 1.25-year flow recurrence interval (H3) at each site. It should be noted that our intention is not to make conclusions about sediment load and turbidity differences between the two methods generally, but rather that we might gain insight into what, if any, differences between the two methods occur at the three study sites specifically given their stream and watershed characteristics. This research is intended to add to a growing number of similar studies that in aggregate would allow for a more complete understanding of the impact of the two methods, and possible hydrologic, watershed, geomorphic, or construction characteristic thresholds.

H1. The turbidity resulting from Wet construction will be higher during active construction, but turbidity will not be completely eliminated during Dry construction, with an expected spike in turbidity when the stream flow is released for the night and elevated levels of turbidity expected for both cases after construction ends for the day.

This hypothesis includes two sub-hypotheses, related to the average baseflow turbidity (NTU) during construction during the Wet as well as the frequency of exceedance of Maryland’s 150 NTU turbidity standard. Overall, we hypothesize that Wet construction will result in higher turbidity during construction (H1A), but that the speed of construction associated with this technique will result in similar total time where turbidity standards are exceeded (H1B):

- H1A. The observed average Turbidity (Average NTU) will be higher during the Wet construction Period.
- H1B: The estimated hours exceeding Maryland’s turbidity standards for Wet construction are less than 50% greater than the exceedance time for Dry construction.

H2. The suspended sediment load associated with Dry construction will not be meaningfully different than the load associated with Wet construction, such that absolute difference between total suspended solids loads (lbs.) is less than 25% of the average suspended sediment load between the two methods.

H3. The sediment load associated with the Construction in the Wet or Construction in the Dry will be significantly less than the sediment load associated with the 1.25-year storm for the watershed.

2.2. Study Design

The study was conducted across three distinct sites, each selected to provide a representative sample of various stream environments. At each site, there were two comparable stream reaches, where one reach underwent construction in Wet conditions and the other in Dry conditions. This setup allowed for a controlled, side-by-side comparison of the effects of construction practices in different conditions at each site. Continuous measurements of water level, precipitation, and turbidity were collected before, during, and after construction. Water level can be correlated to discharge (i.e., stream flow) through the measurement of velocity. Velocity was measured at each cross section where water level measurements were taken. Turbidity can be correlated to Total Suspended Solids (TSS) through the collection of TSS samples.

<u>Site Layout and Reach Selection</u>

Each of the three research sites comprises two reaches, which are similar in length, width, substrate composition, and other relevant physical characteristics. Each reach contained a comparable number and type of structures (e.g. riffle grade control, toe bolder, etc.). The comparable reaches at each site were designed to ensure that any differences observed in the study can be attributed primarily to the construction conditions (Wet vs. Dry) rather than natural variability between the sites.

The construction timeline for each reach was estimated to be approximately 4-6 days; however, the actual duration of work observed was directly influenced by the construction crew's efficiency in completing the designated length and number of structures within that reach. This target duration was based on a balance between maintaining a reasonable project timeline and ensuring sufficient time for data collection and observation of potential environmental changes, such as alterations in water quality parameters, particularly turbidity.

<u>Alternating Wet and Dry construction Conditions</u>

The key experimental variable in this study is the construction condition: whether the reach is “Wet” (i.e., with water flow present during construction) or “Dry” (i.e., water flow is diverted or minimal during construction). To manage potential biases and confounding factors, the decision regarding which reach—upstream or downstream—was constructed in Wet or Dry conditions was alternated across the sites.

This alternation helps to ensure that any observed differences in environmental impact are not solely due to a fixed pattern of construction but reflect the effects of varying conditions. The alternating pattern also helps account for potential site-specific variations, such as differences in flow regime, sediment load, or other natural factors that could influence water quality.

Turbidity Equipment Setup Locations

To measure and evaluate the impacts of construction under different conditions, a comprehensive water quality monitoring strategy was developed for each site. This strategy involved the use of three turbidity sondes positioned at strategic locations along the stream reaches.

The first sonde is positioned upstream of both the Wet and Dry construction reaches to establish a baseline turbidity level. This sonde provides continuous measurements of natural turbidity levels before any construction activities begin, serving as a control against which changes in turbidity due to construction can be compared.

A second sonde is placed immediately downstream of the upstream monitoring section. This device captures changes in turbidity caused by construction activities in the upstream reach (whether Wet or Dry). By comparing readings from this sonde with the baseline measurements, researchers can determine the immediate impact of the upstream construction on water quality.

The third sonde is installed downstream of the entire monitoring section, beyond both the Wet and Dry reaches. This sonde measures the cumulative effect on turbidity after water has flowed through both constructed reaches. The data from this sonde are crucial for understanding how construction activities in different conditions (Wet vs. Dry) interact and affect downstream water quality.

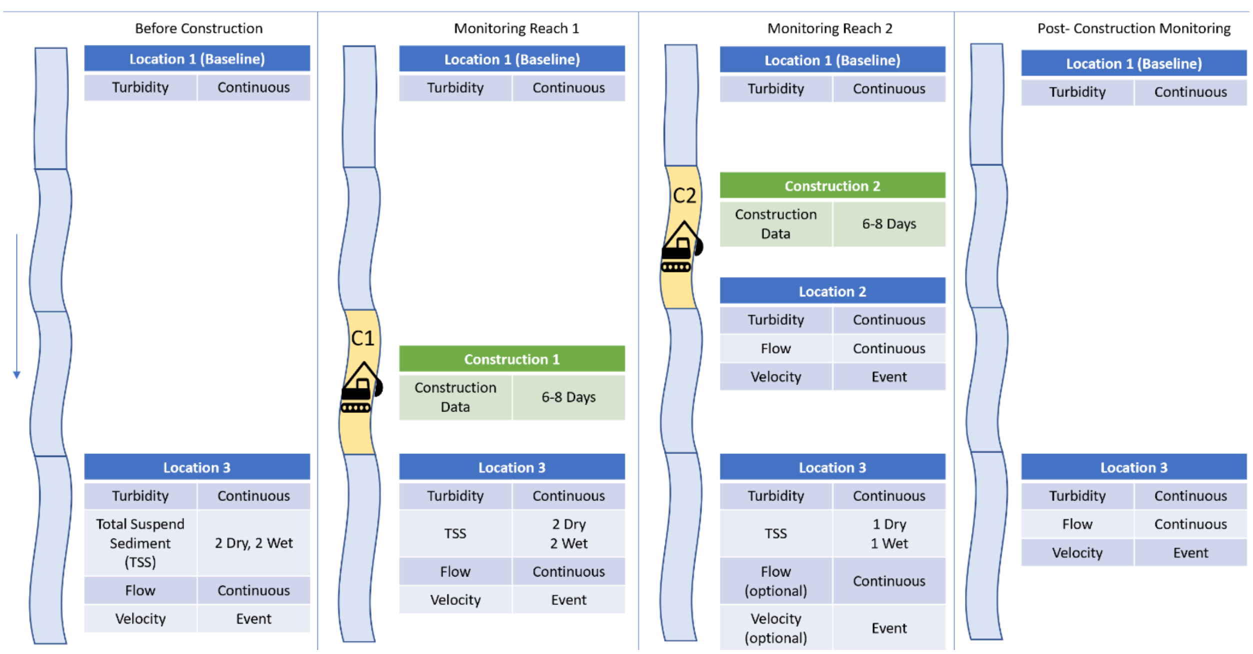

Figure 1: Monitoring configuration schematic at each site (Note: Site 2 utilized location numbering of 4, 5, and 6 to avoid confusion with Site 3 locations since monitoring timelines overlapped.)

The monitoring configuration schematic (Figure 1) illustrates the configuration of equipment and components used for data collection at the study location. The placement of the weir downstream of a natural pool regulates water flow into the monitoring pool. Within the monitoring pool, a sonde is positioned for continuous water quality monitoring, along with a pressure transducer installed in the stream and a second transducer outside the stream to account for atmospheric pressure. The schematic also depicts the discrete total suspended solids (TSS) sampling locations.

Construction Sequence and Rationale

To further refine the study's accuracy, the construction sequence is designed to always begin with the downstream reach and then sequentially construct the upstream reach. This approach is adopted to limit the potential for upstream activities to affect downstream conditions. By starting at the downstream reach, the researchers aim to reduce the risk of confounding variables—such as sediment transport or altered flow dynamics—that could skew the data collected from the downstream sonde. This methodical sequence ensures that any changes observed at the downstream monitoring location can be more confidently attributed to the construction activities under study.

3. Methods

3.1. Site Selection

The selection of study sites for evaluating sediment loads associated with stream restoration activities in Dry versus Wet conditions required careful consideration of multiple factors. The transport and origin of suspended sediment vary significantly within a stream network and across watersheds, influenced by a complex interplay of hydrological, geomorphological, and anthropogenic variables. These variables can be quantified through direct measurements or assessed using established analytical methods and are generally categorized into three primary groups:

1. **Watershed Characteristics** – Includes drainage area, land use, and land cover characteristics that influence sediment supply and transport.
2. **Reach Characteristics –** Encompasses stream order, Maryland stream use classification, channel morphology (e.g., width, depth, area), channel slope, substrate composition (bed and bank material), and riparian vegetation.
3. **Restoration Activities –** Includes the specific design approach, stream closure period, project length, projected construction duration, limits of disturbance, level of restoration effort, pump-around requirements, and the type of restoration structures proposed.

To minimize variability between research sites and enhance the comparability of sediment load measurements, a **site selection evaluation form** (Appendix A) was developed. This form was distributed to various agencies with knowledge of upcoming stream restoration projects, and the responses were used to assist in identifying suitable research sites. The intent of this evaluation process was to systematically reduce extraneous variability and prioritize sites with conditions conducive to controlled comparative analysis.

The site selection form was designed as an initial screening tool to identify candidate sites based on key physical and administrative criteria.

The final selection of study sites was based on a structured ranking system. The site selection process prioritized locations that aligned with project feasibility, research objectives, and administrative considerations.

Selection Criteria

Study sites were assessed using a predefined set of ranking criteria to ensure consistency in data collection and project implementation. The primary selection factors included:

1. **Construction Schedule** – Sites with restoration activities to occur within the research performance period.
2. **Project Length Requirements –** Sites that met the necessary length criteria for evaluation were preferred, while those that did not were considered with lower priority.
3. **Restoration Approach –** Preference was given to projects implementing Natural Channel Design (NCD) principles. Valley restoration techniques and beaver dam analogs (BDA) projects were considered.
4. **Hydrologic Considerations –** Higher priority was assigned to streams with consistent base flow to ensure reliable data collection under both Wet and Dry conditions.
5. **Funding Availability** – Sites with guaranteed funding were prioritized to reduce financial uncertainties and ensure project completion.
6. **Administrative Feasibility –** Willingness of project managers, agency heads, and other stakeholders to participate in additional administrative tasks required for research coordination was considered.

Sites failing to meet key requirements, such as construction scheduling or project length, were deprioritized in the selection process. This ranking system ensured that selected sites met both research and logistical needs while maintaining project feasibility.

A total of 40 project sites were initially identified as candidate locations for the study. Of these, seven met the key study requirements based on factors such as restoration approach, hydrologic considerations, and administrative feasibility. Following further evaluation, the selection was narrowed to three (3) sites that satisfied both the key study criteria and were scheduled for construction within the study's period of performance. These final sites ensure alignment with research objectives while maintaining feasibility for data collection and analysis.

The three selected sites for the study include the Mellen Court Stream Restoration Project in Howard County, Maryland, and two segments of the Minebank Run at Metfield in Baltimore County, Maryland (see Figure 2). The Mellen Court project is owned by Howard County, with KCI serving as the project engineer and SMC, LLC. responsible for construction. The Minebank Run at Metfield sites, designated as Cowpens Lower (Minebank Downstream) and Beeches Lower (Minebank Upstream), are owned by Baltimore County. McCormick Taylor was the engineering firm designing both projects, with Meadville Land Service conducting construction activities. These sites were selected based on their alignment with study criteria, scheduled construction within the study period, and their potential to provide comparative data on sediment loads associated with in-stream restoration activities conducted under Dry and Wet conditions. Table 1 shows a comparison of watershed and reach conditions for each site and for the preferred characteristics identified in the Quality Assurance Project Plan (QAPP).

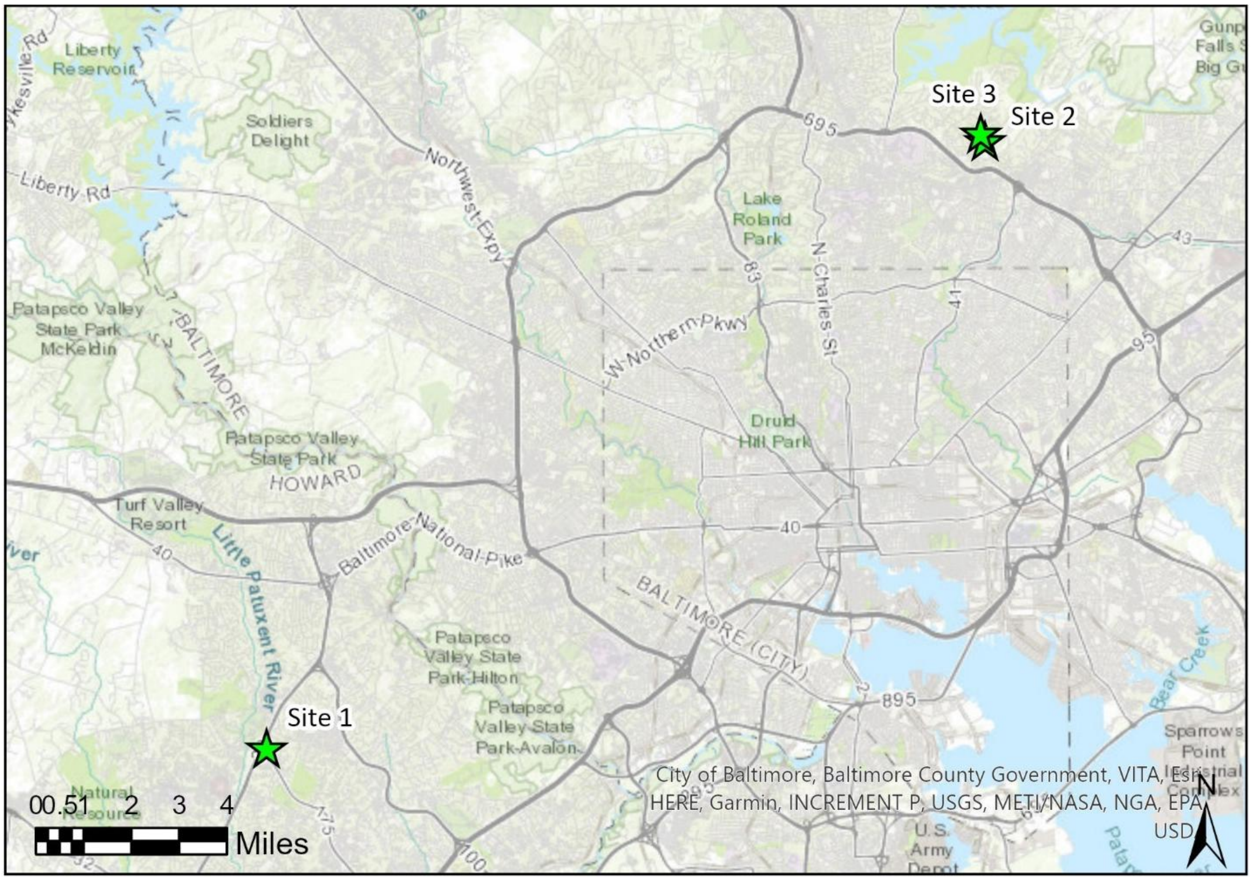

Figure 2: Map of site locations

Study Research Site	Study Site Name	Project Length (ft)	Study Reach Length (ft)	Channel Width (ft)	DA (Mi^2)	Slope	Stream Order	Pump Size	# Instream Structures	Design Approach	Stream Bed Material
Site 1	Mellen Court	3022	500 (Wet = 280, Dry = 220)	14.00	0.8	1.1%	3	4"	**DRY**= 3 riffle grade control/ 5 stone toe protection/3 toe boulder/3 coir fiber roll bank treatment/1 embedded log **WET**= 2 riffle grade control/4 stone toe/3 woody toe/ 1 toe boulder/2 coir fiber roll bank treatment	NCD Priority 2	Gravel Cobble
Site 2	Minebank Run At Metfield-Cowpens Lower (Minebank Downstream)	1920	450 (Wet = 265, Dry = 185)	20.20	0.53	1.5%	2	4"	**DRY**= 3 riffle grade control/ 1 cascade structure/ 1 log cascade structure/1 toe boulder protection **WET** = 2 riffle grade control/2 log cascade/2 toe boulder protection/ 1pool enhancement	NCD Priority 2	Gravel Cobble
Site 3	Minebank Run At Metfield - Beeches Lower (Minebank Upstream)	1020	550 (Wet = 130, Dry = 420)	9.00	0.13	3.99%	1	4"	**DRY**= 5 cascade structure/2 toe boulder/ 1 wood toe/ 1 pool enhancement **WET**= 4 cascade structure/ 2 log cascades/ 1 wood toe/ 1 log toe stabilization	NCD Priority 2	Gravel Cobble
QAPP	3 Sites	1000	500	N/A	N/A	N/A	2 or 3	6"	Must have similar structures	Must use similar design approach	Must have similar bed material

Table 1: Comparison of the characteristics of each site

3.2. Data Collection

The collection of water level, velocity, precipitation, turbidity, TSS, and construction activity followed the study design at each site. The monitoring location, site configuration, and measurements are shown in Figures 3 and 4 and Tables 2 and 3 below.

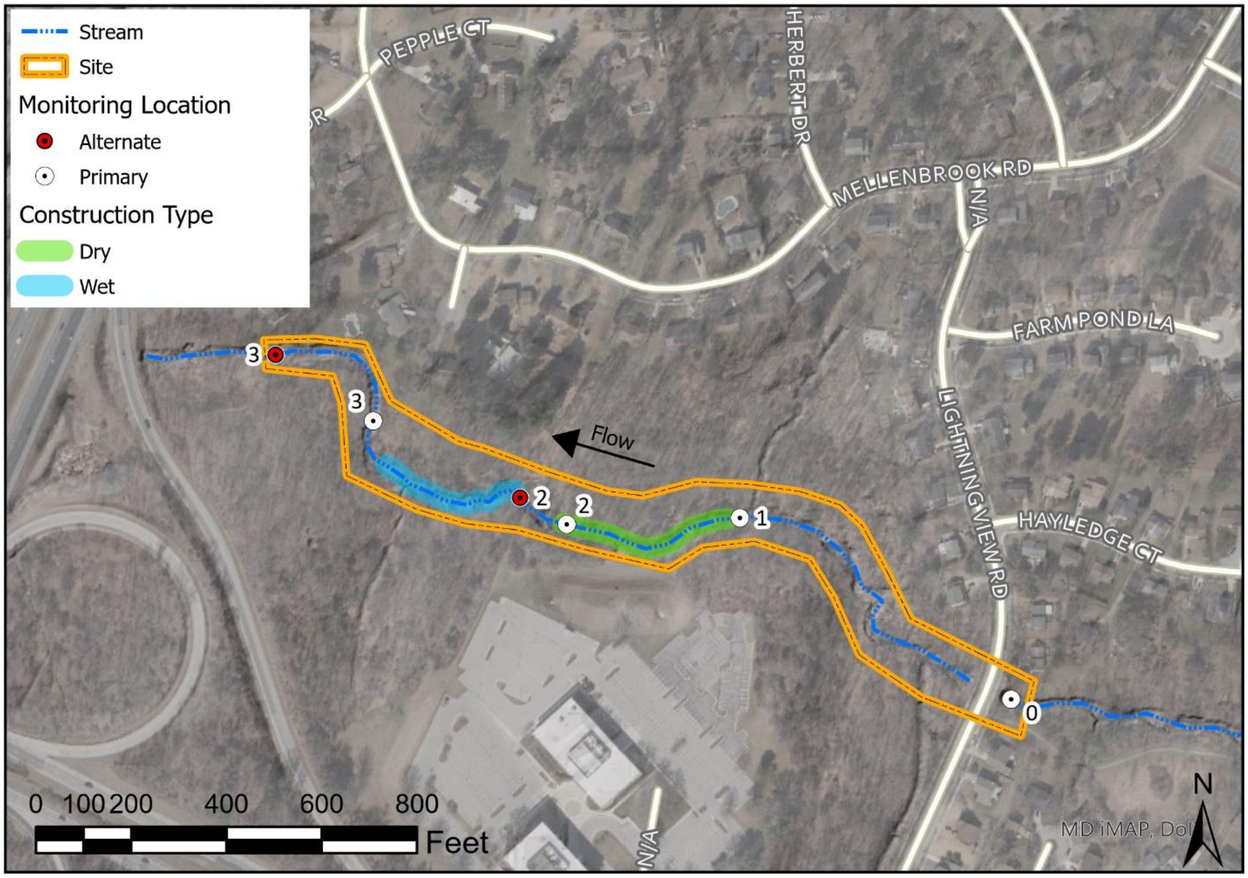

Figure 3: Site 1, Mellen Court, depicting stream reach configuration and monitoring locations

Table 2: Monitoring location key for Site 1 (Figure 3) identifying monitoring equipment (measurement) at each location

Location	Purpose	Equipment (Measurement)
0	Baseline	Sonde (turbidity)
1	Baseline	Sonde (turbidity)
2	Construction	Sonde (turbidity), Pressure transducer (flow)
3	Construction	Sonde (turbidity), Automatic sampler (TSS), Pressure transducer (flow)

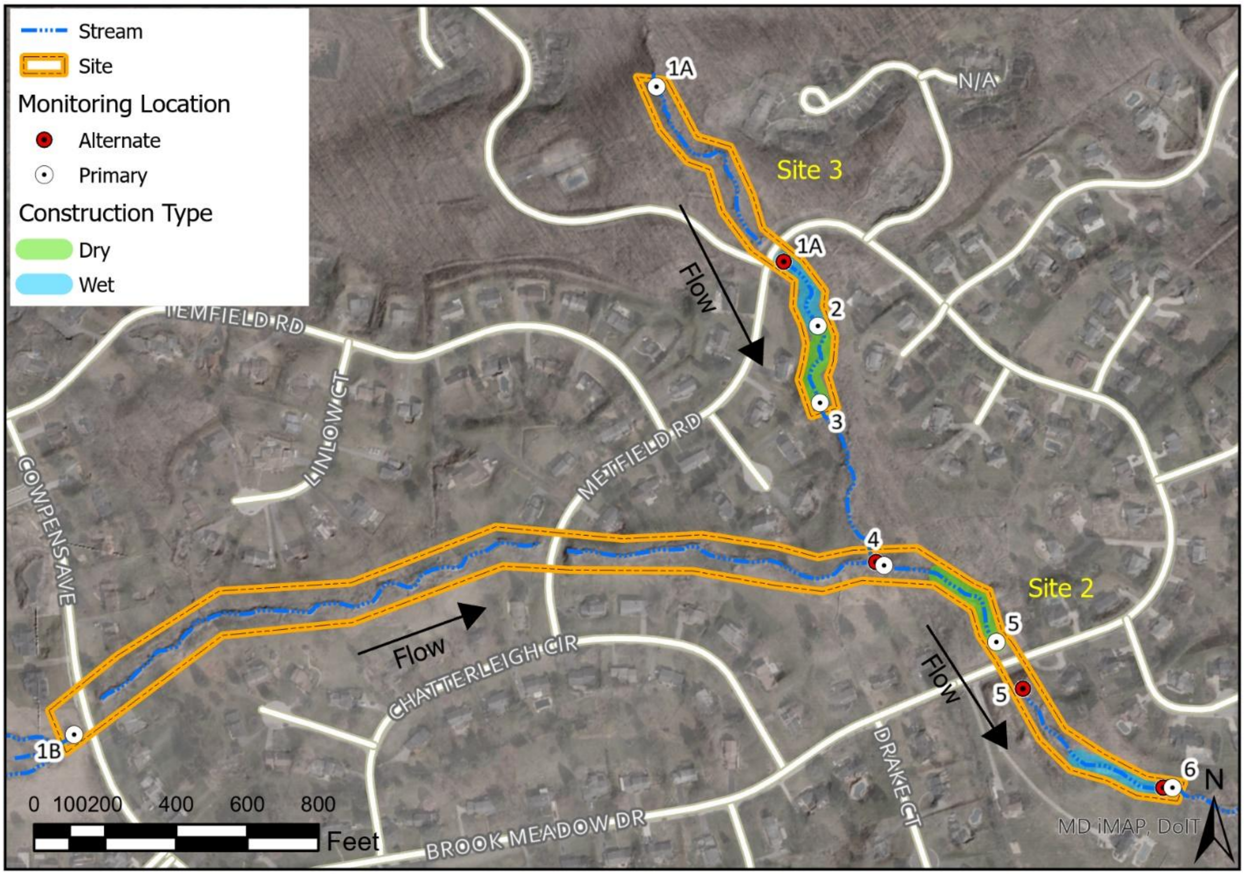

Figure 4: Site 2 and 3, Minebank, depicting stream reach configuration and monitoring locations

Table 3: Monitoring location key for Sites 2 and 3 (Figure 4) identifying monitoring equipment (measurement) at each location

Location	Purpose	Equipment (Measurement)
1A	Baseline	Sonde (turbidity), grab sample (TSS)
1B	Baseline	Sonde (turbidity)
2	Construction	Sonde (turbidity)
3	Construction	Sonde (turbidity), pressure transducer (flow), grab sample (TSS)
4	Baseline	Sonde (turbidity)
5	Construction	Sonde (turbidity), pressure transducer (flow), automatic sampler (TSS)
6	Construction	Sonde (turbidity), pressure transducer (flow), automatic sampler (TSS)

Below is a summary of the data collected at each site and the dates on which the data was collected for.

