RESEARCH & DEVELOPMENT

Continuing Intensive Monitoring of Nutrient and Material Load in Claridge Nursery Stream "The Canal": assessing the water quality impacts & benefits of a stream restoration in the coastal plain

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16. Abstract

This report constitutes the second phase to document the water quality benefits of a stream restoration in the coastal plain of North Carolina. This phase compares the pre-restoration and post-restoration states of the water quality and hydrochemical signature of 'the canal' at the Claridge nursery in Goldsboro, NC. We made the hypothesis that a robust way to quantify the water quality benefits of this stream restoration was the use of cumulative nutrient load indicators. However, these indicators required the use of state-of-the-art instruments capable of capturing flow and water quality on a near continuous basis over the long term. After meticulous correction and all the necessary verifications, we were able to show that the restoration of the Claridge nursery canal, effectively creating a flowing wetland, was able to lower the nitrate loads by about 30% over three post-restoration consecutive years. This was accompanied by an overall carbon sequestration. The seasonality of the nitrate retention suggests that much of the nitrate unaccounted for was associated with the growth of vegetation, either through plant uptake and/or through denitrification associated with the release of organic matter from dead vegetation and the exchange conditions that they provided in the channel and with the floodplain. Increased residence time associated with the aquatic vegetation working as a filter time likely increased the capacity of the stream to retain nitrate. The seasonality of the nitrate retention may suggest that shorter monitoring periods could be chosen to represent a 'summer' vs. a 'winter' effect. However, averaging these effects would not necessarily represent the effective benefits over the long term. Instead, we suggest that monitoring should focus on cumulative indicators used over the long term for projects for which there is a high potential for nutrient retention. Fewer projects may have to be monitored, but using the necessary investment.

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ABSTRACT

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This report constitutes the second phase to document the water quality benefits of a stream restoration in the coastal plain of North Carolina. This phase compares the pre-restoration and post-restoration states of the water quality and hydrochemical signature of 'the canal' at the Claridge nursery in Goldsboro, NC. We made the hypothesis that a robust way to quantify the water quality benefits of this stream restoration was the use of cumulative nutrient load indicators. However, these indicators required the use of state-of-the-art instruments capable of capturing flow and water quality on a near continuous basis over the long term. After meticulous correction and all the necessary verifications, we were able to show that the restoration of the Claridge nursery canal, effectively creating a flowing wetland, was able to lower the nitrate loads by about 30% over three post-restoration consecutive years. This was accompanied by an overall carbon sequestration. The seasonality of the nitrate retention suggests that much of the nitrate unaccounted for was associated with the growth of vegetation, either through plant uptake and/or through denitrification associated with the release of organic matter from dead vegetation and the exchange conditions that they provided in the channel and with the floodplain. Increased residence time associated with the aquatic vegetation working as a filter time likely increased the capacity of the stream to retain nitrate. The seasonality of the nitrate retention may suggest that shorter monitoring periods could be chosen to represent a 'summer' vs. a 'winter' effect. However, averaging these effects would not necessarily represent the effective benefits over the long term. Instead, we suggest that monitoring should focus on cumulative indicators used over the long term for projects for which there is a high potential for nutrient retention. Fewer projects may have to be monitored, but using the necessary investment.

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1.1 Introduction

In 2011, North Carolina Department of Transportation (NCDOT) began construction on Transportation Improvement Program R-2554 U.S. Highway 70 Goldsboro Bypass (TIP R-2554). As part of the planning process for R-2554, NCDOT was required to follow a three-step plan to avoid, minimize and mitigate for impacts to aquatic systems. Section 404 of the Clean Water Act (CWA) requires environmental mitigation follow these three steps (EPA, 2008). NCDOT distributed the required compensatory mitigation across nine mitigation sites. The largest of these sites is the restoration at the North Carolina Forestry Service (NCFS) Claridge Nursery located in Section A of R-2554 (NEU, 2011). Table 1 lists the unavoidable impacts, which required compensatory mitigation at the NCFS Claridge Nursery.