Table 4: Summary of monitoring data collection at each site

	Site 1	**Site 2**	**Site 3**
Turbidity (collected every 5 minutes)	7/27/22-2/28/24	9/1/23-12/9/24	12/1/23-1/31/24; 6/11/24- 12/9/24
Wet construction Monitoring Logs	07/31/23-08/03/23, 08/07/23-08/08/23 (6-days)	11/13/23-11/16/23, 11/20/23-11/22/23, 11/27/23-11/28/23 (9-days)	6/26/2024-6/27/24, 7/1/24-7/3/24, 7/8/2024 (6-days)
Dry construction Monitoring Logs	08/22/23-8/24/23, 8/28/23-08/30/23 (6-days)	12/26/2023-12/27/23, 1/2/24-1/4/24, 1/8/24-1/11/24, 1/15/24 (10-days)	6/17/24-6/20/24, 6/24/24-6/25/24 (6-days)
TSS Samples Collected	7/27/22, 8/14/22, 8/15/22, 8/3/23, 8/23/23, 8/24/23, 9/14/23, 10/11/23, 12/19/23, 1/31/24	9/7/23, 11/13/23, 11/15/23, 11/15/23, 11/27/23, 11/30/23, 1/4/24, 1/9/24, 7/22/24, 9/18/24, 9/25/24, 10/1/24, 12/11/24	1/31/24, 6/17/24, 6/26/24, 7/1/24, 6/26/24, 7/22/24, 9/18/24, 9/25/24, 10/1/24
Stream and Rain Gage	7/27/22-2/28/24	9/01/23-9/4/24	12/08/23-9/4/24
Velocity Measurements	2022: 9/26, 10/03, 11/30, 12/22 2023: 2/7, 9/26, 12/18	2023: 11/23, 12/08, 12/18 2024: 4/3	2023: 12/08, 12/18 2024: 4/3, 8/9

<u>Turbidity</u>

All sondes were installed in purpose-built monitoring pools. The monitoring pools were constructed by placing a weir downstream of a natural pool, using concrete bags to regulate water flow. The depth of each pool was carefully calibrated to be sufficient for accurate sonde data collection while remaining shallow enough to prevent the pool from functioning as a sump that could accumulate sediment and degrade data quality. Optimal monitoring conditions were achieved by promoting water mixing within the pool, ensuring adequate circulation and alignment with natural stream flow to maintain consistent and reliable data. The meter was placed at the center of the water column during baseflow. Maintenance of the pools involved periodic sediment removal following significant rainfall events. The date and time of any maintenance activities requiring entry into the pool were documented to flag the corresponding data for quality control purposes. Additionally, maintenance included the repair of the weir structure when damaged by significant rain events.

Nephelometric Turbidity Units (NTU) were monitored continuously at all three points throughout the study design period. Data was collected on turbidity using automated loggers (optical turbidity sensor) set to 5-minute intervals. The manufacturer performs a 6-point factory calibration on every sensor to ensure the sensor is linear across the full 0-4,000 NTU range. All sensors were calibrated by the team annually to standard manufacturer solution of 10 NTU and 2000 NTU. The raw turbidity data was downloaded and aggregated into average hourly turbidity readings both to establish TSS-Turbidity relationships and to characterize non-storm turbidity and TSS concentrations. Turbidity was aggregated into 15-minute intervals to characterize sediment loading from storm events.

Every month, the sondes were maintained and the data was downloaded. During the pre-construction phase of Mellen Court, the sondes were visited every 1-3 months, as construction was delayed. During construction monitoring, the sondes were visually assessed every day. They were typically not pulled out of the water, unless there was a visible problem. Removing the sonde invalidates the data before and after since the turbidity is impacted by monitoring interference rather than construction.

Below are the criteria which caused turbidity data to be rejected or changed. A record was kept for every data point that was either rejected or altered.

- The turbidity of the stream can rise for various reasons, but it should always return to baseline if the monitoring set up is functioning correctly. If the turbidity stays elevated for more than a few hours, it is likely the increase is due to environmental factors. The most likely reasons are algae growth on the sonde or water has entered the housing of the sonde.
- When staff maintained the sonde, any visual signs of clogging was noted in the monitoring log and that data was reviewed and replaced with "N/A". The sensor was checked and wiped during each visit where data was downloaded. Any unexplained elevated turbidity that only decreased after staff maintains the sonde was replaced with "N/A".
- If the team walked into the stream within the pool or upstream of the sonde or moved the sonde, this was noted. Any changes in turbidity due to monitoring was replaced with "N/A"
- During large storms, there were various errors that caused the data to be rejected. This includes, sonde dislocation, weir breaching, sediment and debris filling the sonde housing, and sedimentation that buried the sonde. Any of these reasons will cause the data to be inaccurate. During these scenarios, the turbidity data was replaced with "N/A"
- The sonde's sensor range is from 0-4,000 NTU. If turbidity was above 4000 NTU, replaced with 4000 NTU.
- There were instances that the sonde was removed from the stream, but the logger was not turned off. This data still appears in the raw data. All instances of this are noted in the monitoring log and replaced with "N/A".
- A wiper mechanism is integrated within the housing of the sonde, programmed to pass over the turbidity sensor at regular intervals to reduce debris accumulation and minimize fouling. In the collected data, periodic anomalies occurring at consistent intervals suggest that the wiper may be influencing turbidity measurements. These anomalies, characterized by abrupt increases in recorded values at exact hourly intervals, were identified as potential wiper interference. A spike was operationally defined as a data point exhibiting a value at least twice that of the preceding and subsequent measurements. When multiple such spikes (>2) were detected at these regular intervals, they were classified as wiper-induced artifacts and replaced using linear interpolation based on adjacent data points.

The remaining turbidity data was processed to create the final datasets. Each turbidity point was tagged day (8am-8pm) or night (8pm-8am) and either in the Wet or the Dry construction. Since there was no physical monitoring during the nighttime, it was difficult to determine the cause of any observed changes in turbidity during these periods. If nighttime data was included, it also dampens the impact of construction. While not all monitoring data started at 8am or ended at 8pm, there was a general trend during those times that turbidity increased or decreased, respectively. Both 24-hour data (8am-8am) and day and night data were analyzed. There were instances when it started raining or the sonde was removed, which lead to monitoring or construction to end early. These days were not used when comparing daily loads.

Total Suspended Solids

Throughout the project, total suspended solids (TSS) samples were collected during monitoring. Each site had at least 5 samples collected in Wet weather and 5 samples collected in dry weather. Some of the dry weather samples were taken during construction to ensure a range of TSS samples. Samples were collected by an automated sampler or taken as a grab sample when the automated sampler was not feasible. For each TSS sample, there was a sonde within 20 feet of the TSS sample to be used to correlate TSS and turbidity data. Each site had a different correlation curve between turbidity and TSS. The TSS sample was sent to Martel Labs for analysis, using Standard Method 2540 D-97.

TSS Data was collected at Location 3 only (see Figure 1), and for a minimum of 10 samples at each site. Since TSS sampling is much more expensive and time-consuming to collect than turbidity, the goal of TSS sampling was to develop a relationship between turbidity and TSS at each site. Studies have found that using turbidity values is a reliable proxy for TSS (Lewis et al., 2002; Ramussen et al., 2009), but it is important that the observed turbidity values (i.e., the values used to estimate exported sediment) are within the calibration range. For this reason, TSS samples were collected to represent a range of turbidities, including some dry weather events during construction, which are anticipated to have the highest turbidity and TSS concentrations. The methods described in Rasmussen et al. (2009) were used to develop a relationship between turbidity and TSS using the continuous turbidity data from Location 3.

Stage (Flow depth)

Stream stage was collected downstream of construction activities throughout the study period continuously at 5-minute intervals. At each site, a pressure transducer was installed in the stream and a second transducer outside the stream to account for atmospheric pressure allowing the derivation of water levels within the in-stream well. The in-stream pressure transducer was placed in a PVC well and located in a free-flowing stream feature such as a riffle.

Velocity

The flow measurements were taken at the designated cross sections and follow USGS Guidance[1]. Flow measurements were only taken when conditions permitted safe operating and collection procedures. Surveyed cross- sections at the monitoring location, along with velocity measurements obtained using a pygmy current meter, were conducted during at least 4 measurements spanning a range of flow events. The data was used to develop a stage-discharge curve for each site. This curve was then used to generate a continuous record of flow throughout the study period at each site.

Precipitation

An ONSET tipping bucket rainfall gage near each site collected precipitation data throughout the project period. Precipitation data was used to identify the effects of storm events within the flow or

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[1] http://water.usgs.gov/edu/measureflow.html

turbidity data. Additionally, if anomalies (e.g., spikes in the data) were identified when no rainfall could be confirmed, and other locally observed conditions were not responsible, the data were considered for exclusion.

Stream Stage Measurements

Stream stage was continuously recorded at the downstream ends of each stream reach throughout the study period at 5-minute intervals. At each site, a pressure transducer was installed in the stream, and a second transducer was placed outside the stream to account for atmospheric pressure, allowing for the derivation of water levels within the in-stream well.

Gage malfunctions during the monitoring period were not uncommon; however, the use of multiple gages based on the study design, and better performance during the period of construction resulted in continuous water level data. During construction of Site 2, restoration construction resulted in flow going partially subsurface, presumably due to the size of aggregate being placed in the stream to construct the bed, which necessitated the resetting of the instream pressure transducer in a location downstream where surface flow was evident. Each time the pressure transducer was moved to ensure that flow was captured, a new surveyed cross section and velocity measurements were necessary to relate water level to discharge.

The initial study design included two in-stream pressure transducers, one upstream of both reaches of construction and one downstream of both reaches. This setup was revised to prioritize the downstream location for two reasons: one, the flow from upstream to downstream of the two construction reaches were equal; and two, finding free-flowing conditions in a degraded channel was not always possible such that calculating flow would not have been accurate. For sites 1 and 2, water level was measured at Locations 2 and 3, immediately downstream of each construction reach. The flow from these two points provided monitoring redundancy.

Water levels were reviewed to identify anomalies, which included elevated values that could not be associated with storm events or construction practices, changes to water level due to data collection, changes to water level associated with replacement or movement of monitoring locations, or possible suspension of the pressure transducer due to well damage during storm events. Since site observations and precipitation data could confirm or conflict with water level data, anomalies that could not be explained were removed while conditions that were associated with observed changes to monitoring setup could be adjusted by adding or subtracting the discrepancy. This quality control process prioritized baseflow continuity.

Site Surveys

To ensure accurate characterization of site conditions and assess sediment transport dynamics, a comprehensive field survey was conducted at each selected site prior to the commencement of construction activities. The primary objective of the site survey was to document baseline geomorphic, hydrologic, and riparian conditions, allowing for meaningful comparisons of sediment load variability across different restoration approaches.

Field assessments followed standardized protocols and methodologies to ensure consistency across sites. Data collection methods were based on well-established procedures, including those outlined by the U.S. Fish and Wildlife Service, Chesapeake Bay Field Office for developing Maryland regional curves (McCandless, 2002), the Bank Assessment for Non-point Source Consequences of Sediment (BANCS) method (Rosgen, 2006) for evaluating streambank erodibility, and the Final Draft Function-Based Rapid Stream Assessment Methodology (Starr et al., 2015) for characterizing riparian vegetation conditions. Additionally, streambank bulk density samples were collected using the procedures specified in Appendix D of the Consensus Recommendations for Improving the Application of the Prevented Sediment Protocol for Urban Stream Restoration Projects Built for Pollutant Removal Credit (Altland et al., 2019).

The site survey included a range of field measurements designed to document channel morphology, substrate composition, riparian vegetation, and bank stability. The following data were collected:

- Channel Dimension Measurements – Width, depth, and cross-sectional area were measured at 3 designated riffle locations to establish baseline geomorphic conditions.
- Channel Slope Measurement – The overall energy gradient of the stream was characterized to assess sediment transport potential.
- Streambed Pebble Counts and Bank Material Sampling – Substrate composition and sediment availability were evaluated using standard pebble count methodologies at active riffle locations.
- Riparian Vegetation Assessment – Visual observations of riparian vegetation and buffer width, documenting the extent and condition of riparian vegetation.
- Bank Stability and Erosion Potential Assessments – Conducted using the Rapid Bank Erosion Hazard Index (BEHI) Assessment and Bank Height Ratio Analysis, supplemented by the BANCS method for assessing streambank erodibility.
- Streambank Bulk Density Sample – A single bulk density sample was collected per site to assess sediment availability and potential for bank erosion.

These comprehensive field assessments provided the necessary baseline data to evaluate sediment load variations associated with different stream restoration techniques. By employing standardized methodologies, the survey ensured repeatability and comparability across all research sites, supporting robust analysis of the influence of watershed, reach, and restoration characteristics on sediment transport and turbidity.

Construction Monitoring

Construction monitoring commenced at the initiation of in-stream activities, which included either the mobilization of construction equipment within the stream channel or the activation of pumps for dewatering operations. Monitoring continued throughout the duration of in-stream work and concluded at the end of each construction day, when all equipment was removed from the stream and dewatering pumps were deactivated.

Every construction activity occurring within the stream channel or along its banks was systematically documented. The activity that typically occurred first on a given day was activation of dewatering and/or clean water pumps and concluded with the final in-stream construction activity of the day, which most commonly involved shutting down the pumps. Of note, construction at Site 2 occurred during winter months and on several occasions the construction contract allowed pumps to run continuously to the next day to prevent the system from freezing. Additionally, monitoring records extended to any monitoring project-related activities necessitating direct entry into the stream, such as turbidity meter inspections or weir adjustments.

To ensure consistency and standardization in data collection, a structured **daily monitoring log form** was developed (Appendix B). This form was designed to comprehensively capture all relevant construction and monitoring activities and was divided into three primary sections:

1. **Basic Site Information –** This section documented essential details such as the date, name of the data recorder, total duration of construction activities for the day, total length of the stream segment affected, prevailing weather conditions, 24-hour rainfall data, a summary of observed activities, and any additional pertinent notes.
2. **Construction Activity Documentation –** Each in-stream construction activity was described in detail, including the specific task performed (e.g., placement of stone for riffle construction), its location as referenced by stationing on the approved design plan set, and the recorded start and end times of that activity.
3. **Photo Documentation –** Photographs were systematically taken to provide a visual record of construction action, with each image corresponding to specific recorded activities to enhance transparency and accountability in monitoring.

Using this standardized approach to construction monitoring, all in-stream activities were consistently recorded in a manner that facilitated accurate tracking of construction progress both as a function of time and location. The structured documentation process ensured that all project monitoring requirements were met ensuring that the comprehensive dataset for water quality could be directly tied to an instream activity.

3.3. Data Analysis

<u>Stage & Discharge Relationship</u>

Stage-discharge relationships rely on measured velocity with a current meter at points across a channel cross section at a range of water surface stages (Figure 5 below). These points are then plotted, and a relationship is developed between discharge and stage. The trend line that best describes the relationship is dependent on the shape of the channel and other hydraulic conditions.

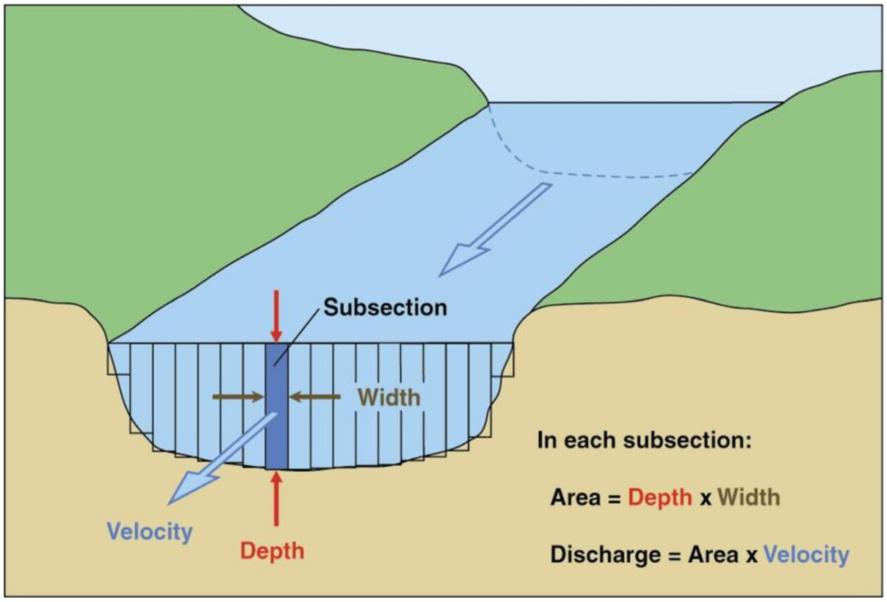
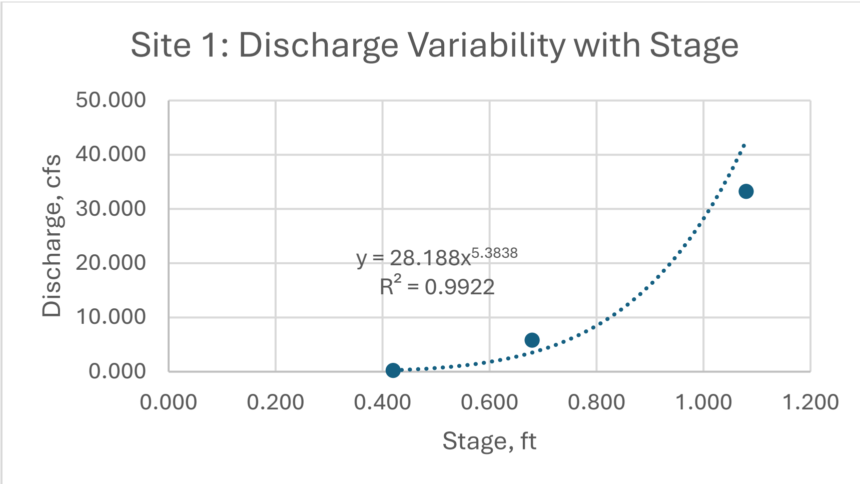


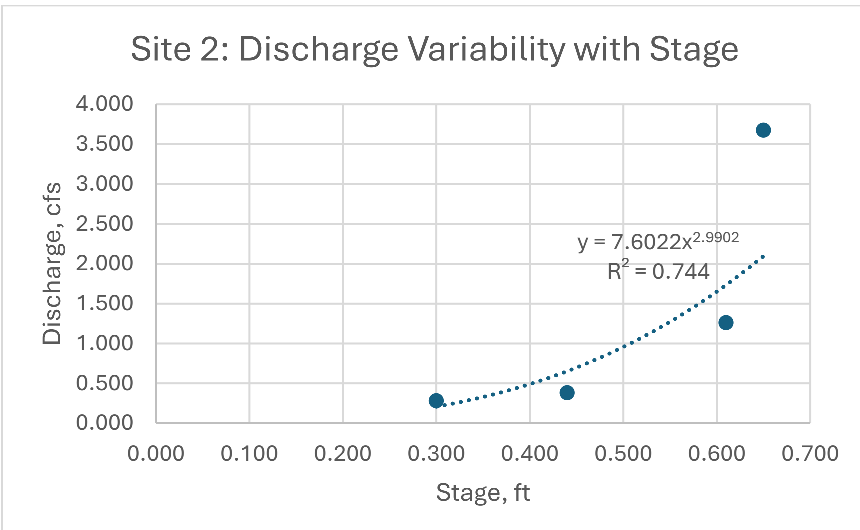
Figure 5: Diagram of channel cross section with subsections where measured depth and velocity are used to calculate the discharge of each subsection (https://www.usgs.gov/special-topics/water-science-school/science/how-streamflow-measured)

To accommodate instream construction, the pressure transducer and associated cross section needed to move during the monitoring duration for Site 2 as discussed in the previous section. Since the changes to location affect the relationship between stage and discharge, a method of relating discharge at one location to another became necessary. Since it is assumed that discharge remains constant in the channel from one location to another (i.e., continuity), a coefficient was developed to relate one location to another so that only one stage-discharge relationship was used for each site.

The coefficient is calculated by using manning's equation to solve for discharge at 0.1' increments and then averaging the ratio between the flowrate with the known stage-discharge relationship to the unknown stage-discharge relationship. The equation for the unknown discharge location takes the form of $\mathrm{Q = CaS^b}$ (with Q representing flowrate, C representing the coefficient, S representing stage, and a and b representing variables describing the known discharge location power-trend relationship).

The resulting stage-discharge relationships representing flow through both reaches of construction are shown in Figure 6. Site 2 has the lower R^2 value of 0.74, which may be due to a portion of the flow going subsurface.





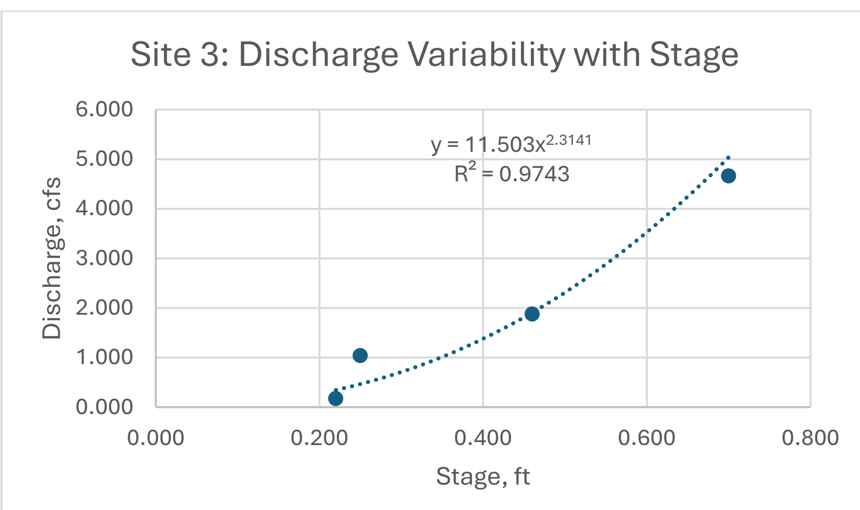


Figure 6: Stage-discharge curves for Sites 1 through 3.

Turbidity

Below are the average hourly turbidity data during the construction monitoring days at each site, separated by Wet construction methods and Dry construction methods. The data shown below are from the dates of construction monitoring from 12:00AM to 11:59PM. Please note that the y-axis range varies in the different figures.

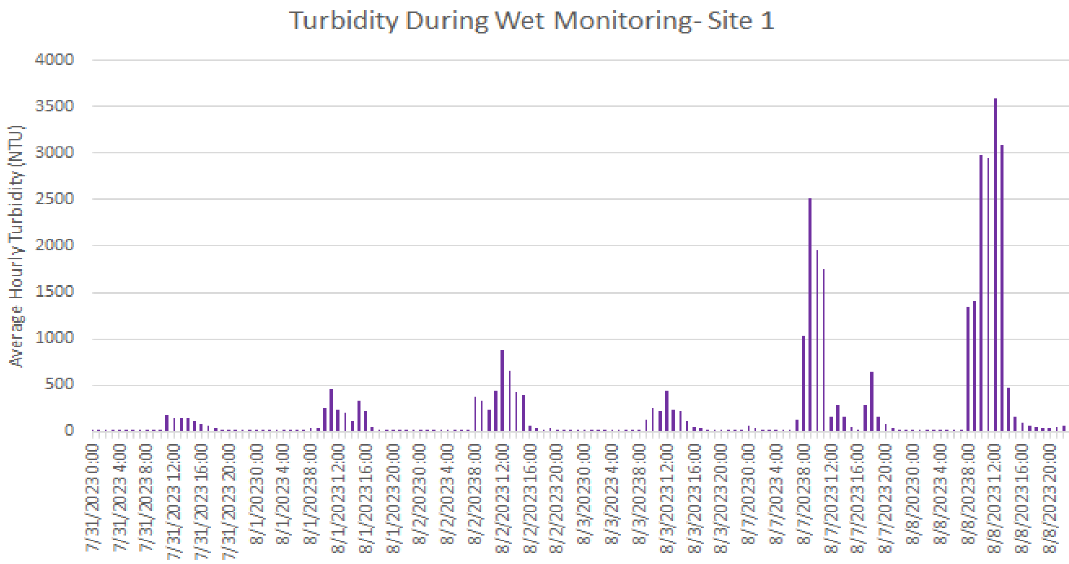


Figure 7: Wet construction Turbidity Data, Site 1, Location 3. This graph shows the average hourly turbidity at the downstream location during the Wet construction monitoring section. The x-axis shows the date and time of construction monitoring.

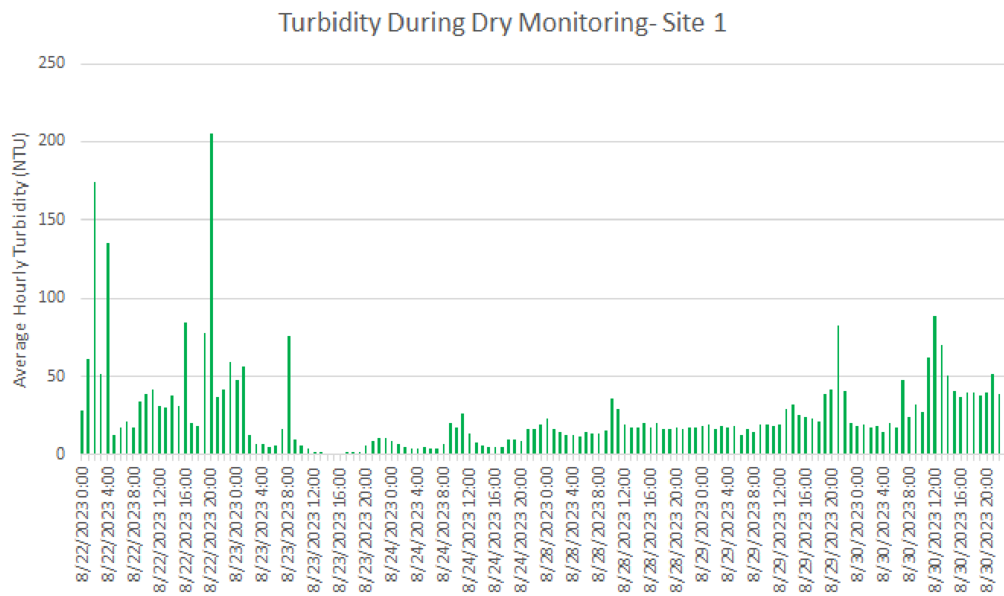


Figure 8: Dry construction Turbidity Data, Site 1, Location 2. This graph shows the average hourly turbidity at the downstream location during the Dry construction monitoring section. The x-axis shows the date and time of construction monitoring.

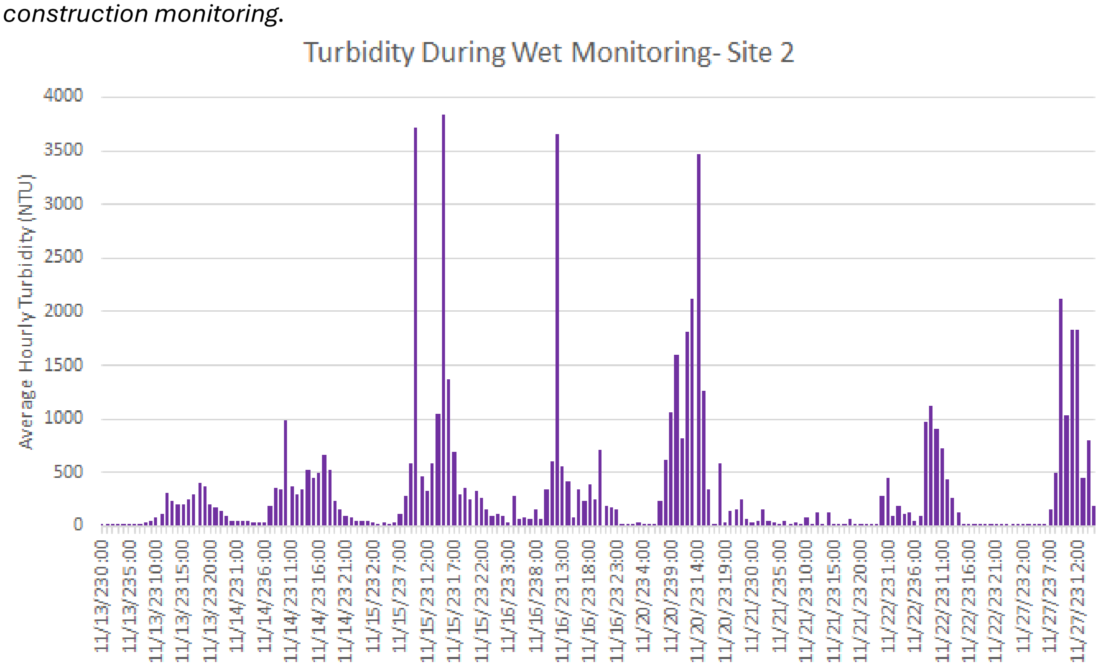


Figure 9: Wet construction Turbidity Data, Site 2, Location 6. This graph shows the average hourly turbidity at the downstream location during the Wet construction monitoring section. The x-axis shows the date and time of construction monitoring.

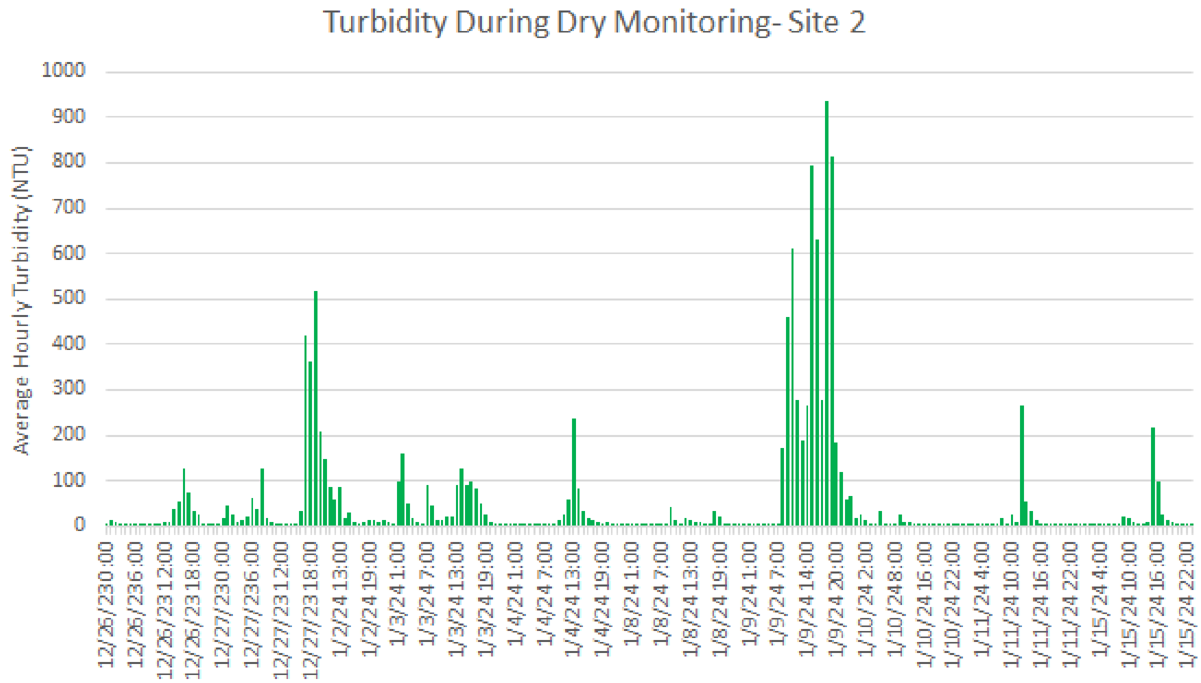


Figure 10: Dry construction Turbidity Data, Site 2, Location 5. This graph shows the average hourly turbidity at the downstream location during the Dry construction monitoring section. The x-axis shows the date and time of construction monitoring.

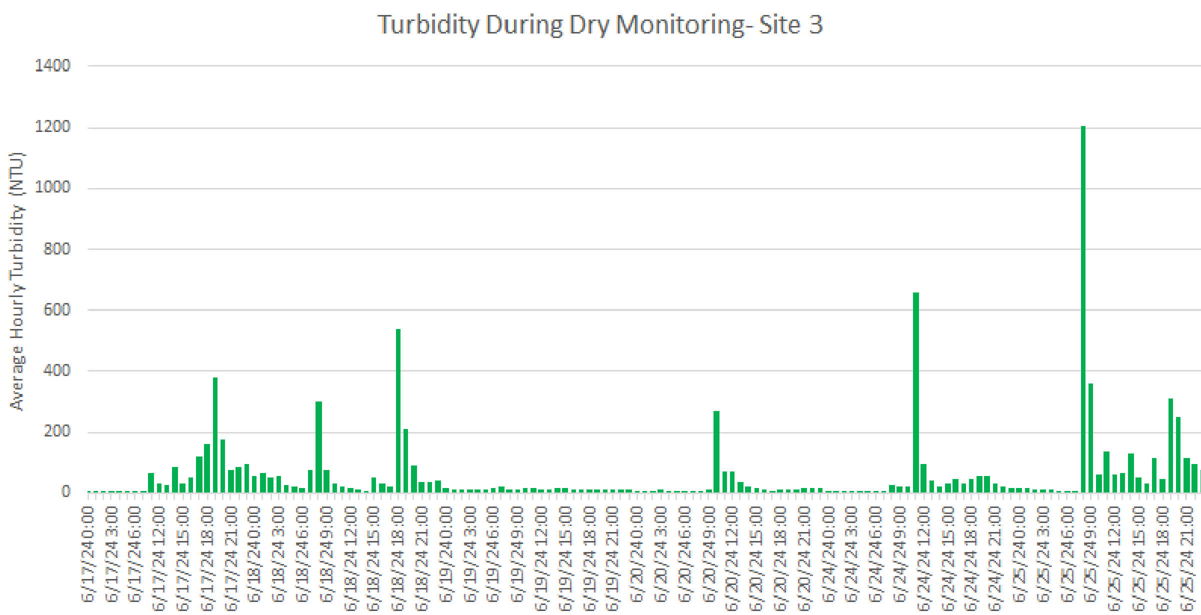


Figure 11: Dry construction Turbidity Data, Site 3, Location 3. This graph shows the average hourly turbidity at the downstream location during the Dry construction monitoring section. The x-axis shows the date and time of construction monitoring.

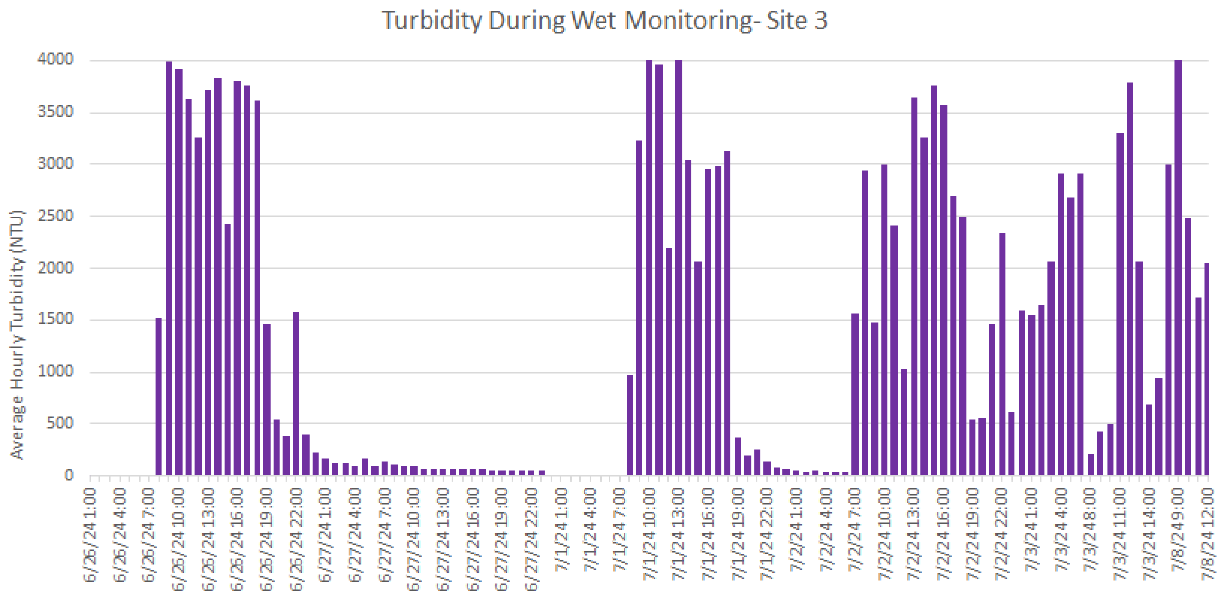


Figure 12: Wet construction Turbidity Data, Site 3, Location 2. This graph shows the average hourly turbidity at the downstream location during the Wet construction monitoring section. The x-axis shows the date and time of construction monitoring.

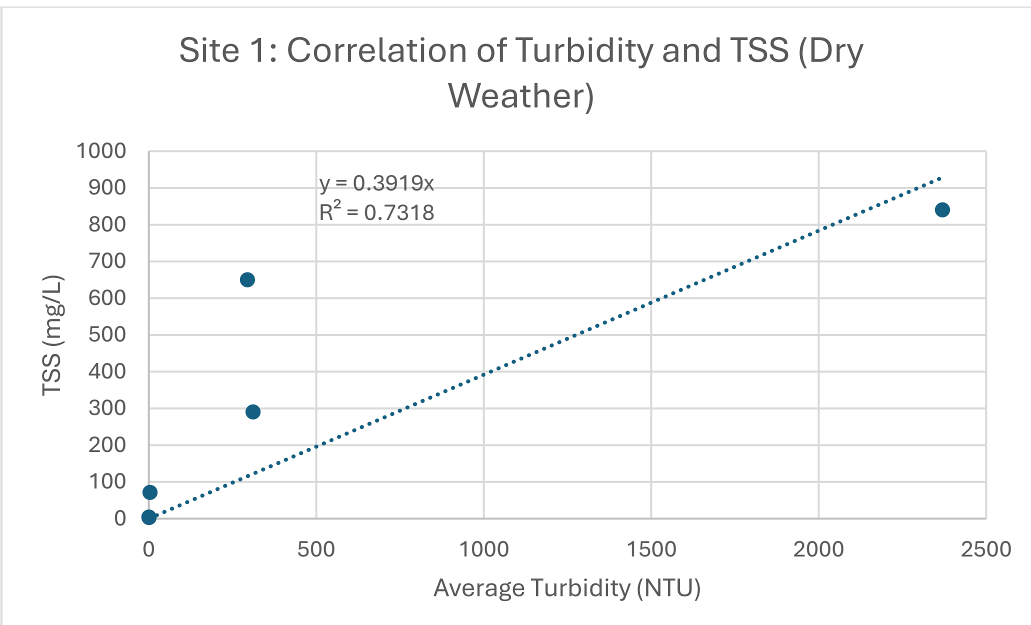
<u>Turbidity and TSS Relationship</u>

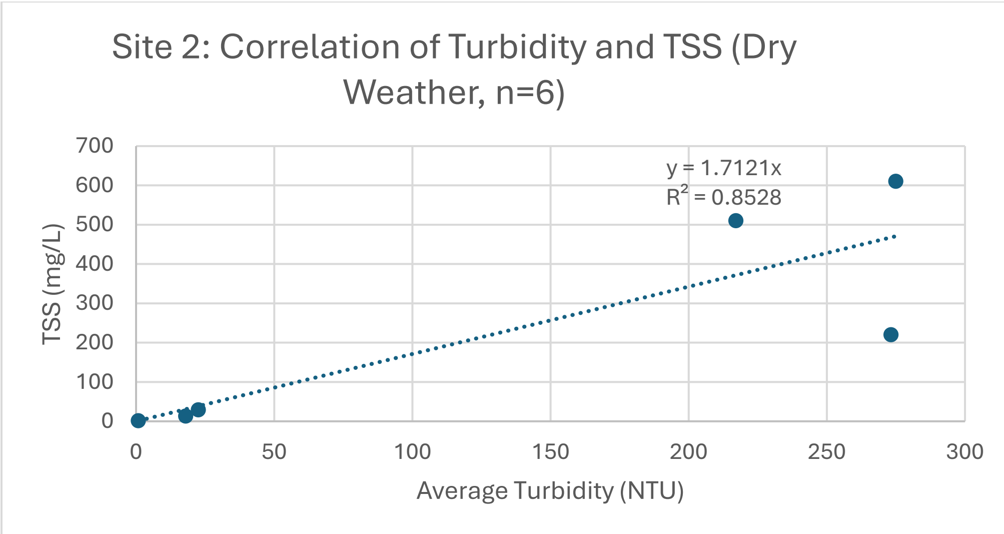
The corresponding turbidity readings 15 minutes before and 15 minutes after the TSS sampling were used to create an average turbidity. The Average Turbidity (NTU) and the TSS results (mg/L) were used to create a correlation curve at each site. Only the dry weather data was used to correlate turbidity and sediment since construction only occurred during dry weather. While we aimed to collect samples in a range of turbidities and TSS concentrations, that did not occur for Site 2. The samples during high turbidity had to be removed (see below for explanation), leaving the highest turbidity used for the correlation curve at 275 NTU. Construction monitoring ended before another TSS sample could be collected; therefore, the correlation curve did not have a higher turbidity represented. It is also important to note that only 4-6 data points were used to correlate the TSS and turbidity data due to budget constraints. We understand the uncertainty related to the limited data used to create the correlation curve and as a result, confidence intervals were estimated using a bootstrapping technique and simulations to estimate the range of possible outcomes for annual sediment loads (see Appendix E: Statistical Analysis Overview for further explanation of methods).

Below are the situations in which the TSS data collected was not used for the correlation.

- 1D3: Project staff came into the stream from the upstream during construction. While project staff waited for 30 minutes before collecting a TSS sample, it appeared that the turbidity was still raised due to interference from project staff.
- 2D5, 2D4, 3D6: The TSS or turbidity was outside the range of the sonde or TSS testing

- 2D3: After this sample was collected, it was found that there was a lot of sediment at bottom of the monitoring pool. There was a chance this sample took some of the un-suspended sediment, therefore it was removed.
- 3D5, 2W5: Identified as outliers from rest of TSS and turbidity datasets and therefore removed.
- 2W1: This rain sample was collected when construction was still occurring upstream. It likely was impacted by construction sediment, therefore was not representative of turbidity/sediment correlation during a rain event.
- 2W8: Sonde lost power, therefore cannot make correlation
- 2W6: During sampling, a hole was found in the automated sampler tubing. Another grab sample was taken and that data point was used in the correlation curve.





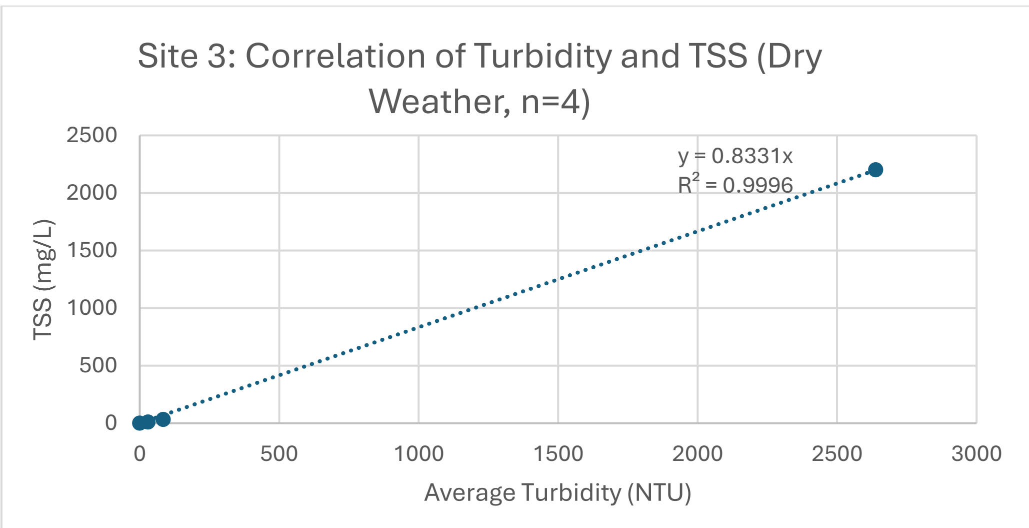


Figure 13: Turbidity and TSS correlation for dry weather conditions for each site

<u>Sediment Load</u>

The turbidity data was converted to TSS using the established turbidity and TSS correlation curves for each site in dry weather conditions as shown in Figure 13. The TSS data was multiplied by the flow data to derive a mass rate. Each mass rate was summed across its corresponding time step to calculate the corresponding sediment load.

This data is used for hypothesis 2 and 3 to calculate the total sediment load during Dry construction and during Wet construction. It is important that no rain data is included in hypothesis 2 analysis, as that is not representative of construction sediment. If there was an increase in flow when construction was not happening, this is likely due to rain or malfunctioning of the pressure transducer. During construction, the upstream data that is outside of the construction site should not change. If this was found, the construction log was checked to see if construction was occurring or if there was note of rain.

All of the data was converted to EDT.

4. Results & Conclusion

4.1. Hypothesis 1: Turbidity

Hypothesis 1A: The observed average Turbidity (Average NTU) will be higher during the Wet construction Period

The data analyzed for hypotheses 1 and 1A were confined to the construction period and include hourly turbidity data measured downstream of each construction reach. Data incorporated into this analysis were confined to the time 8AM, which approximated the time where construction activity resulted in an increase in downstream turbidity, until 8AM the following day. Because the data was skewed it was log transformed for analysis (See Appendix E for explanation).

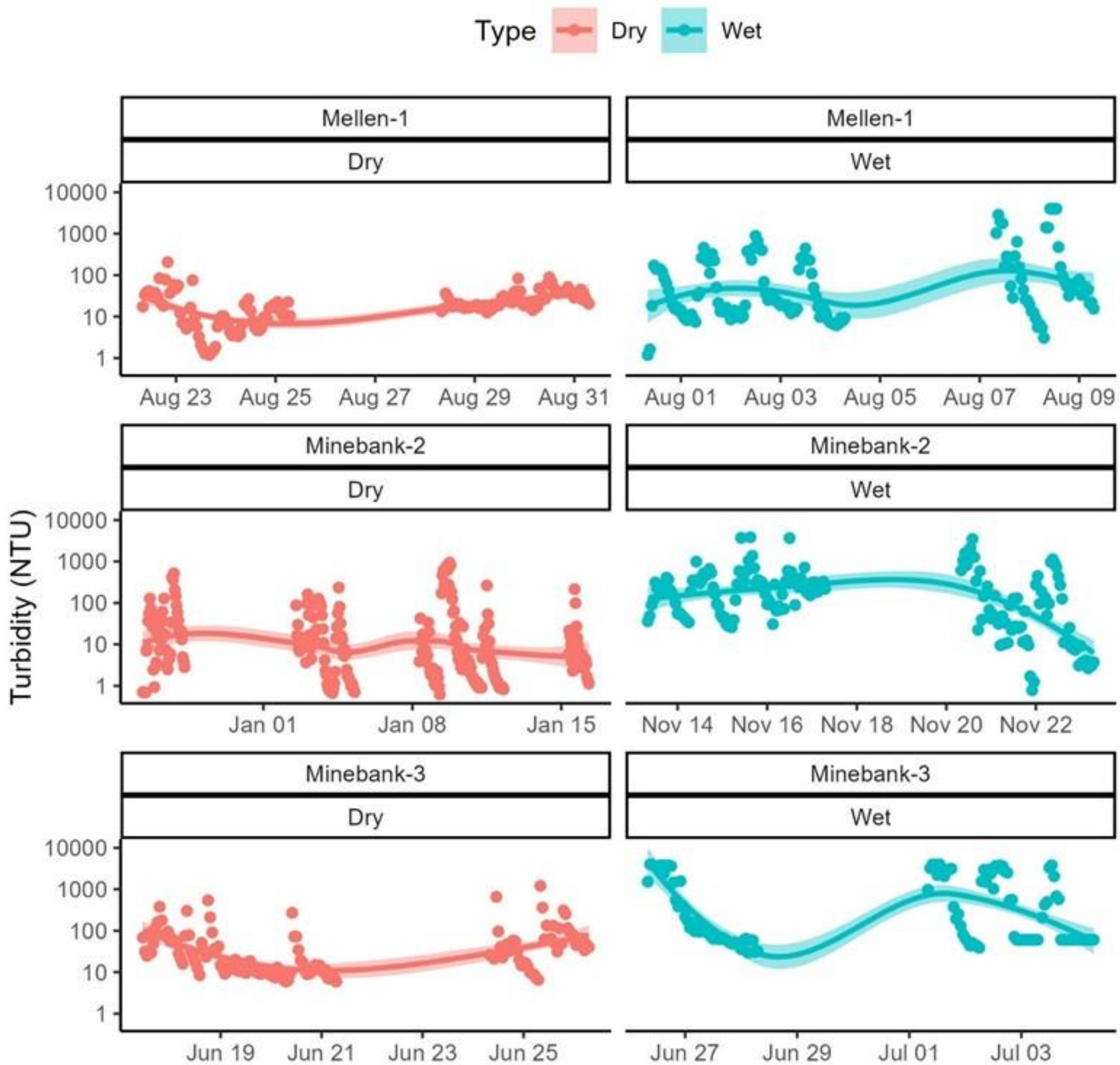


Figure 14: Observed Turbidity at Each Site

As an initial exploratory measure, we compared the log-transformed data between the Dry and Wet Construction methods using three groupings: 1) Across all sites; 2) Between Sites and 3) Between "Day" and "Night." Day and Night values represent the time periods from 8AM and 8PM (Day) and between 8 PM and 8AM the following Day (Night)[2]. Appendix E describes how these time breaks were selected. The results of these comparisons suggest that turbidity for Wet construction is

[2] Initially, the project team had considered using upstream turbidity as a predictor of downstream turbidity to account for daily variability but instances of missing upstream data, combined with days where elevated upstream turbidity was explained by other factors that did not translate to downstream turbidity such as local disturbances, made this predictor unusable for this analysis.

higher than turbidity for Dry construction, and that both the site and time of day contribute to the variability of observed values. See Appendix E for additional statistical analysis.

Table 5: Summary Statistics for Turbidity Data

Site	Night/Day	Type	n	Statistics for Transformed Values: log10(Turbidity+1)		Turbidity Ranges[1]		
				Mean	SD	Geometric Mean	Upper Bound	Lower Bound
All	All	Dry	517	1.23	0.59	15.89	64.63	3.35
		Wet	431	2.16	0.87	143.01	1065.29	18.45
Site 1	All	Dry	144	1.26	0.37	17.18	41.85	6.71
		Wet	144	1.70	0.73	49.16	267.14	8.38
Site 2	All	Dry	232	1.05	0.69	10.30	54.64	1.29
		Wet	168	2.07	0.73	116.67	625.89	21.09
Site 3	All	Dry	141	1.48	0.48	29.38	90.76	9.06
		Wet	119	2.84	0.80	685.24	4297.66	108.55
All	Day	Dry	231	1.39	0.58	23.42	92.42	5.39
		Wet	198	2.56	0.77	365.94	2146.51	61.70
All	Night	Dry	286	1.10	0.56	11.54	44.89	2.43
		Wet	233	1.81	0.80	64.04	409.83	9.30

[1] The Upper Bound and Lower Bound are back-transformed values of the Mean plus or minus one standard deviation of the log-transformed values.

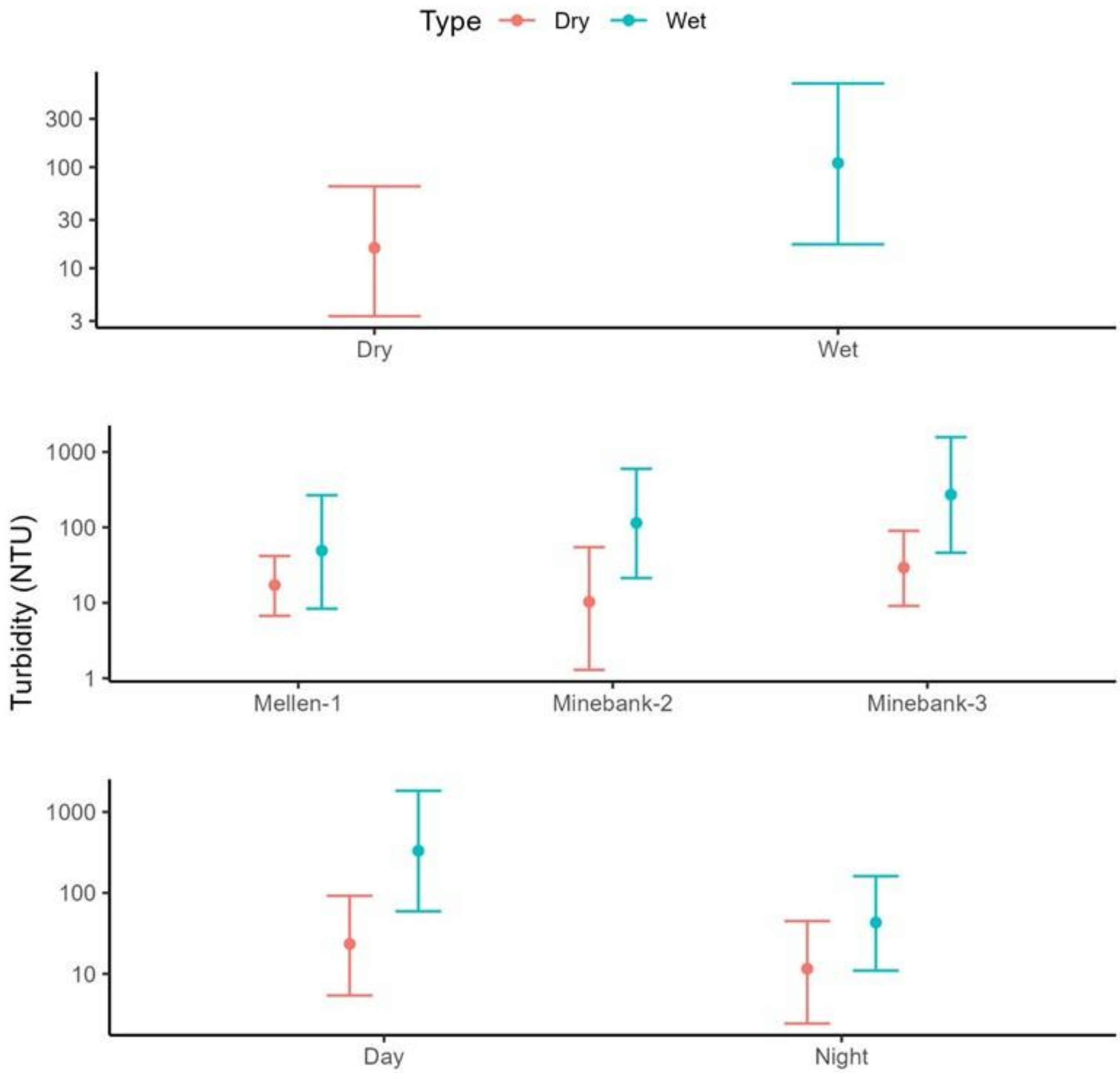


Figure 15: Range of Observed Turbidity Data (+/- on SD of log-Transformed Values)

The results suggest that the average turbidity is higher under Wet construction for all sites, with a p-value of <0.001. The effect size of Wet construction is also substantial, with the effect of Wet construction being on average 5.7 times that of Dry construction, with a 95% confidence range of between 3.3 and 9.9 times that of Dry construction.

Table 6: Summary Results for Hypothesis 1A

Statistic	Modeled Values
Mean (Log Ratio)	0.76
Standard Error of (Log Ratio)	0.12
Geometric Mean of (Ratio)	5.73
Confidence Interval of the Ratio	3.32-9.86

<u>Hypothesis 1B: The estimated hours exceeding Maryland's turbidity standards for Wet Construction are less than 50% greater than the exceedance time for Dry construction.</u>

To interpret Hypothesis 1B, data were converted to daily ratios (i.e., the fraction of values that exceeded the Maryland standard of 150 NTU) for the Day and Night periods of each day of construction. A ratio was used rather than a count to adjust for the fact that some missing data is present. The range of data used for this hypothesis is the same as 1A. When the ratios are aggregated across all days and compared across the three sites, the cumulative probability of exceeding 150 NTU is consistently higher for Dry construction, and for Day periods than for Night periods.

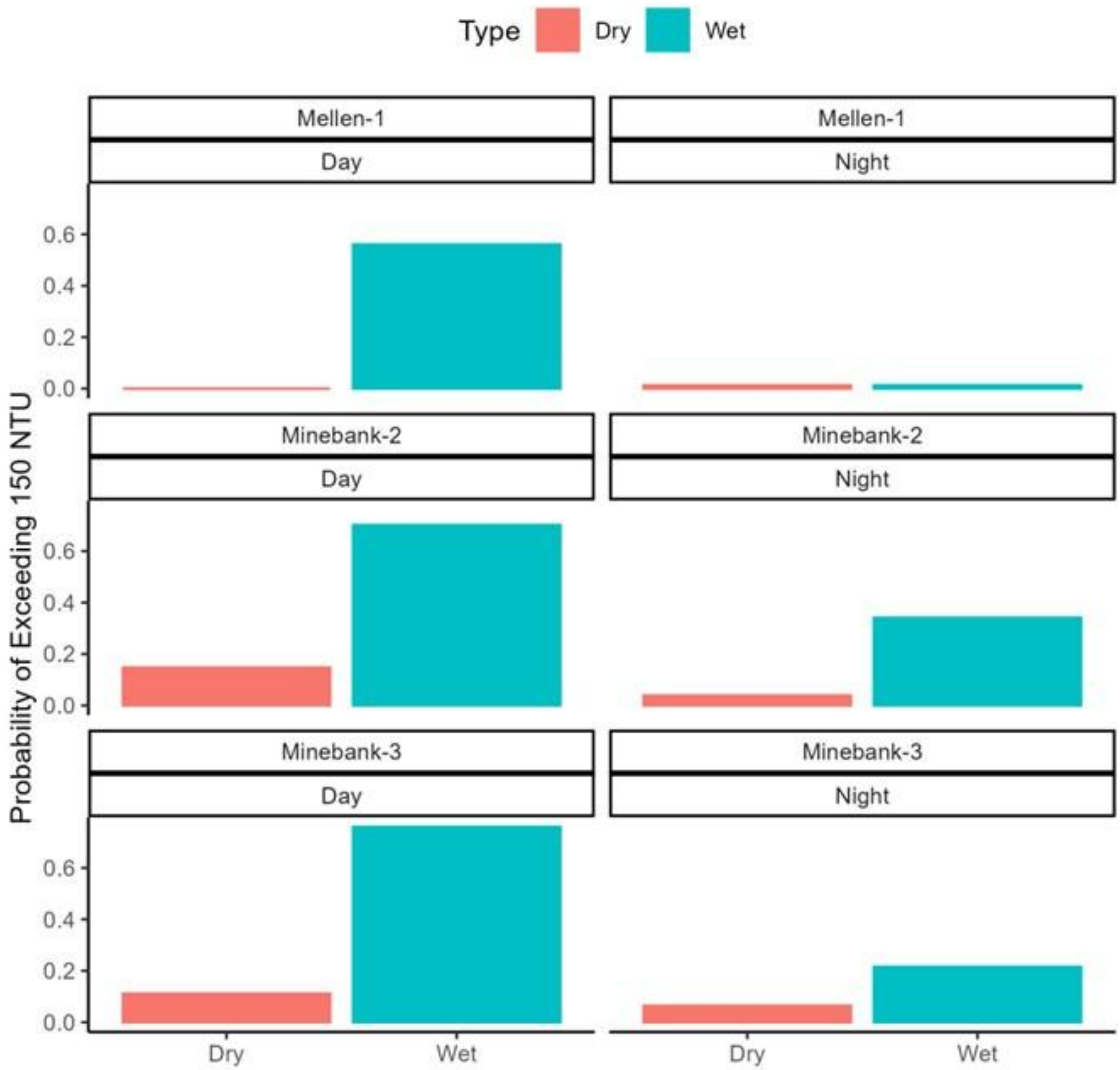


Figure 8: Percent Exceedance of 150 NTU for Dry and Wet construction

The results suggest that the hours of exceedance under Wet construction are more than 50% higher than those under Dry construction, with a p-value of <0.001. Rather than calculating the hours of exceedance, we calculated the probability of exceedance during construction. The model results suggest that the chances of exceeding the Maryland standard of 150 NTU is on average 16.6 times higher under Wet construction than Dry construction, with a 95% confidence interval of between 4.0 and 68.9 times higher.

Table 7: Summary Results for Hypothesis 1B

Statistic	Value
Log Odds Ratio	2.81
Standard Error of the Log Odds Ratio	0.73
Odds Ratio	16.55
Odds Ratio Confidence Interval	3.97-68.95

4.2. Hypothesis 2: Total Suspended Sediment Loading

<u>Hypothesis 2: The suspended sediment load associated with Dry construction will not be meaningfully different than the load associated with Wet construction, such that absolute difference between total suspended sediment loads (lbs.) is less than 25% of the average suspended sediment load between the two methods.</u>

For Hypothesis 2, using the TSS sediment load data created for each 5-minute period, the sediment loads were summed to get the total sediment load for the length of construction recorded for that day at each site during monitored construction. The resulting data were evaluated as a daily series of unit loads (i.e., the load per unit length of construction). The data was log-transformed (see Appendix E for more details).

Table 8: Summary statistics for daily unit load data

Site	Construction Type	n	Statistics for Transformed Values: $\log_{10}$(Unit Load)		Unit Load Ranges[1] (lbs./lf of restoration)		
			Mean	SD	Geometric Mean	Upper Bound	Lower Bound
All	Dry	17	-0.36	0.88	0.44	3.30	0.06
	Wet	16	0.89	0.96	7.77	70.50	0.86
Site 1	Dry	6	-1.30	0.35	0.05	0.11	0.02
	Wet	5	-0.26	0.75	0.55	3.11	0.10
Site 2	Dry	6	0.02	0.62	1.05	4.35	0.25
	Wet	7	1.29	0.43	19.68	53.09	7.29
Site 3	Dry	5	0.32	0.56	2.08	7.56	0.57
	Wet	4	1.62	0.40	41.89	105.87	16.57

1: The Upper Bound and Lower Bound are back-transformed values of the Mean plus or minus one standard deviation of the log-transformed values.

The analysis suggests that the unit load under Wet construction is significantly higher than under Dry construction. The results further suggest that the load from Wet construction is much higher than the load from Dry construction and far exceeds the 25% increase predicted in the hypothesis. On average, the predicted load from construction in the Wet construction is 16.0 times higher than Dry construction, with a 95% confidence interval of between 6.8 and 37.4 times higher.

Table 9: Summary Results for Hypothesis 2

Statistic	Value
Mean (Log Ratio)	1.20
Standard Error of (Log Ratio)	0.18
Geometric Mean of (Ratio)	15.98
Confidence Interval of the Ratio	6.82-37.44

4.3. Hypothesis 3: Total Suspended Sediment Compared to Annual Load

Hypothesis 3: The sediment load associated with the Construction in the Wet or Construction in the Dry will be significantly less than the sediment load associated with the 1.25-year storm for the watershed.

The 1.25-yr storm event, equivalent to an 80% annual exceedance probability (AEP) discharge, and watershed characteristics were estimated using USGS Streamstats for each site (Table 10). Using the NRCS dimensionless unit hydrograph, a synthetic hydrograph was developed to determine incremental discharge and storm volume for each site (Figure 16). Table 11 shows the derived watershed and runoff characteristics associated with the synthetic hydrographs for each site.

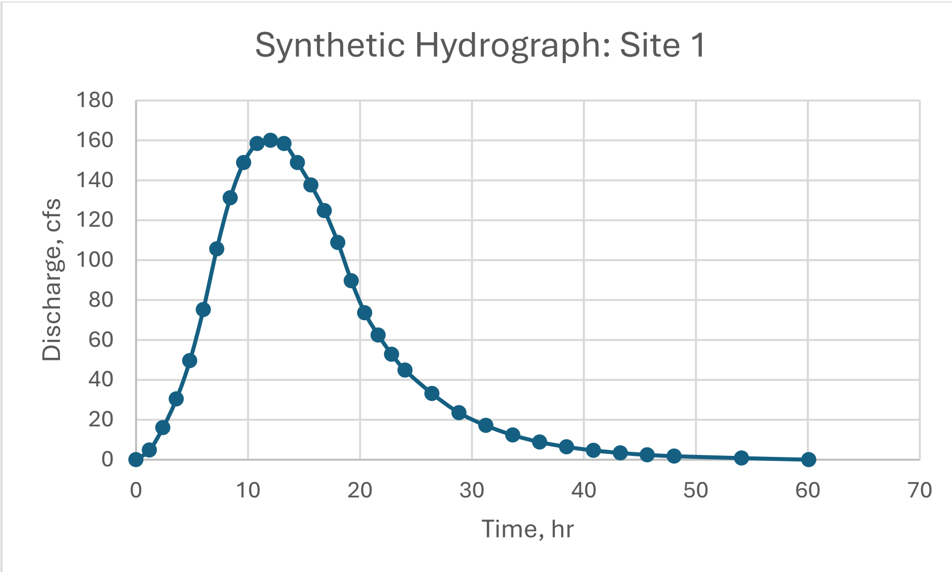
For Hypothesis 3, we compared the total project unit loads measured at each site to the load from the 1.25-year storm at each site. Since there were only between five and seven observations of daily loading rates for each Type-Location combination, we did not attempt to develop confidence intervals around these loading rates.

Table 10: USGS Streamstats peak flow for 1.25-year storm and watershed characteristics

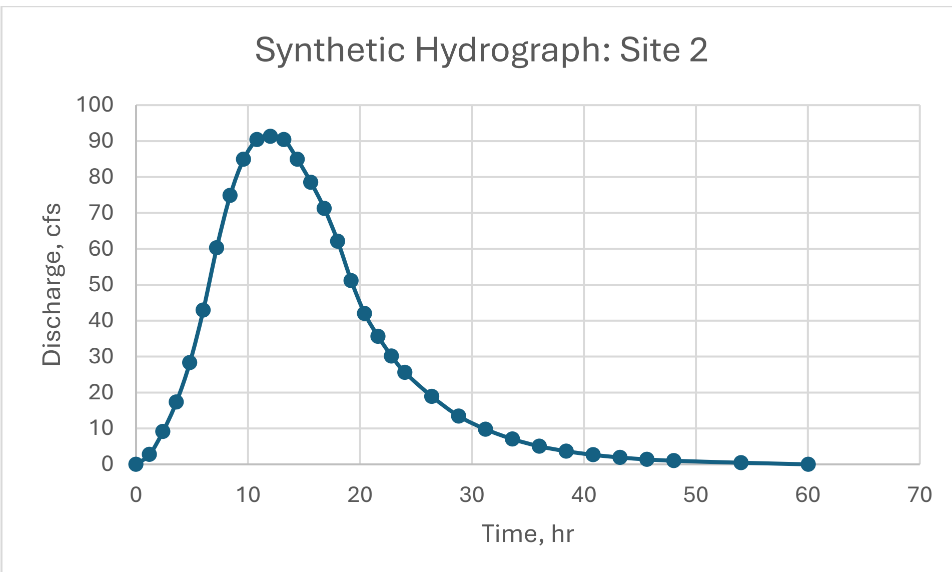
Site	Peak discharge, cfs	Watershed area, mi^2	Watershed slope	Storm duration, hr.
Site 1	160	0.89	0.0489	24
Site 2	91.3	0.49	0.1	24
Site 3	31.4	0.11	0.11	24

Table 11: Watershed calculations and runoff volume for 1.25-yr storm

Site	Watershed length, mi	Time of concentration, hr.	Lag time, hr.	Time to peak, hr.	Total volume, cf
Site 1	1.3	0.031	0.018	12.018	9,248,219.0
Site 2	0.91	0.018	0.011	12.011	5,273,848.0
Site 3	0.37	0.009	0.005	12.005	1,812,962.0



Synthetic Hydrograph: Site 1
Discharge, cfs
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
Time, hr



Synthetic Hydrograph: Site 2
Discharge, cfs
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
Time, hr

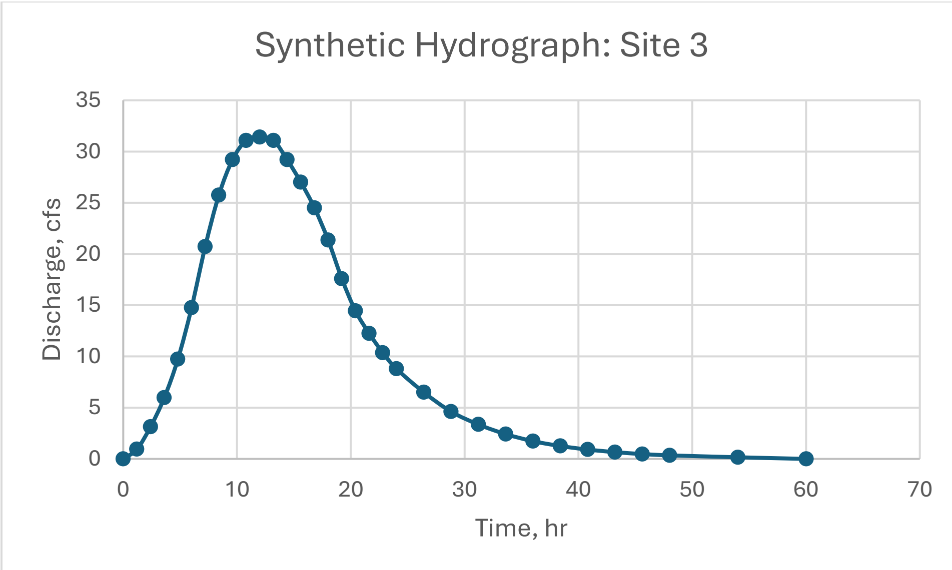


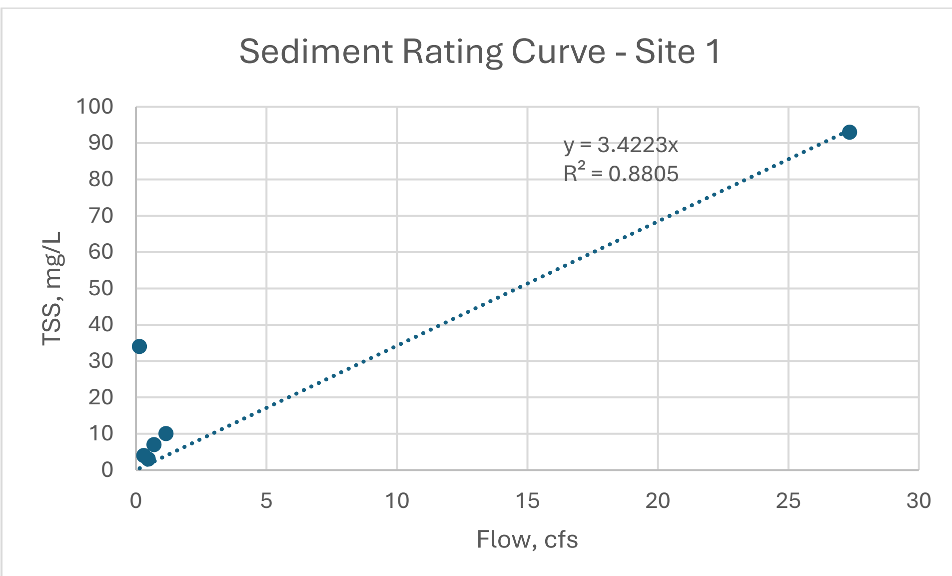
Figure 16: Synthetic 1.25-yr storm (80% AEP) hydrograph for each site

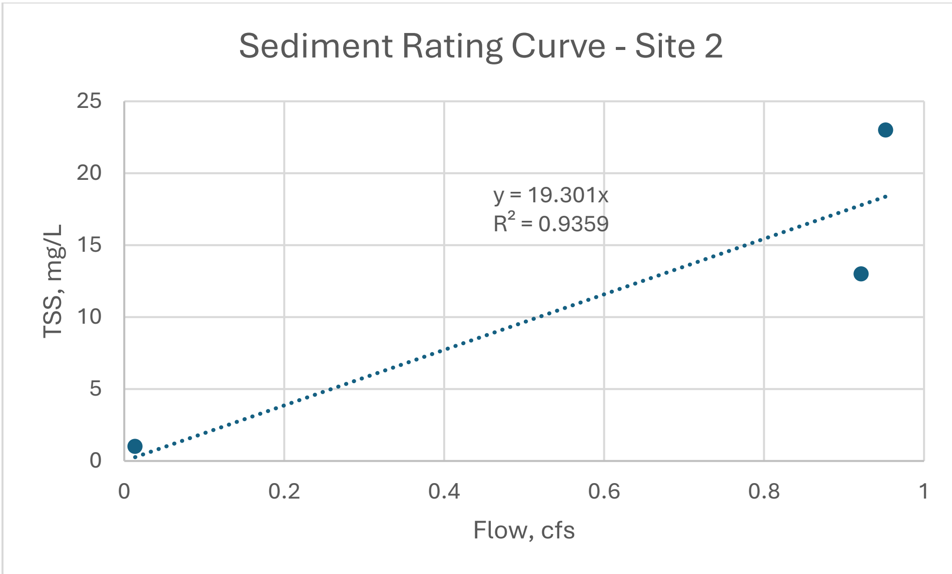
The TSS samples were correlated with flow data to derive a sediment rating curve for estimating sediment load at different discharge rates (Figure 17). Since sediment load would be zero when there is no discharge, the y-intercept was set to zero and a trend line was plotted for each rating curve. The TSS and flow relationship was used to estimate TSS for the hydrograph. The sediment load was derived by calculating the area under the mass rate curve. It should be noted that the flows of the 1.25-yr storm exceed the range of sampled TSS used to build the sediment rating curve, which introduces uncertainty. Extrapolating sediment rating curve data is common in studies due to the difficulty of sampling during flow events. TSS-flow relationships often have inflection points since as the flow exceeds the channel banks, the relationship moves from being transport limited to being supply limited at higher flows. Since the 1.25-yr storm is expected to be largely contained within the channel banks, the calculation of TSS for the 1.25-yr flows through extrapolation reduces the uncertainty introduced through this method. A greater number of TSS-flow points would improve the accuracy of this calculation.

Table 12: TSS samples and associated flow rate for each site, and derived sediment load

Site	Sample Taken	Time	Weather	Flow, cfs	TSS, mg/L	Sediment Load, lbs. (1.25-yr Storm)
Site 1	7/27/2022	3:25:00 PM	Dry	0.48	3	213,404.09
	8/14/2022	10:40:00 AM	Dry	0.31	4	
	8/15/2022	8:43:00 AM	Wet	1.15	10	

	8/24/2023	9:09:00 AM	Wet	0.14	34	
	3/6/2024	1:45:00 PM	Wet	0.70	7	
	3/23/2024	1:10:00 PM	Wet	27.35	93	
Site 2	9/7/2023	9:00:00 AM	Dry	0.01	1	391,637.95
	11/30/2023	3:12:00 PM	Dry	0.92	13	
	7/22/2024	6:18:00 PM	Wet	0.95	23	
Site 3	1/31/2024	2:00:00 PM	Dry	0.48	0.25	37,212.84
	7/22/2024	7:25:00 PM	Wet	0.58	13	
	6/17/2024	3:23:00 PM	Dry	0.40	9	





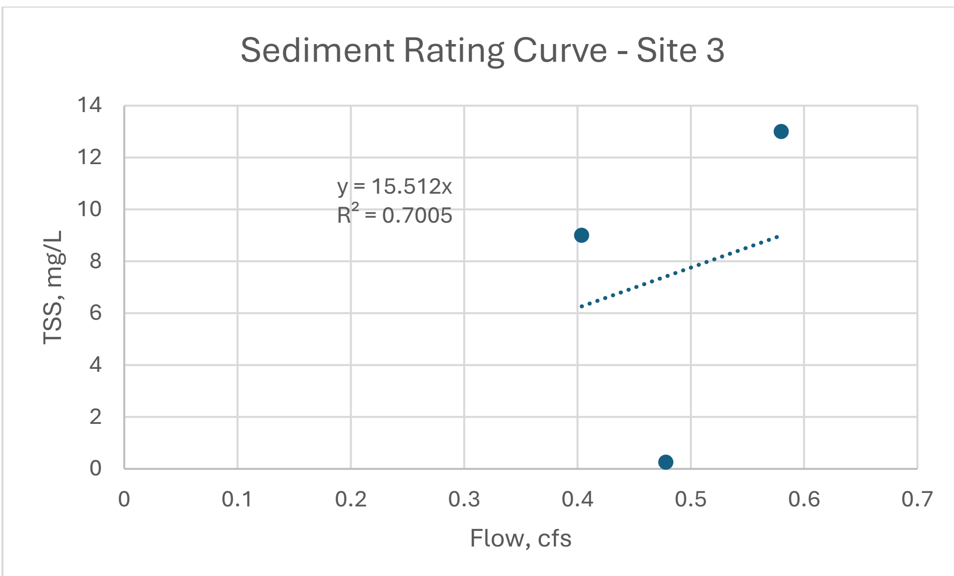


Figure 17: Correlation between TSS and flow for each site

Table 13: Sediment load assuming entire restoration project was conducted under Wet construction methods compared to sediment load produced by 1.25-yr storm for all sites

Site	Monitoring Type	Total median load (lb.) during monitoring	Linear feet of monitoring	Total linear feet of restoration	Median Load (lb) per linear foot	Total load for restoration (lb.)[1]	% load for reach restoration of 1.25-yr storm sediment load
Site 1	Wet	575	280	2386	2.05	4900	2.30%
Site 1	Dry	45	350	2386	0.13	305	0.14%
Site 2	Wet	8335	265	4718	31.5	148389	37.9%
Site 2	Dry	540	105	4718	5.15	24285	6.20%
Site 3	Wet	7562	130	1396	58.2	81207	218%
Site 3	Dry	661	245	1396	2.70	3767	10.1%

As indicated in Table 13, the annual load, estimated as the total load per unit length, suggests that the load at each site is much higher for the 1.25-year storm than for either Wet or Dry construction for Site 1 and 2. In fact, the total load from construction under Wet construction is never greater than 40% of the load from that storm, and the load from Dry construction is never greater than 7% of the 1.25-year storm. Site 3 showed that the load from Wet construction is higher than that from the 1.25-yr storm; therefore, we cannot broadly apply that Wet construction methods will produce less sediment than a 1.25-yr storm. See the discussion section for more information.

5. Discussion

5.1. Turbidity

Turbidity exceedances of 150-NTU are assumed to cause an impact to aquatic life in stream ecosystems. The two construction methods showed differences in the number and duration of exceedances of the turbidity standard. Wet construction methods produced notably greater turbidity than Dry construction methods. It was not observable in the data whether a subsequent spike in turbidity occurred for Dry construction methods when flow was returned to the channel. This observation was complicated by changes to construction methods to account for freezing weather at Site 3 and due to the necessary removal of the sonde after construction, which may have obscured any associated spike if it occurred much later. Site observations of turbid water during construction corroborate the data. For this study, the sonde measuring turbidity was immediately downstream of the reach for each construction method. This was important to capture turbidity that could be attributed to the construction method and not impede construction of the subsequent reach. While the location of the sonde downstream of construction allowed for mixing of the suspended sediment, site observations further downstream noted that turbidity was visually reduced close to baseline or natural conditions. The measured turbidity cannot confirm this observation; however, the duration and extent of turbidity exceedances downstream during construction is an important factor in determining the impact to aquatic life and should be studied further.

5.2. Sediment Load

Aquatic life impairments in the Chesapeake Bay watershed are frequently the result of elevated levels of suspended sediment. While important to stream processes and aquatic habitat, suspended sediment can negatively impact aquatic life at elevated levels. The contribution of suspended sediment during stream restoration construction is considered to be an important resource and regulatory consideration. This study confirmed that the total load for stream restoration construction was greater on average for Wet construction methods. The two Minebank Run restoration sites (Site 2 and 3) had greater sediment loads and greater differences between the two construction methods than the Mellen Court restoration site (Site 1). They also had smaller drainage areas, lower average flows, and steeper stream slopes, which may have contributed to those differences. Site 3 was a first order stream, which presumably would reduce the upstream drainage network and could influence the incoming baseline sediment load. While the scope of this study cannot determine the specific conditions that resulted in higher loading, it contributes data, that when combined with additional sites in the future, could begin to correlate watershed or reach-scale conditions to sediment load from stream restoration construction.

Since stream restoration construction causes a temporary increase to sediment load, it has been compared to, and assumed to be less than, the increases in sediment load due to frequent storm events. The results of this study suggest that stream restoration using Wet or Dry construction methods may contribute less sediment than storm events that have a high frequency of occurring in a given year depending on watershed and stream conditions; however, to reduce uncertainty in calculating the loading of frequent events like the 1.25-yr storm, future research may consider utilizing a greater number of TSS samples for a greater range of flow events. These results combined with previous studies suggest that stream restoration construction may have a limited impact on aquatic life, similar to the impact that would occur naturally in these watersheds due to runoff from frequent storms under some watershed and stream conditions, but importantly the study also suggests that Wet construction methods could contribute loading that is greater than that of frequent storms.

5.3. Construction Efficiency

The rate of stream-restoration construction is influenced by a probable set of field variables. Chief among these is stream order, which determines base-flow volume. On first- through third-order channels, flows are sufficiently low that in-stream work can proceed “in the Dry” with limited effort: pumps are deployed quickly, dewatering time is minimal, operating costs are minor (relative to overall construction costs), and maintenance of flow seldom constrains productivity. Conversely, Wet construction methods on smaller order streams with minimal flow conditions will likely have a minimal effect to the rate of construction. Additional influences include crew proficiency, project site layout, haul distances for materials, material availability, weather, and the baseline condition of the riparian corridor. Because Wet construction methods eliminate the need to build cofferdams and perform dewatering, it is often assumed to be more efficient. While this study aimed to directly compare the pace of Wet versus Dry Construction methods, results showed that the actual differences in construction speed were relatively modest, ranging from 9% to 15% across the three study sites.

Table 14: Summary of construction efficiency rates and associated TSS loading rates.

Site	Method	Length	Time (Hr.)	Rate of Production (LF/Hr.)	Unit Load Rate (Lbs./Ft)
Site 1: Mellen Cout	WET	280	38	7.37	0.55
	DRY	350	39	8.97	0.05
Site 2: Minebank (Downstream)	WET	210	60.85	3.45	19.68
	DRY	130	44.55	2.92	1.05
Site 3: Minebank (Upstream)	WET	185	38.3	4.83	41.89
	DRY	245	44.15	5.55	7.56

Several practical and study-specific conditions likely account for these small differences in efficiency. First, crew consistency was not controlled as part of the study design. Variability in crew composition due to vacations, illness, or general availability likely influenced productivity, as changing personnel often brings varying levels of experience. Second, the participating crews had significantly more experience working in Dry conditions, with limited exposure to working in the Wet. This lack of familiarity can reduce efficiency during Wet Construction, if flow conditions hinder visibility of the streambed and does not reflect performance by crews experienced in those conditions. Weather conditions also play a significant role. While Wet Construction can often continue during light precipitation or increased baseflow, Dry construction is more sensitive to rising stream flow, particularly when flows exceed pump capacity. In these instances, Dry construction is forced to halt, resulting in downtime that does not occur under Wet Construction. However, interruptions fell outside the study's accounting framework; if a crew left the site for the remainder of a shift, the unworked hours were excluded from the monitoring record.

To further explore how construction efficiency influences environmental outcomes, a comparative analysis of actual vs. idealized construction durations was conducted. Idealized durations were based on the best observed construction rate (ft/min) per site, assuming fully experienced crews and no downtime. This scenario also excludes the time typically required to set up and manage pump-arounds and sediment filtration systems, steps necessary for Dry Construction methods but not for Wet construction methods.

Using these optimized durations, the study estimated how much Total Suspended Sediment (TSS) might have been released if all construction had occurred under ideal conditions. This approach enables assessment of both the environmental implications of construction methods and the potential benefits of improving efficiency through additional experience and enhanced operational practices.

At Site 1 (Mellen Court), Wet Construction proceeded at 7.37 ft/hr., compared to an optimal Dry Construction rate of 8.97 ft/hr. Operating using Wet construction methods at the Dry construction rate could have reduced exposure time by over 5 hours, decreasing cumulative TSS by approximately 37.5 lbs. (a 17.5% reduction).

At Site 2 (Minebank Downstream), Wet Construction was 3.45 ft/hr. versus 2.92 ft/hr. under Dry Construction. Because Wet construction performance already surpassed Dry construction, the difference in potential sediment savings was minimal.

At Site 3 (Minebank Upstream), Wet construction proceeded at 4.83 ft/hr., while Dry construction reached 5.55 ft/hr. Had Wet construction matched the pacing of Dry construction, total construction time could have been reduced by over 2 hours, lowering sediment output by an estimated 87 lbs. (a 10.5% reduction).

<u>Comparison of Total Turbidity Load Potential Between Wet and Dry construction Methods</u>

To evaluate the relative turbidity impact of Wet versus Dry construction methods, an analysis was performed using geometric mean turbidity values (NTU/hr.) derived from the log-transformed monitoring data. Assuming an 8-hour workday and constant turbidity output per hour, total daily turbidity (NTU/day) was estimated as a function of NTU/hr. To determine the operational feasibility of Wet construction methods under Dry-equivalent turbidity thresholds, the required increase in Wet Construction speed was calculated as the ratio of Wet to Dry geometric mean turbidity. This value represents the multiplier by which Wet Construction would need to increase its speed to maintain turbidity outputs equivalent to those of Dry Construction. Results indicated that Wet Construction would need to proceed between 2.86 and 23.33 times faster than Dry Construction depending on the site.

Table 15: Comparison of Wet and Dry construction turbidity at each site and the required speed increase for Wet construction Methods to equal the turbidity under Dry construction methods.

Required Speed Increase for Wet construction to Match Dry NTU/day			
Site	**Dry NTU/hr.**	**Wet NTU/hr.**	**Required Wet Speed Increase**
All	15.89	143.01	9.00× faster
Site 1	17.18	49.16	2.86× faster
Site 2	10.3	116.67	11.33× faster
Site 3	29.38	685.24	23.33× faster

A similar analysis was conducted to determine the length of Dry Construction required to produce an equivalent sediment load to that of Wet Construction. Sediment generation efficiency for each method was evaluated by calculating unit sediment loads (lbs./linear foot) using geometric means of log-transformed monitoring data. This approach provides the linear footage of Dry Construction necessary to equal the total sediment load generated by one linear foot of Wet construction.

Results indicate that, depending on the site, Dry construction could complete 10 to 20 additional feet of restoration while producing the same total sediment load as just one foot of Wet construction. Effectively, the sediment load generated by constructing one foot under Wet construction methods is equivalent to that produced by 11 to 21 feet in Dry conditions. At Site 3, Wet construction generated approximately 41.89 lbs./ft, while Dry construction produced 2.08 lbs./ft, meaning that 20.13 feet of Dry construction would be required to equal the sediment output of 1 foot of Wet construction. At Site 1, this ratio was lower but still significant, with Wet construction producing 0.55 lbs./ft compared to 0.05 lbs./ft for Dry construction yielding an equivalent Dry construction length of 11 feet.

Table 16: Comparison of Wet and Dry construction load rates at each site and length of Dry construction to equal loading of 1-foot of Wet construction.

Feet of Dry construction Needed to Equal TSS load associated with 1 Foot of Wet construction			
Site	**Wet Load (lbs./ft)**	**Dry Load (lbs./ft)**	**Extra Dry Feet for 1 Wet Foot TSS**
All Sites	7.77	0.44	+16.66 ft
Site 1	0.55	0.05	+10.00 ft
Site 2	19.68	1.05	+18.75 ft
Site 3	41.89	2.08	+20.13 ft

Appendix A: Site Selection Evaluation Form

Turbidity Values at Stream Restoration Sites: Site Selection Form

General Project Information			
Project Name:			
Project Location (Address & Lat/Long)			
Project Drainage Area:			
Stream Order:			
MD Stream Use Class:			
Designer:			
Constructor:			
Constructor Experience Working in Wet:			
Existing Land Use (percent):			
Impervious:		Residential:	
Agriculture:		Forested:	
Commercial:			

Proposed Restoration Characteristics	
Project Length (ft. or mi.):	
Proposed Stream Width (ft.):	
Proposed Stream Depth (ft.):	
Proposed Stream Cross-Sectional Area (sqft.):	
Proposed Stream Slope (%):	
Wetted Perimeter (ft):	
Velocity (cfs):	
Proposed Stream Slope (%):	
Dominant Streambed Material (sand, gravel, clay, etc.):	
Dominant Streambank Material and Density (sand, gravel, clay, etc.):	
Dominant Existing Bank Vegetation:	
Dominant BEHI/NBS Condition:	
Average Bank Height and Percent Eroding Banks:	
Average Bank Height Ratio:	
Projected Construction Start Date:	
Projected Construction Duration (days or months):	
Instream Work Closure Dates:	
Limits of Disturbance Size (ft.^{2} or AC):	

Restoration Activities	
Design Approach:	
Level of Restoration Effort*:	
Current Construction Sequence:	
Can Construction Sequence be Altered:	
Can Staging Area Locations be Altered:	
Can Haul Road Locations be Altered:	

Type of Restoration Activities/Structures (check all that apply)			
	Cobble weirs		Brush Toe/Toe Wood Bank Protection
	Grade control (rock or log)		Brush Mattresses
	J-hooks (rock or log)		Geolifts/Soil Lifts
	Vane arms (rock or log)		Bank Toe Protection (rock or log)
	Cross vanes (rock or log)		Sills (rock or log)
	Constructed riffles (rock or wood)		Groin Deflector
	Step pools (rock or log)		In-stream habitat structures (rock or log)
	Others (please describe)		

Erosion and Sediment Control	
Is pump around required? (Y/N)	
If yes, what is the pump diameter?	
If yes, is the contractor willing to provide pump around costs?	

***Level of Restoration Effort Definitions:**	
Major	Major channel and floodplain reconfiguration (mostly all new channel and floodplain)
Moderate	Moderate channel and floodplain reconfiguration (50% new channel and floodplain)
Slight	Slight channel and floodplain restoration (installing lateral and vertical structures within existing alignment)

Version: 10/27/2021

Appendix B: Construction Log Form

Wet Versus Work in the Dry for Stream Restoration

Project Site:

Construction Monitoring– DAILY LOG

Date:	**Weather:**	**24 hr. Rainfall:**
Total Construction Time:	**Total Construction Length:**	**Monitoring Personnel**:
Pump Around Inspection:		
Summary of Daily Construction Activities		

Construction Activities								
Activity	**Plan Sheet**	**Station Start**	**Station End**	**Start Time**	**End Time**	**Area Disturbed**	**Photo Number(s)**	**Comments**

ANY ACTIVITY WITHIN THE CHANNEL (WITHIN THE CHANNEL TOP OF BANKS) MUST BE RECORDED.

Every day you are onsite, you will record the time at which construction crews:

- **WRITE LEGIBLY**
- Complete Site information at top of daily log and summarize work that was completed during monitoring – specifically type of work, Stationing of work, and work start time and end time.
- Use “comment” column to describe anything activity, if needed.
- “Area Disturbed” column will be completed in the office based on log notes.
- Always include “am” or “pm” when recording times.
- Always include Stationing when recording activities (start and end locations) and provide design sheet page number.
- Take pictures of water quality at turbidity meter before any work occurs and then take pictures periodically through out the day. Also, for working in dry, take pictures of water quality at clean water pump around at the same time as the turbidity meter.
- When the first construction activity begins within the channel – typically either pump around pump turned on or pump around dam is built.
- When the last construction activity ends within the channel – typically either pump around pump turned off or pump around dam is removed.

  It is important to note the difference when recording construction end time for working in the wet versus working in the dry:

  - ONLY FOR WORKING IN THE DRY REACH: the construction end time for the pump around is when pump around shuts off and water returns to channel. Record the exact time pump is turned off, temporary dam is removed and water begins flowing back into channel (1^{st} flush)
  - ONLY FOR WORKING IN THE WET REACH: the construction end time is the moment when all channel and bank work is halted for the day AND no construction activities are occurring within the channel.

Recording Points of Structure Installs:

1. Dewatering process
2. Start of structure install, as soon as any ground is disturbed (i.e., excavator excavating a bank)

   a. Record every construction activity association with a structure install (e.g., bank grading, channel grading, placement of structure materials, placement of Geotech fabric, etc.)

3. Completion of structure
4. Bank and/or in channel grading. Distinguish between bank and bed construction activities, if appropriate.
5. Any bank stabilization activities, including matting (i.e., when matting is finished being laid out and staked)
6. If you are uncertain whether an activity should be recorded, record it. It is better to have too much information than not enough.
7. Record water quality appearance and take a picture at:
   a. Before construction starts
   b. During construction when water quality appearance changes
   c. After construction at the end of the day is complete

Appendix C: Photograph Exhibit

Wet vs Dry Project Photos– Site 1: Mellen Ct Site Photo Log

Mellen Court Set up- Survey/Reach Assessment

Mellen Court Velocity Measurement

Wet vs Dry Project Photos– Site 1: Mellen Ct Site Photo Log

Mellen Court Sakrete Weir Structure

Mellen Court Wood Weir Structure

Wet vs Dry Project Photos– Site 1: Mellen Ct Site Photo Log

Mellen Court Wet Construction

Mellen Court Wet Construction turbidity

Wet vs Dry Project Photos– Site 1: Mellen Ct Site Photo Log

Mellen Court Work in Wet Construction

Mellen Court Work in Wet Turbidity

Mellen Court Wet Construction

Mellen Court Wet Construction Turbidity

Wet vs Dry Project Photos– Site 1: Mellen Ct Site Photo Log

Mellen Court Dry Construction

Mellen Court Dry Construction Turbidity

Wet vs Dry Project Photos– Site 1: Mellen Ct Site Photo Log

Mellen Court Dry Construction

Mellen Court Dry Turbidity

Wet vs Dry Project Photos– Site 2: Minebank Photo Log

Minebank Downstream up- Survey/Reach Assessment

Site 2 Minebank pressure transducer set up

Wet vs Dry Project Photos– Site 2: Minebank Photo Log

Site 2 Minebank downstream Weir Structure

Minebank Upstream Weir Structure

Wet vs Dry Project Photos– Site 2: Minebank Photo Log

Site 2 Minebank Wet Construction

Site 2 Minebank Wet Construction turbidity

Wet vs Dry Project Photos– Site 2: Minebank Photo Log

Site 2 Minebank Work in Wet Construction

Site 2 Minebank Work in Wet Turbidity

Wet vs Dry Project Photos– Site 2: Minebank Photo Log

Site 2 Minebank Work in Wet Construction

Site 2 Minebank Wet Construction Turbidity

Wet vs Dry Project Photos– Site 2: Minebank Photo Log

Site 2 Minebank Work in the Dry Construction

Site 2 Minebank Dry Construction turbidity

Wet vs Dry Project Photos– Site 2: Minebank Photo Log

Site 2 Minebank Work in the Dry Construction

Site 2 Minebank Work in the Dry Turbidity

Wet vs Dry Project Photos– Site 3: Minebank Photo Log

Site 3 Minebank Weir and monitoring pool

Site 3 Minebank pressure transducer set up

Wet vs Dry Project Photos– Site 3: Minebank Photo Log

Site 3 Minebank Wet Construction

Site 3 Minebank Wet Construction turbidity

Wet vs Dry Project Photos– Site 3: Minebank Photo Log

Site 3 Minebank Work in Wet Construction

Site 3 Minebank Work in Wet Turbidity

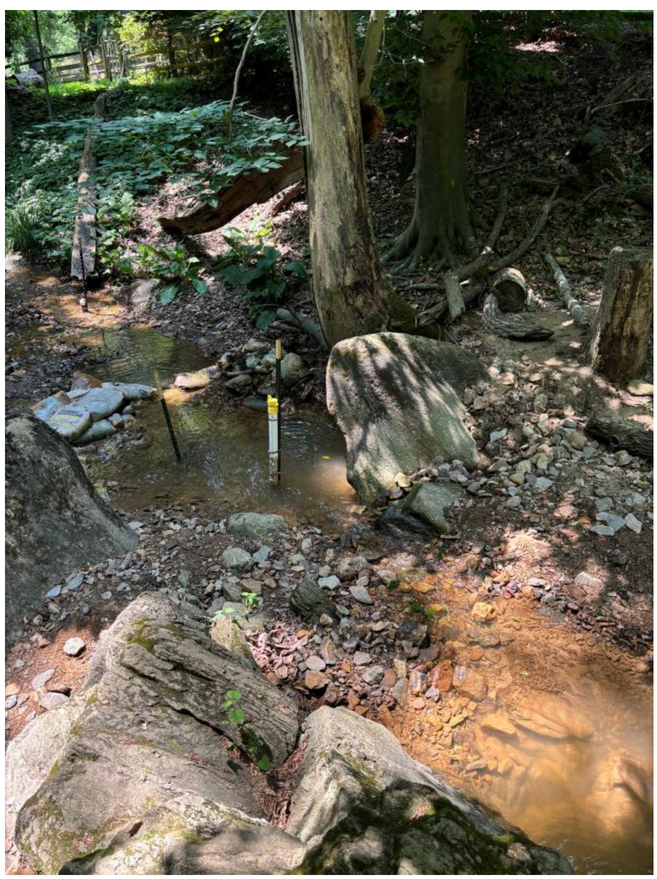
Wet vs Dry Project Photos– Site 3: Minebank Photo Log

Site 3 Minebank Work in Wet Construction

Site 3 Minebank Wet Construction Turbidity

Wet vs Dry Project Photos– Site 3: Minebank Photo Log

Site 3 Minebank Work in the Dry Construction



Site 3 Minebank Dry Construction turbidity

Wet vs Dry Project Photos– Site 3: Minebank Photo Log

Site 2 Minebank Work in the Dry Construction

Site 3 Minebank Work in the Dry Turbidity

Appendix D: Lessons Learned

- Managing Freezing Conditions: During freezing weather, the construction contractor ran pumps overnight to prevent freezing and avoid delays in the following day's work.
- Challenges with Monitoring Pools: Creating monitoring pools using weirs presented several challenges. The weirs needed to be deep enough for the sonde to function properly but not so deep that mixing was insufficient. If the initial pool was too shallow, sediment accumulation compromised data collection. Additionally, weirs were not strong enough to withstand storm events during the monitoring period. The design of weirs varied throughout the project. While the first wooden weir at Mellen Court was the most durable, it was also highly labor-intensive. Later weirs were constructed using Sakrete or built by the construction team to balance durability with efficiency.
- Sonde Positioning and Maintenance: The sonde was much less likely to clog when positioned vertically rather than horizontally, as vertical placement reduces the surface area in contact with the ground. However, this setup decreases overall stability. Regardless of placement, the sonde should be checked at least monthly and after major storm events. The sensor should be wiped to remove fouling and inspected for cracks or water intrusion.
- Visibility Issues in Wet Conditions: Construction crews experienced difficulty seeing their work clearly when working in Wet conditions, leading to some frustration.
- Extended Workability During Rain Events: During work in the Wet conditions when pumps could not keep up with runoff, construction crews were able to continue working during rain events that would have otherwise caused shutdowns.
- Sediment Management: When working from downstream to upstream, completed structures helped reduce sediment loads in receiving waters by capturing and removing sediment from the stream, even when flow remained subsurface.
- Filter Bag Placement: The positioning of filter bags was not always optimal, sometimes preventing filtered water from re-entering the stream in a way that could be effectively measured by the turbidity meter.
- Space Constraints Impacting Monitoring: In certain constrained sections of the project, monitoring had to be shortened in at least one instance to prevent interruptions to construction.
- Pressure Transducer Data Management: Pressure transducers should be downloaded every other day to minimize the risk of data loss or multiple monitoring locations could be used to create redundant datasets.
- Turbidity Meter Stability: Turbidity meters need to be securely anchored to ensure reliable data collection across all flow rates.
- Efficiency of Sampling Methods: The ISCO sampler was not well suited for the types of samples required for this project, making grab sampling a much more efficient alternative.

- Crew and Material Variability: Changes in crew members, equipment operators, and material availability had a more significant impact on productivity and efficiency than whether work was conducted in Wet or Dry conditions.

Appendix E: Statistical Analysis Overview

Methods

Data collected at three sites: Mellen-1 (Site 1), Minebank-2 (Site 2), and Minebank-3 (Site 3) were used to complete analyses described in this appendix. The specific data and methods used was different between hypotheses, in that Hypothesis H1 refers only to turbidity values, while Hypotheses H2 and H3 incorporate flow and TSS data to estimate sediment loads. In addition, different statistical methods were used to investigate each hypothesis (Table 17).

Table 17: Summary of Statistical Methods and Data Used to Test Each Hypothesis

Hypothesis	Model Input Data	Metric Modeled	Modeling Technique	Test Used to Evaluate Hypothesis.
1A: The observed average Turbidity (Average NTU) will be higher during the Wet construction Period.	Hourly Turbidity Data	Log-Transformed Turbidity Values	Linear Mixed Effects Model with Autoregressive Residuals. Sites are used as a random blocking factor.	p-value of the Geometric Mean of the Ratio of Wet versus Dry Turbidity exceeding 1.0.
1B: The estimated hours exceeding Maryland's turbidity standards for Wet construction are less than 50% greater than the exceedance time for Dry construction.	Percent Exceedance of Turbidity> 150 NTU for Each Day or Night Observed	Logit (Exponential Odds)	Logistic Regression	Test if the 95% Confidence Interval for the Odds Ratio (Odds of Exceedance for Wet versus Dry construction) Exceeds 1.5.
2: The suspended sediment load associated with Dry construction will not be meaningfully different than the load associated with Wet construction, such that the absolute difference between total suspended sediment loads (lbs.) is less than 25% of the average suspended sediment load between the two methods.	5-Minute Observed Turbidity and Stage Data Regressions of TSS vs Turbidity and Flow vs Stage derived from calibration data Construction Lengths Monitored	Ratio of the (Difference Between Wet and Dry Unit Loads) And Average Unit Loads	Simulation of model variability using Bootstrap Techniques	Test if the upper confidence interval (95% for simulated statistics is less than 25%)

Hypothesis	Model Input Data	Metric Modeled	Modeling Technique	Test Used to Evaluate Hypothesis.
3: The sediment load associated with the Construction in the Wet or Construction in the Dry will be significantly less than the sediment load associated with the 1-year storm for the watershed.	Data Used for Hypothesis 2 *plus Sediment Rating Curve derived from observed TSS and Flow Data* And *Total Construction Lengths*	Estimated Annual Loads	Simulation of Model Variability Using Bootstrap Techniques	Ratio of Unit Loads from Construction to the Equivalent Unit Load from the 1.25-Year Storm at each Site and Construction Type.

Hypothesis 1A:

The observed average Turbidity (Average NTU) will be higher during the Wet construction Period.

The data analyzed for hypotheses 1 and 1A were confined to the construction period and included hourly turbidity data measured downstream of each construction reach. Data incorporated into this analysis were confined to the time 8AM, which approximated the time where construction activity resulted in an increase in downstream turbidity, until 8AM the following day.

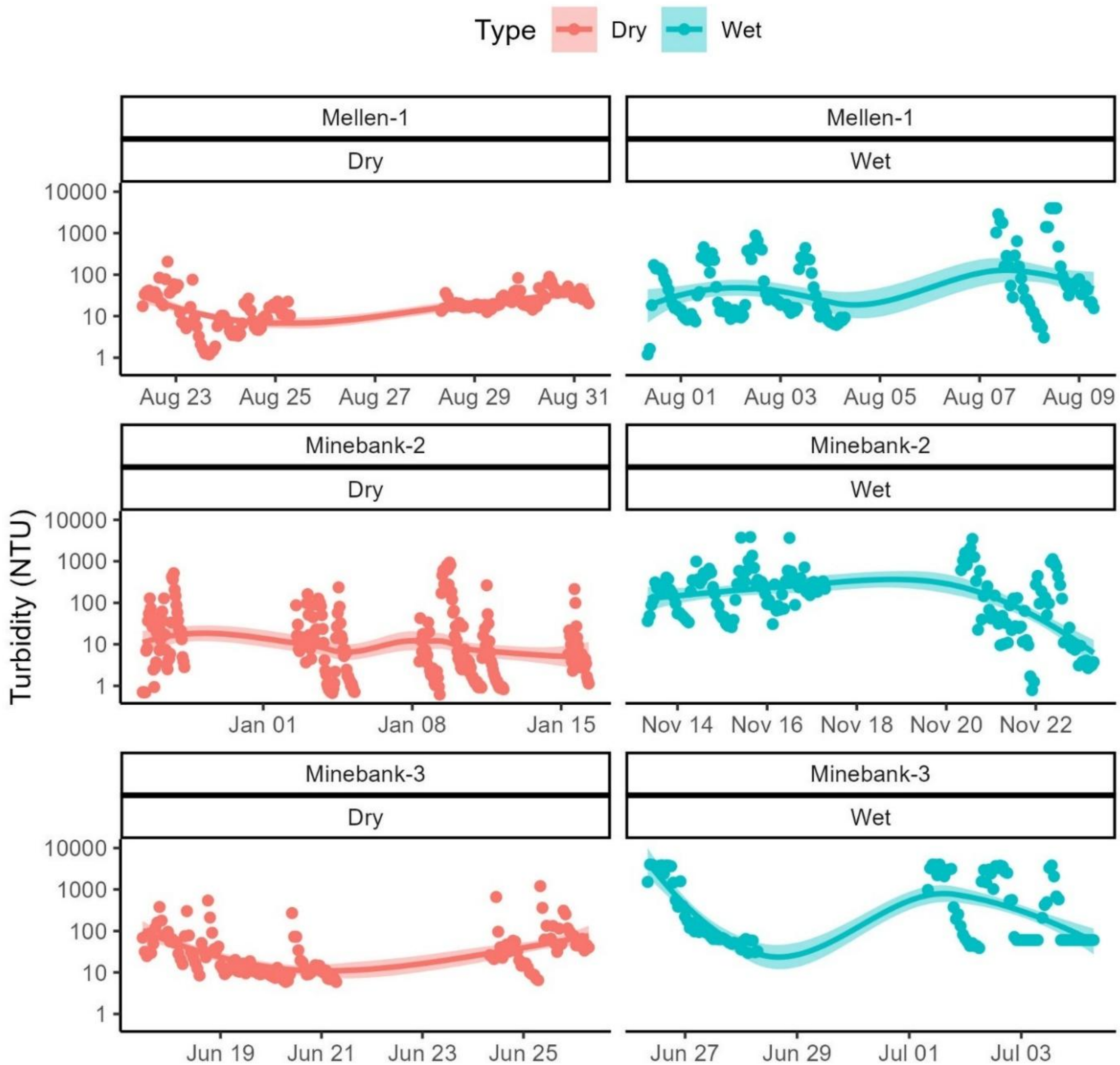


Figure 18:Hourly Turbidity Data During Construction

Transformation of Turbidity Data

The data in Figure 19, and in the analyses for Hypothesis 1A were log-transformed because the original data were highly right-skewed, while the log-transformed data were minimally skewed, with the exception of a relatively large number of values at 4,000 likely caused by capping the maximum Turbidity value at 4,000 (Figure 20). Because of the large sample size of this study, it was initially assumed that the log-transformed data will be appropriate for analysis, and the normality of model residuals was checked after regressions were developed. The data were transformed using the following equation to eliminate infinite values for log(0):

$$LogTurbidity = \log_{10}(Turbidty + 1)$$

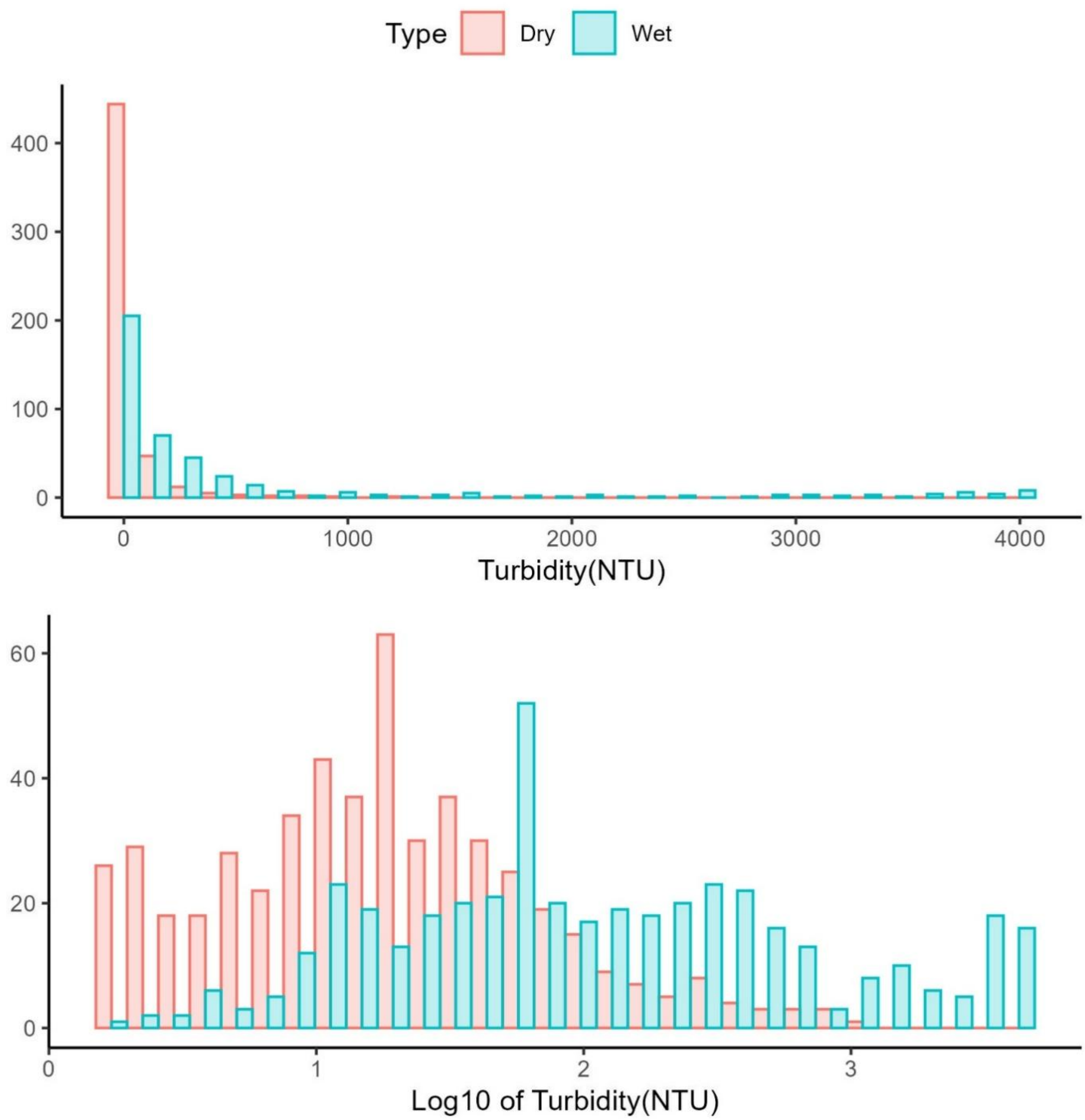


Figure 19: Distribution of Raw and Log-Transformed Turbidity Data

Initial Comparison of Turbidity Data and Selection of Predictor Variables

As an initial exploratory measure, we compared the log-transformed data between the Dry and Wet construction methods using three groupings: 1) Across all sites; 2) Between Sites and 3) Between "Day" and "Night." Day and Night values represent the times from 8AM and 8PM (Day) and between 8 PM and 8AM the following Day (Night)[3]. The next section describes how these time breaks were

[3] Initially, the project team had considered using upstream turbidity as a predictor of downstream turbidity to account for daily variability but instances of missing upstream data, combined with days where elevated upstream turbidity was explained by other factors that did not translate to downstream turbidity such as local disturbances, made this predictor unusable for this analysis.

selected. The results of these initial comparisons (Figure 3 and Table 18) suggest that turbidity for Wet construction methods is higher than turbidity for Dry construction methods, and that both the site and time of day contribute to the variability of observed values.

Table 18: Summary Statistics for Hourly Averaged Turbidity Data

Site	Night/ Day	Construction Type	n	Statistics for Transformed Values: $\log_{10}(\text{Turbidity}+1)$		Turbidity Ranges[1]		
				Mean	SD	Geometric Mean	Upper Bound	Lower Bound
All	All	Dry	517	1.23	0.59	15.88	64.47	3.35
		Wet	431	2.04	0.78	109.80	673.45	17.20
Mellen-1	All	Dry	144	1.26	0.37	17.18	41.85	6.71
		Wet	144	1.05	0.69	10.29	54.63	1.29
Minebank-2	All	Dry	232	1.48	0.48	29.32	89.97	9.11
		Wet	168	1.70	0.73	49.16	267.14	8.38
Minebank-3	All	Dry	141	2.06	0.71	114.56	596.94	21.33
		Wet	119	2.44	0.76	271.41	1571.7	46.18
All	Day	Dry	231	1.39	0.58	23.39	91.95	5.40
		Wet	198	2.52	0.74	330.56	1826.30	59.16
All	Night	Dry	286	1.10	0.56	11.54	44.89	2.43
		Wet	233	1.64	0.57	43.03	161.13	10.96

[1] The Upper Bound and Lower Bound are back-transformed values of the Mean plus or minus one standard deviation of the log-transformed values.

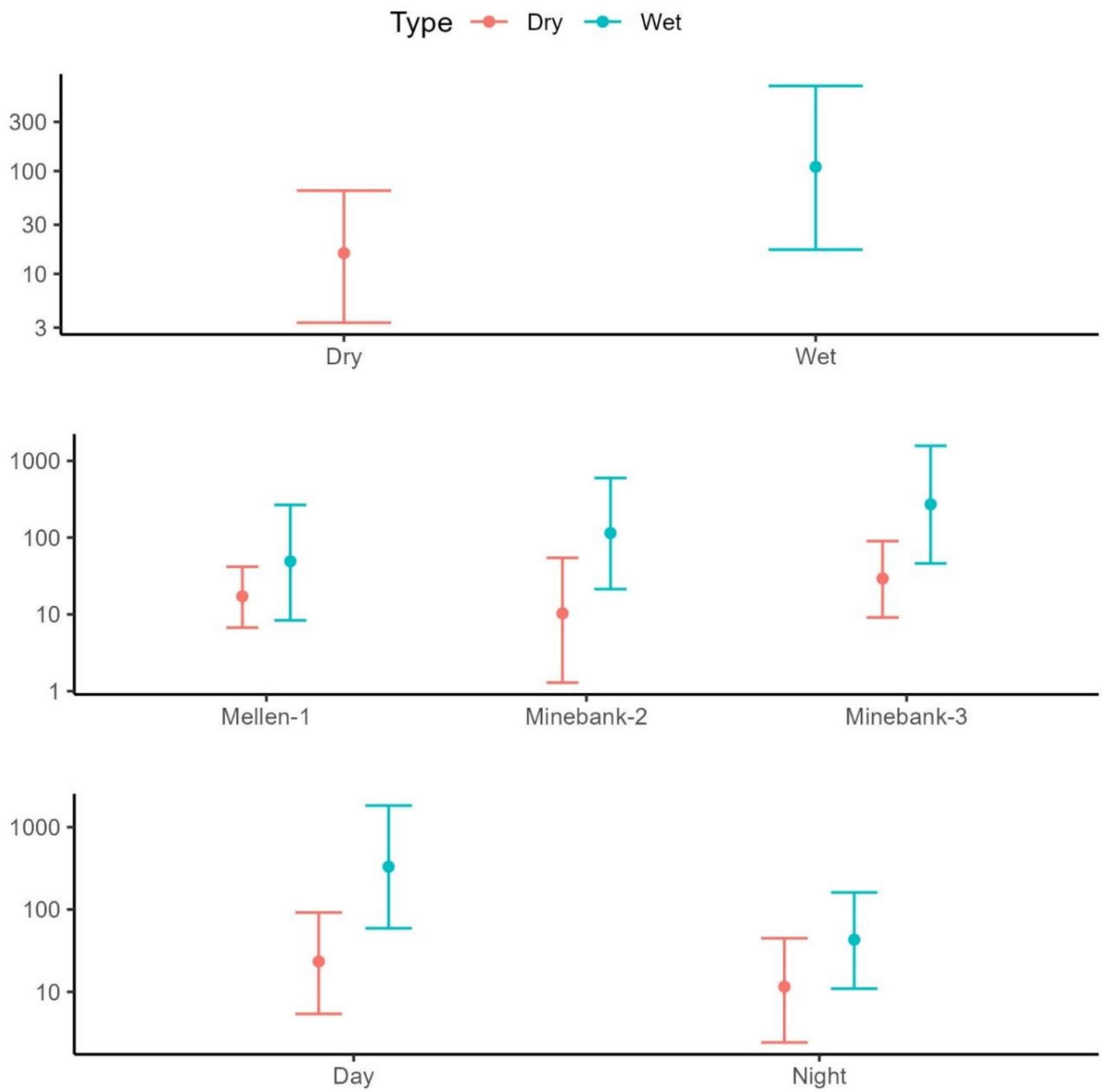


Figure 20: Range of Observed Turbidity Data (+/- on SD of log-Transformed Values)

The project team experimented with several options for determining “Day” versus “Night”. Ultimately, we settled on starting at 8 AM (8AM is hour 1), since this break showed the clearest distinction in turbidity values, particularly for Wet construction (Figure 21).

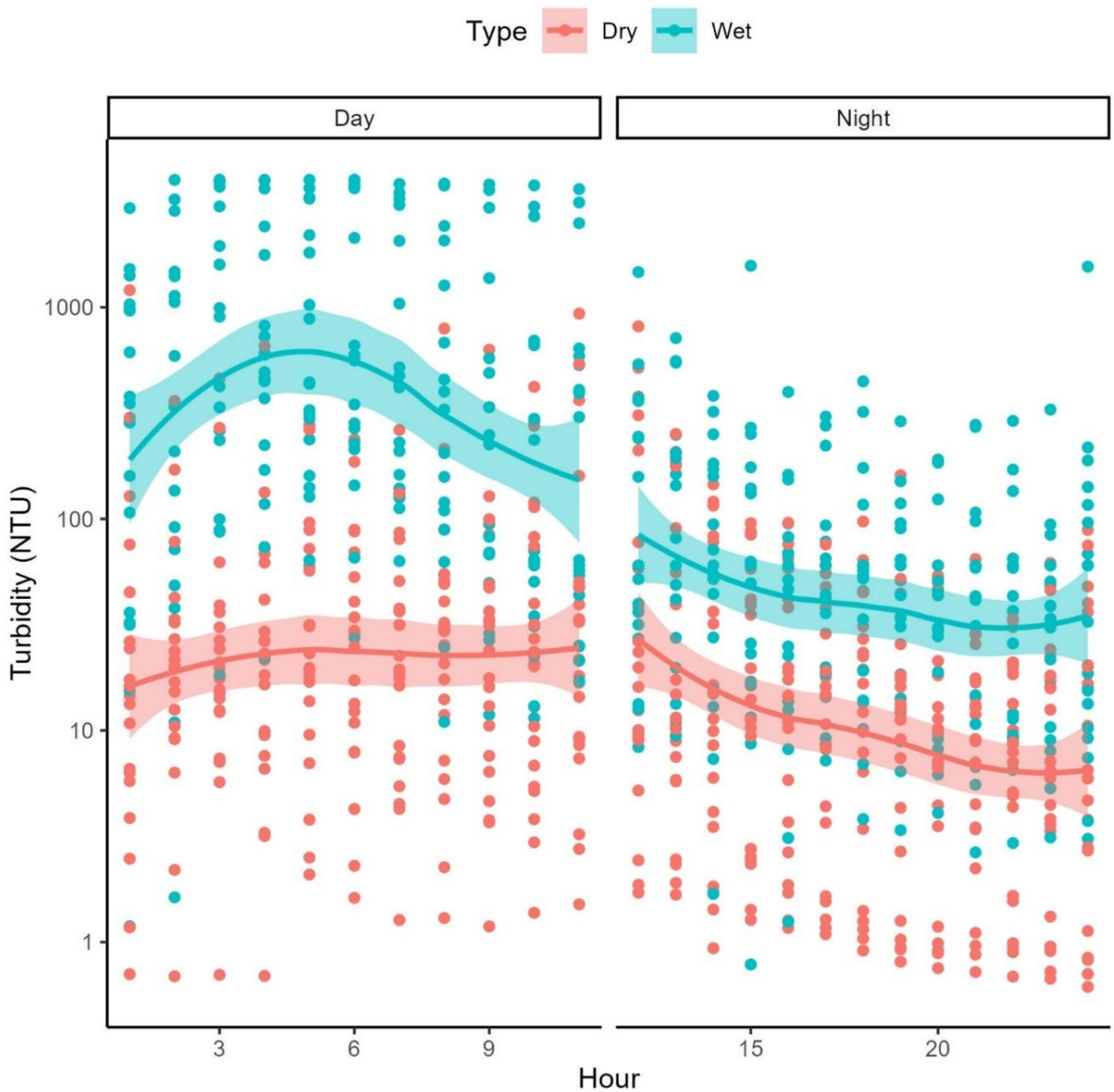


Figure 21: Comparison of Day (8AM to 8PM) Versus Day (8 PM to 8 AM) Turbidity Values

Model Selection

To test hypothesis 1A, the project team selected a linear mixed effects model, using the R package "nlme" (ref.). This package was selected because it allows the user to incorporate the impacts of serially correlated residuals, while also incorporating random variables (in this case the Site). It was suspected that, since the data evaluated for this project are sequential hourly data, the raw data and model residuals might be autocorrelated. When selecting the appropriate model, four options were compared (Table 19). The models were compared using the Akaike Information Criterion (AIC; Akaike, 1973).

Model Comparison

The model with the lowest AIC value is the best when using this comparison. As indicated in Table 19, the results of this model comparison suggested that including both the time of day (the "Day/Night" variable) and the Site as predictor variables, and accounting for autocorrelation resulted in the best model.

Table 19: Comparison of Statistical Models for Hypothesis 1A

Model Name	Predictors[1]	Residuals Correlation Structure[2]	DF	Akaike Information Criterion (AIC)
model[3]	Type	None	3	1986.05
modelT	Type	AR1	4	799.68
modelTSite	Type, (Site)	AR1|Site	5	783.05
modelTSiteND	Type, Night/Day, (Site)	AR1|Site	6	719.87

1: Random variables are in parentheses. In these models, Site was used as a blocking variable to account for the effects of each site.

2: An Autoregressive residual structure with a single lag (AR1) was used for all models. For models where Site was used as a blocking variable, a separate AR parameter was used for each site.

3: In addition to having a relatively high AIC value, this model had highly auto-correlated residuals.

Model Diagnostics

The selected model was evaluated to ensure that linear model assumptions were met. First, the residuals versus fits plots were evaluated (Figure 22) and suggest that the residuals show no pattern relative to fitted values, either in the dispersion or in the values of the residuals. Residuals were also close to normal, with slightly long tails (Figure 23). Finally, the model residuals show almost no autocorrelation, with a barely significant lag at 7 hours.

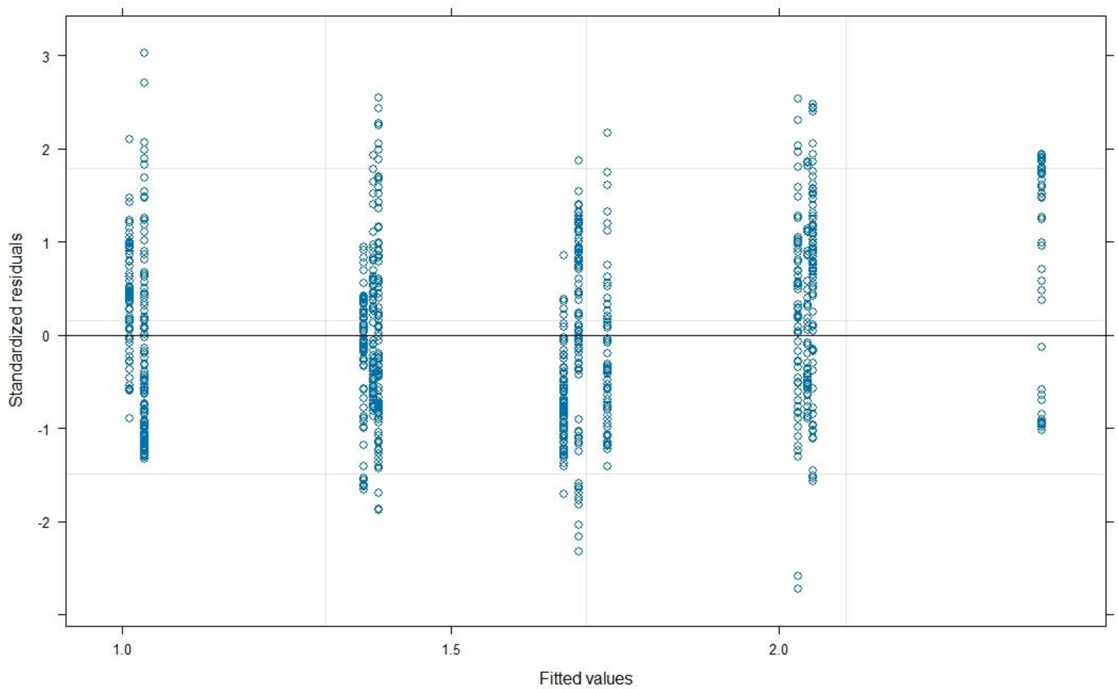


Figure 22: Residuals Versus Fits for the Selected Model for H1A (includes Time, Site, Night/Day and Type)

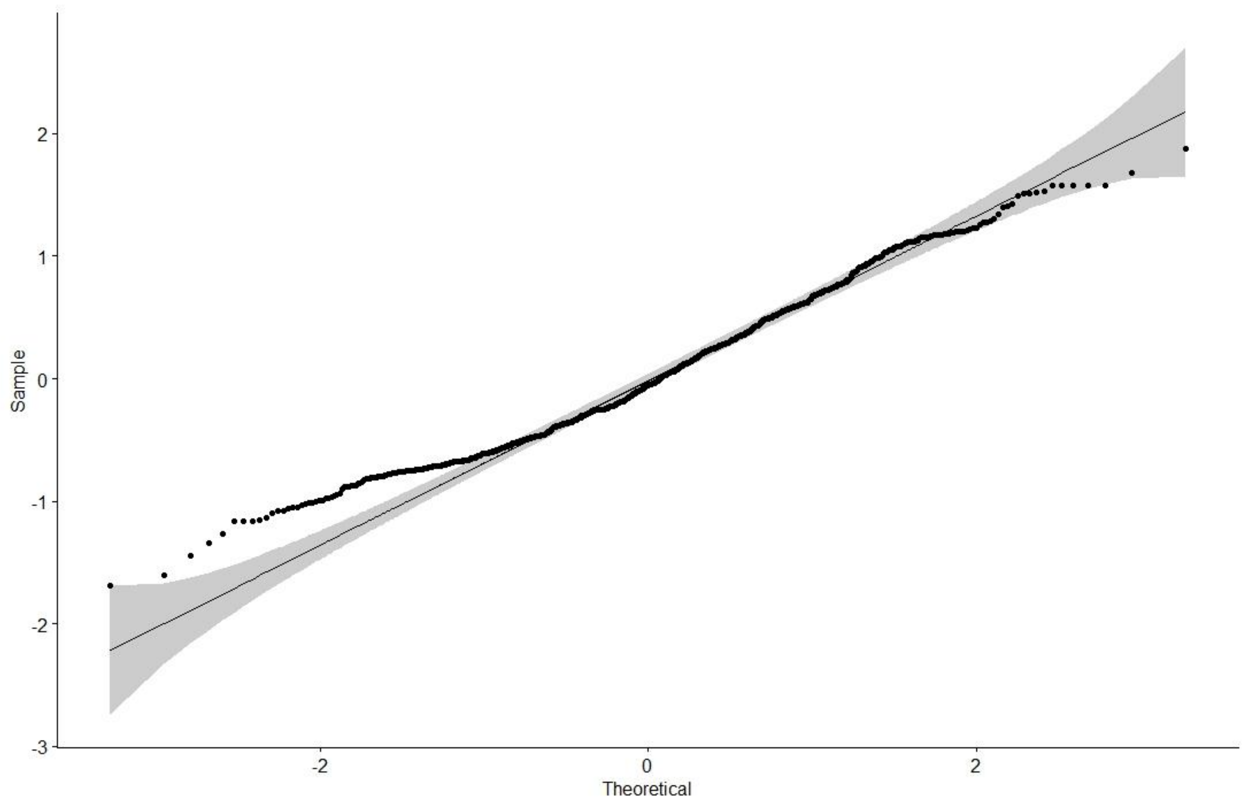


Figure 23: QQ Plot for Residuals of the Selected Model for H1A (includes Time, Site, Night/Day and Type)

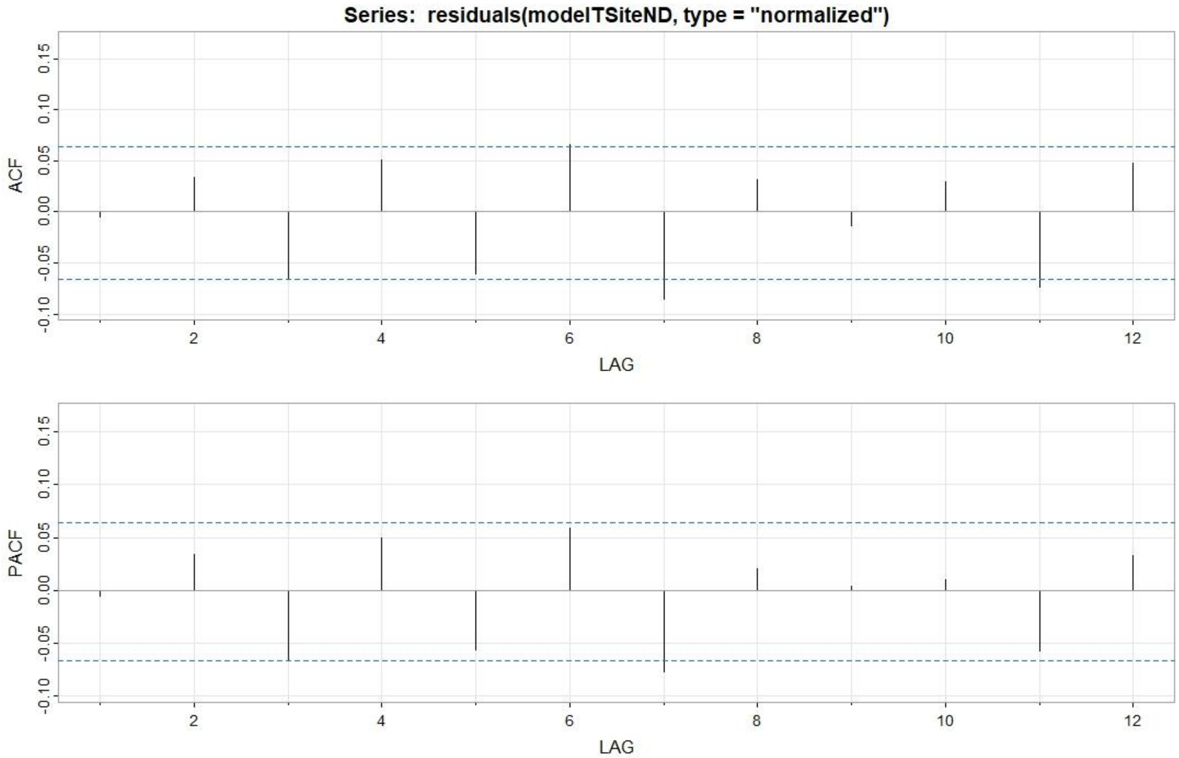


Figure 24: Autocorrelation for the Selected Model (modelTSiteND)

Interpretation of results

The p-values from the analysis were taken from the model output, and a range of the effect size (i.e., the effect of Wet construction methods), were calculated using the R package emmeans. Since the data were log-transformed, the effect is a multiplicative factor

Hypothesis 1B

The estimated hours exceeding Maryland's turbidity standards for Wet construction are less than 50% greater than the exceedance time for Dry construction.

To interpret Hypothesis 1B, data were converted to daily ratios (i.e., the fraction of values that exceeded the Maryland standard of 150) for the Day and Night periods of each day of construction. A fraction was used rather than a count to adjust for the fact that some missing data is present. The range of data used for this hypothesis are the same as 1A. When aggregated across all days, the cumulative probability of exceeding 150 appears to be higher for the Wet condition (Figure 25), and definitely higher during the day than night. The site may also be important, but this effect is somewhat unclear.

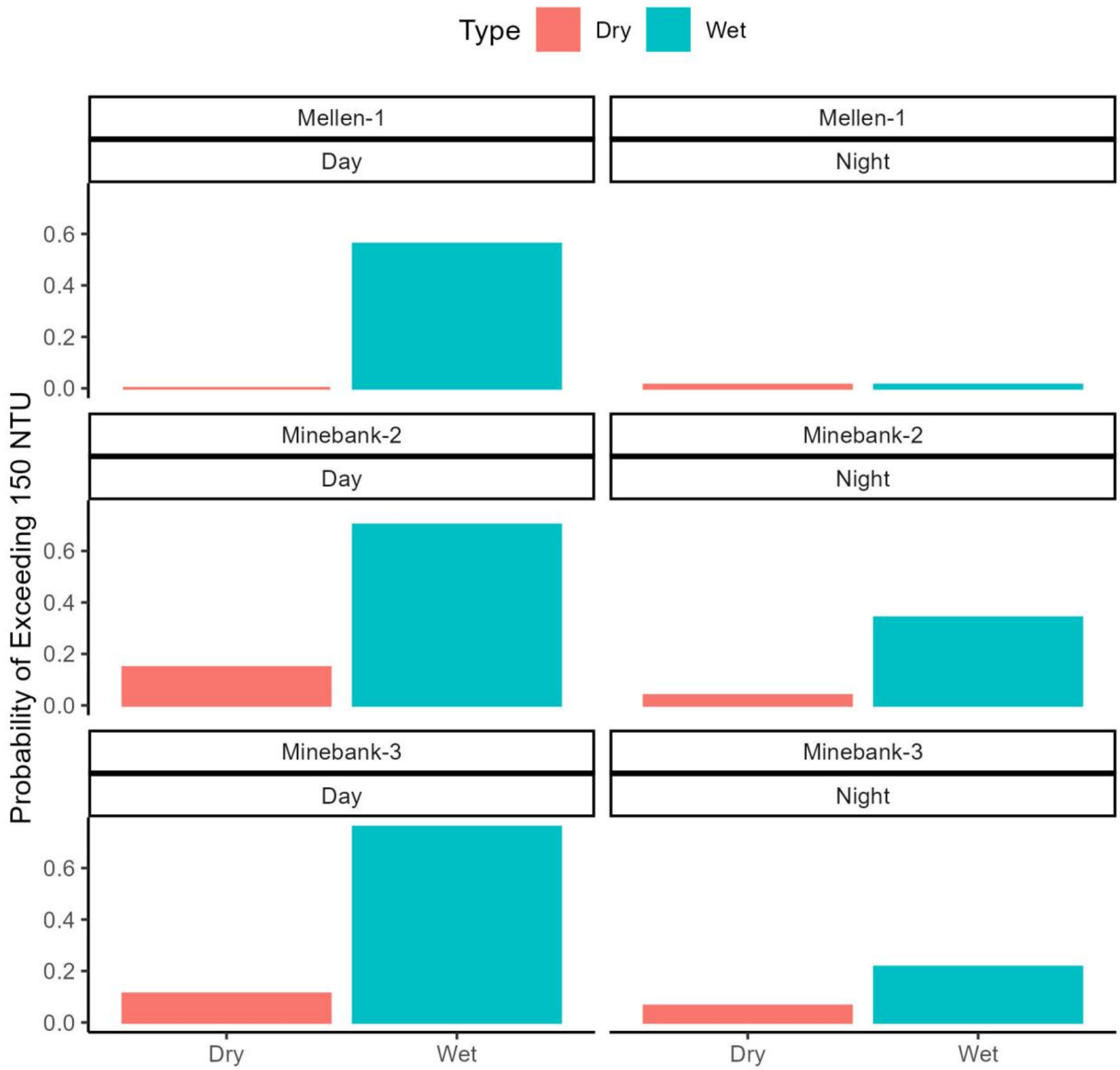


Figure 25: Percent Exceedance of 150 NTU for Dry and Wet construction

Model Selection

This hypothesis was tested using a logistic regression using the R package glm. Three different models were tested (Table 20), each using the daily probability of exceedance as the predicted variable. While including the "Night/Day" parameter improved the model, adding Site made the model perform slightly worse, so this factor was not included in the final model.

Table 20: Model Comparison for Hypothesis 1B

Model Name	Predictors[1]	DF	Akaike Information Criterion (AIC)
Exceedmodel[3]	Type	1	64.88
ExceedmodelND	Type+Night/Day	2	50.86
ExceedmodelSite	Type+Night/Day+Site	3	52.95

Model Diagnostics

The chosen model was evaluated for overdispersion. In a logistic model, the dispersion is assumed to be equal to 1, so that the residual deviance is approximately equal to the number of degrees of freedom of the residuals. This model has a deviance of 29 on 77 degrees of freedom. This means that the model is not over dispersed. It may be slightly underdispersed, which is less of a concern for hypothesis testing.

Model Interpretation

To evaluate the model, we developed confidence intervals around the odds ratio (the relative chance of exceedance) between Dry and Wet construction, using the emmeans function “pairs”, and transforming the log Odds back to an Odds Ratio.

Hypothesis 2

The suspended sediment load associated with Dry construction will not be meaningfully different than the load associated with Wet construction, such that the absolute difference between total suspended sediment loads (lbs.) is less than 25% of the average suspended sediment load between the two methods.

Testing Hypothesis 2 relied on two underlying regressions: 1) the relationship between TSS and Turbidity and 2) the relationship between Flow and Stage. (See Figure 6 in the main report). Both of these regressions were developed with relatively few points, and consequently confidence intervals using least squares assumptions were considered unreliable. As a result, confidence intervals were estimated using a bootstrapping technique and simulations to estimate the range of possible outcomes for annual sediment loads.

Step 1: Create Bootstrap Predictions

To develop confidence intervals, bootstrap series of TSS and Discharge (i.e. boot cases) were created for each combination of Site and Type (Wet/Dry). The bootstrapping technique develops confidence ranges by repeatedly refitting the model using a subset of the original model data. Since the sample size was very small, we used a slightly modified method to avoid fitting models with only one repeated point (e.g., only one stage-discharge used to develop the stage-discharge regression). Since the Stage-Discharge regression was modeled as a power relationship, the linear model was log-transformed and then transformed back to complete this step. For each refitted model the TSS or Discharge was calculated for a 5-minute time series of the appropriate input parameter (Turbidity or Stage). The result of this step was a 1000 5-minute time series of TSS and Flow for each Site/Type combination.

Step 2: Calculate Loads from Series in Step 1

Total loads were estimated by summing an observed time series of Turbidity (NTU) and Stage (ft) to calculate loads in 5-minute intervals so that:

Load = ΣTSS ×Discharge×.018712

Where:

TSS_i = Total Suspended Sediment (mg/L) at time interval i

$Discharge_i$= Discharge (cfs) at time interval i

Load = Load over the entire construction period lbs

0.01872 = conversion factor

The result of step 2 is a series of 1,000 load estimates for each Site-Type combination.

Step 3: Convert the estimates from Step 2 to Unit Loads

The length monitored varied between sites. Consequently, the loads developed in Step 2 were converted to unit loads using the following equation:

Unit_Load = Load/Length×100

Where:

Unit_Load = Load/ft monitored (lb/ft)
Load= Load in lbs (from step 2)
Length = Length monitored (ft))

The resulting estimates of Unit Load are summarized in Tables 21 and Figure 26.

Table 21: Loads and Unit Loads

Site	Construction Type	Median Load (lbs.)	Monitored Length (ft)	Unit Loads (lbs./ft Monitored)		
				Median	Lower Quartile	Upper Quartile
Mellen-1	Dry	45	350	0.13	0.09	0.47
	Wet	575	280	2.05	1.55	6.77
Minebank-2	Dry	540	105	5.15	3.32	7.06
	Wet	8,335	265	31.5	22.2	43.2
Minebank-3	Dry	661	245	2.70	1.50	3.47
	Wet	7,562	130	58.2	33.5	75.4

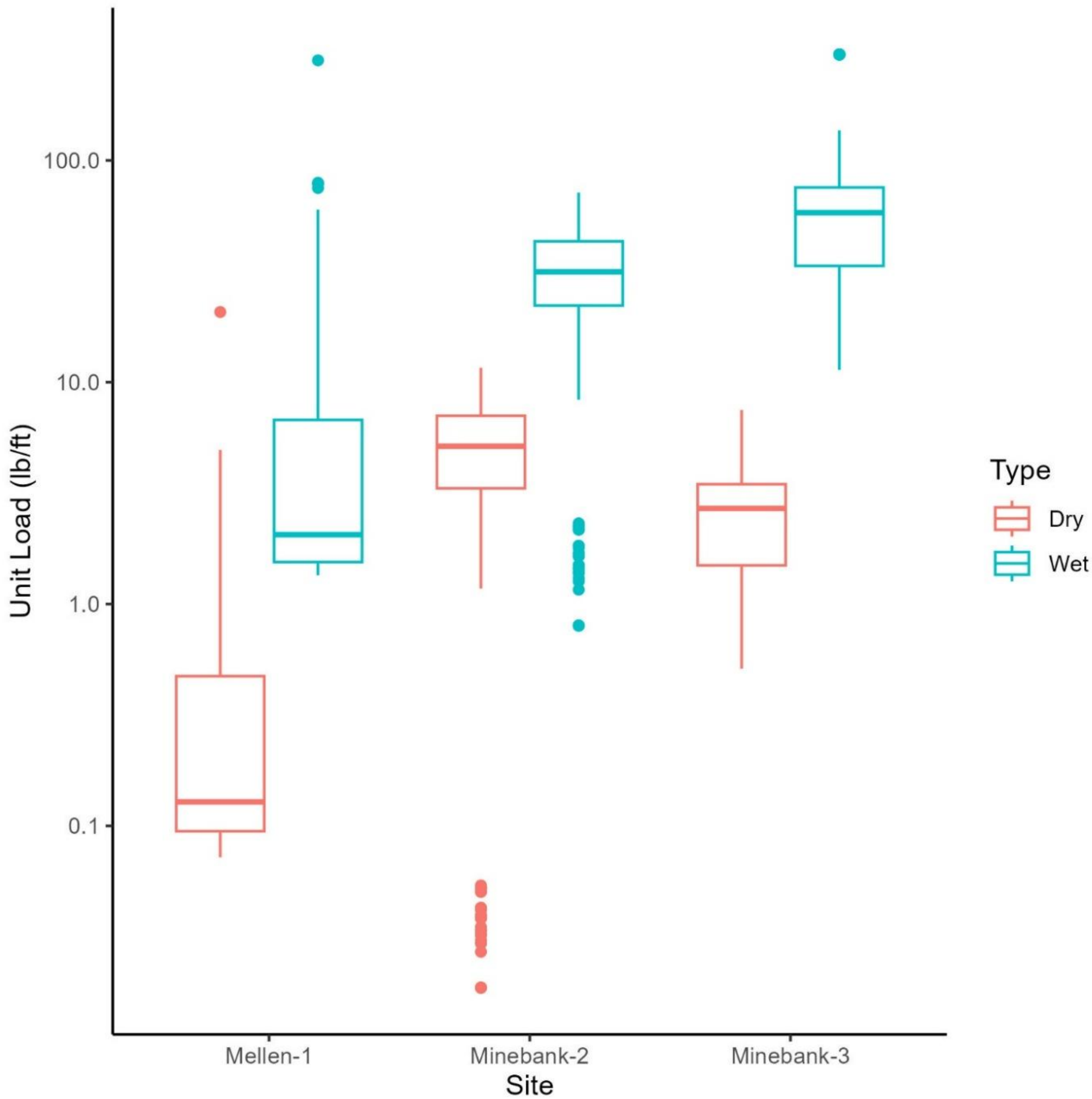


Figure 26: Box Plots of Unit Loads (Boxes reflect First and Third Quartile Values)

Step 4: Develop confidence intervals around the test statistic

In this step, Unit Load series constructed in Step 3 are compared to create a series of test statics, calculated as.

$$T = \frac{Unit\_Load_{wet} - Unit\_Load_{Dry}}{Unit\_Load_{wet} + Unit\_Load_{Dry}} \times 200$$

Where:

T=Test Statistic (Percent Increase above average Loading Rates)

200= Conversion Factor to percent and average of Wet and Dry

Since each model was refitted for a particular site, and the same refitted models were applied to both Wet and Dry construction types, simply calculating the test statistic for each boot estimate had the potential to underestimate the range of values calculated. To avoid this problem, the estimates from each boot case were randomized so that, for example, a test statistic may be calculated using boot case 1 of Wet Condition at Site 1 and boot case 100 of the Dry Condition at Site 1. Typical ranges for these test statistics are presented in Figure 27.

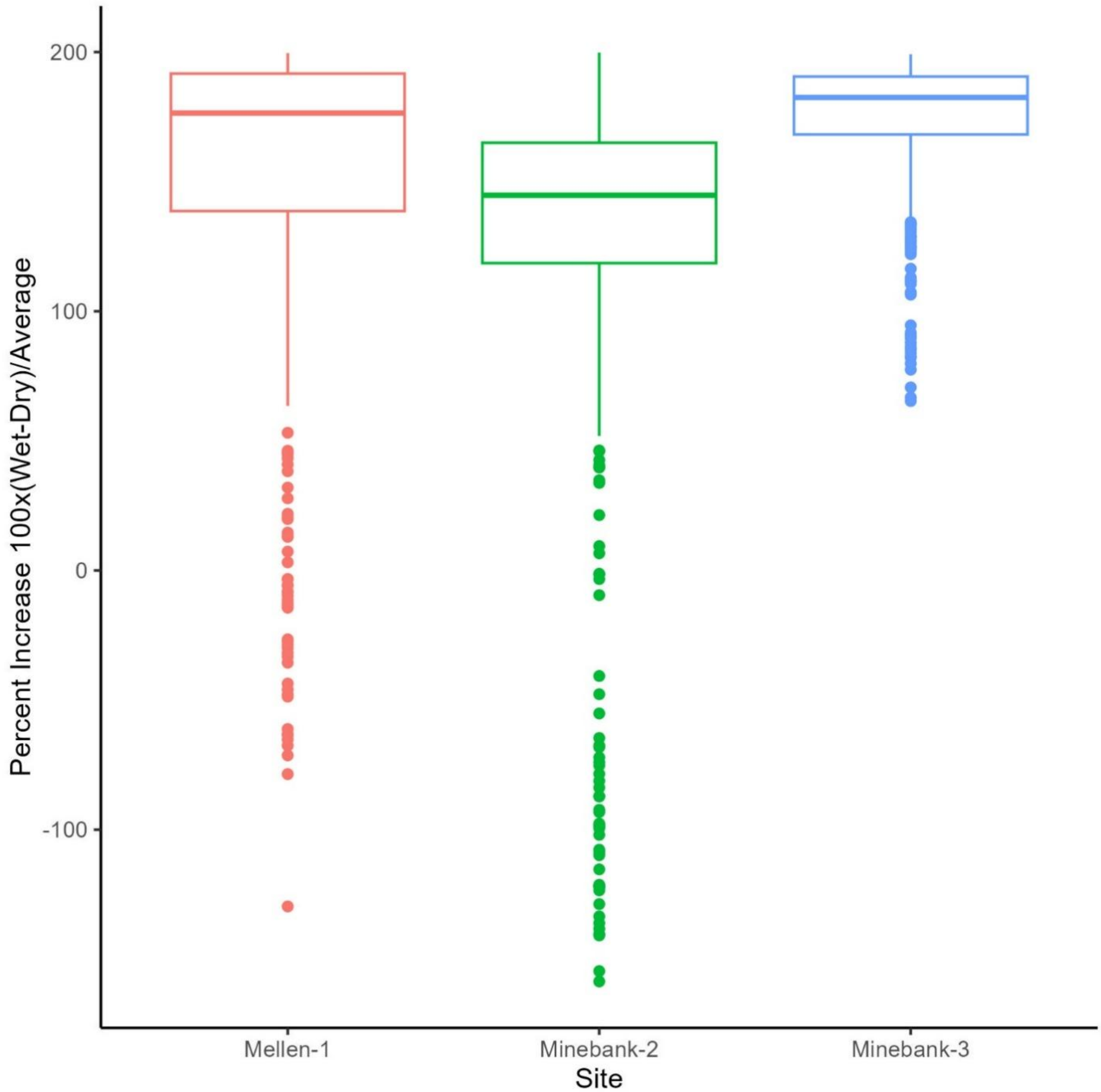


Figure 27: Box Plots of the Difference of Wet and Dry construction Unit Loads as a Fraction of the Average Unit Loads

Step 5: Interpret Results

The range confidence intervals developed in Step 4 both for each site and across all sites, are used to evaluate Hypothesis 2. This is a one-sided hypothesis, since we hypothesize that the test statistic is *less than* 25%. Consequently, we evaluate the 90% confidence interval to draw conclusions at p=0.05.

Hypothesis 3

The sediment load associated with the Construction in the Wet or Construction in the Dry will be significantly less than the sediment load associated with the 1.25-year storm for the watershed.

For Hypothesis 3, we used the Unit Load predictions developed for Hypothesis 2 to develop 90% confidence intervals around the Unit Load for each Site/Type combination. These unit loads were then multiplied by the total restoration lengths to estimate a range of load estimates.

The 1.25-year storm was estimated from sediment rating curves (See Figure 16 in the main report). Although these values were quite uncertain, they were treated as a point estimate for the purposes of this Hypothesis.

Step 1: Develop confidence intervals for the unit loads generated as a part of Hypothesis 2

In this step, 90% confidence intervals are generated for the unit loads developed for Hypothesis 2.

Step 2: Estimate the total loads for each restoration project

The total loads are calculated by multiplying the Unit Load confidence intervals developed in step 1 by total construction lengths for each site.

Calculations for steps 1 and 2 are summarized in Table 22.

Table 22: Estimates of Total Load for Each Restoration Project

Site	Type	Total Restoration Length (ft)	Unit Loads (lbs./ft)		Total Loads (lbs.)	
			Median	90% Confidence Interval	Median	90% Confidence Interval
Mellen-1	Dry	2,386	0.13	0.08-1.99	305	181-4,749
	Wet		2.05	1.38-27.1	4,900	3,304-64,747
Minebank-2	Dry	4,718	5.15	1.27-9.28	24,285	5,998-43,789
	Wet		31.5	8.91-56.7	148,389	42,055-267,427
Minebank-3	Dry	1,396	2.70	0.69-6.44	3,767	968-8,993
	Wet		58.2	15.5-134	81,207	21,590-186,790

Step 3: Compare the loads to the point estimate of the 1.25-year storm event

The results are then interpreted by comparing the load confidence intervals to the estimate of the 1.25-year load. The hypothesis will be considered true if the 95th percentile load is less than the point estimate for the 1.25-year load.

Results

This section summarizes the results for each hypothesis (Summarized in Table 23).

Table 23: Summary Results

Hypothesis	Result
1A: The observed average Turbidity (Average NTU) will be higher during the Wet construction Period.	Hypothesis is confirmed with Wet construction significantly and meaningfully higher.
1B: The estimated hours exceeding Maryland's turbidity standards for Wet construction are less than 50% greater than the exceedance time for Dry construction.	The hypothesis was ***not*** confirmed, with exceedances under Wet construction significantly more than 50% more likely when compared with Dry construction conditions.
2: The suspended sediment load associated with Dry construction will not be meaningfully different than the load associated with Wet construction, such that the absolute difference between total suspended sediment loads (lbs.) is less than 25% of the average suspended sediment load between the two methods.	This hypothesis was ***not*** confirmed, with data suggesting that the load increase is significantly higher than 25%.
3: The sediment load associated with the Construction in the Wet or Construction in the Dry will be significantly less than the sediment load associated with the 1.25-year storm for the watershed.	This hypothesis was supported, with the hypothesis proving definitively true in 5 of 6 sites.

Hypothesis 1A

The observed average Turbidity (Average NTU) will be higher during the Wet construction Period.

The results suggest that the average turbidity is higher during the Wet construction period across all sites, with a p-value of <0.001. The effect size of Wet construction methods is also substantial, with the effect of Wet construction methods being on average 4.6 times that of Dry construction methods, with a 95% confidence range of between 2.8 and 7.6 times that of Dry construction methods.

Table 24: Summary Results for Hypothesis 1A

Statistic	Modeled Values
Mean (Log Ratio)	0.66
Standard Error of (Log Ratio)	0.11
Geometric Mean of (Ratio)	4.58
Confidence Interval of the Ratio	2.75-7.61

Hypothesis 1B

The estimated hours exceeding Maryland's turbidity standards for Wet construction are less than 50% greater than the exceedance time for Dry construction.

The results suggest that the hours of exceedance for Wet construction are much more than 50% higher than those of Dry construction, with a p-value of <0.001. Rather than calculating the hours of exceedance, we calculated the probability of exceedance during construction. In fact, the model results suggest that the chances of exceeding the Maryland standard of 150 is on average 14.1 times higher under Wet construction versus Dry, with a 95% confidence interval of between 3.3 and 60.1 times higher.

Table 25: Summary Results for Hypothesis 1B

Statistic	Value
Log Odds Ratio	2.65
Standard Error of the Log Odds Ratio	0.74
Odds Ratio	14.09
Odds Ratio Confidence Interval	3.30-60.14

Hypothesis 2

The suspended sediment load associated with Dry construction will not be meaningfully different than the load associated with Wet construction, such that the absolute difference between total suspended sediment loads (lbs.) is less than 25% of the average suspended sediment load between the two methods.

The modeling results suggest that the % increase at each site and pooled across all locations is much higher than 25%. As the results in Table 26 suggest, the median increase is not less than 25%. In fact, the results suggest that the median loading rate is significantly higher than 25% at each site, and among pooled data.

Table 26: Results for Hypothesis 2

Site	Statistic Ranges (% of Average Load)	
	Median	90% Confidence Interval
Mellen-1	176	69-197
Minebank-2	145	41-187
Minebank-3	182	133-196
All Sites (Pooled Data)	171	77-196

Hypothesis 3

The sediment load associated with the Construction in the Wet or Construction in the Dry will be significantly less than the sediment load associated with the 1.25-year storm for the watershed.

This hypothesis was generally true, with one notable exception. In general, the load estimates for restoration were much lower than estimates of the 1.25-year storm load, with the median typically less than 40% of the 1.25-year load. At the upper confidence interval, the estimated loads for all but one site did not exceed 70% of the estimated 1.25-year storm load.

The Minebank-3 site in the Wet condition, however, appeared to have loads meaningfully but not significantly higher than the 1.25-year storm load. One possible explanation for this unexpected result is that the sediment rating curve for Minebank-3 has a much lower R^2 value than the regressions developed for Sites 1 and 2 and includes one point with very low TSS concentration. It is possible that the 1.25-year storm at this location has been underestimated.

Table 27: Summary Statistics for Hypothesis 3[1]

Site	Construction Type	1.25-Year Storm Load (lbs.)	Estimated Load (lbs.)		Estimated Load as a percentage of the 1.25-year storm	
			Median	90% Confidence Interval	Median	90% Confidence Interval
Mellen-1	Dry	213,405	305	181-4,749	<1%	<1%-2.2%
	Wet	213,405	4,900	3,304-64,747	2.3%	1.5%-30.3%
Minebank-2	Dry	391,638	24,285	5,998-43,789	6.2%	1.5%-11.2%
	Wet	391,638	148,389	42,055-267,427	37.9%	10.7%-68%
Minebank-3	Dry	37,213	3,767	968-8,993	10.1%	2.6%-24%
	Wet	37,213	81,207	21,590-186,790	218.2%	58%-501.9%

1: Text in red represent cases where the estimated load exceeds the estimate of the 1.25-year storm load,