Table 1. Environmental impacts of R-2554 and the required mitigations (NUE, 2011)

	Impacted by R-2554	Required by mitigation	Mitigated at Claridge
Streams (feet/m)	15,125 / 4,610.1	15,263 / 4652.2	10,397 / 3169 (68%)
Wetlands (acres/hectare)	27.16 / 10.99	29.36 / 11.88	-
Riparian Buffer (ft^2/hectare)	1,358,482 / 12.6	1,453,479 / 13.5	994,657 / 9.2 (68%)

The goal of the research team, directed by Dr. Birgand from the department of Biological and Agricultural Engineering at NC State University, is to answer questions posed by NC DOT, which include: (1) What is the magnitude of the water quality benefit of a stream restoration in rural North Carolina? (2) What are the likely drivers at play? (3) Can one derive monitoring guidelines for future restoration projects? The research team has proposed to use state of the art continuous water quality monitoring methods before, during, and after restoration to capture the bulk water quality effect of the restoration in this Claridge stream. The research team has proposed to quantify the restoration effect by monitoring the changes in cumulative loads at the middle and downstream end of the reach relative to the cumulative loads entering the beginning the reach, during both the pre- and post-restoration. The study uses the data collected by Chiao-Wen Lin (Lin, 2017) from 2013 until 2015 and the data collected during the first post-restoration year, 2017 until 2018. A full breakdown of the monitoring timeline is in Table 2.

Table 2. Monitoring and Personnel Timeline

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2013												▨
2014	**Pre-restoration Monitoring by Chiao-Wen Lin (Lin et al., 2017)**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2015	▨							**DN Monitoring by Danielle Winter**				
2016	░	░	░	░	░	░						
2017						**Post-restoration Monitoring by Cyrus Belenky**	▨	▨	▨	▨	▨	▨
2018	▨ **Post-restoration monitoring by Qianyu Hang**	░	░	░	░	░	░	░	░	░	░	░
2019	**Post-restoration monitoring by Qianyu Hang**	░	░	░	░	░	░	░				

An Introduction to Stream Restoration Monitoring

Lack of Monitoring Consensus

Stream restoration is a growing field around the world. In the United States, stream restoration and environmental mitigation projects spent roughly $15 billion between 1990 and 2005 (Bernhardt et al., 2005). This equates to roughly $1 billion spent annually on restoration and mitigation. Bernhardt et al. (2005) made a conservative estimate of annual restoration spending and the actual cost of restorations since 2005 has likely exceeded $12 billion ($1 billion/year over 12 years) (Kenney, Wilcock, Hobbs, Flores, & Martínez, 2012). While spending on mitigation and restoration is plenty, there is little consensus on the efficacy of restoration. This is a result of lack of data, insufficient data, or poor quality data. Data collected on roughly 37,000 river and stream restorations by the National River Restoration Science Synthesis (NRRSS) showed that a fifth of compiled projects listed no objectives for the restoration. Downs and Kondolf (2002) emphasize that it cannot take for granted that restoration projects are inherently "good" or positive. Only one tenth of the projects conducted any kind of monitoring or assessment, with the majority not intending to analyze the collected data (Bernhardt et al., 2005). Previous studies analyzed the effect on water quality by comparing the restored reach to a nearby reference reach (Bosch & Hewlett, 1982; Colangelo, 2014; Howson, Robson, & Mitchell, 2009). While this method is less time intensive, only requiring monitoring of the restored and reference reach post-restoration, it does not compare the state of water quality pre-restoration to that post-restoration. Predetermined restoration goals and adequate pre- and post-restoration data are required to determine the success of a restoration. Without monitoring pre- and post- restoration and comparing the change between the two states, it becomes hazardous to reliably quantify the restorations effect on the area (Morandi, Piégay, Lamouroux, & Vaudor, 2014).

In addition to non-existent monitoring plans, many projects implementing monitoring, did it poorly. The same study concluded that projects with the worst monitoring methods reported the highest success rates, showing that current techniques improperly quantify the restoration effect (Morandi et al., 2014). Contemporary water quality monitoring for environmental mitigation in North Carolina relies on infrequent sampling of surface waters. The U.S. Army Corps of Engineers (USACE), Wilmington District guidelines require sample collection at six-month intervals. The sampling interval for water quality is infrequent because the USACE does not evaluate mitigation success based on water quality data (USACE & EPA, n.d.). Figure 1. shows a comparison between measured electrical conductivity at monthly, weekly, daily and hourly intervals. The results show that monthly and even weekly sampling fail to capture detailed system behavior. While, daily and hourly intervals capture events of shorter duration and show a more detailed picture of the processes taking place in the body of water (Kirchner, Feng, Neal, & Robson, 2004).

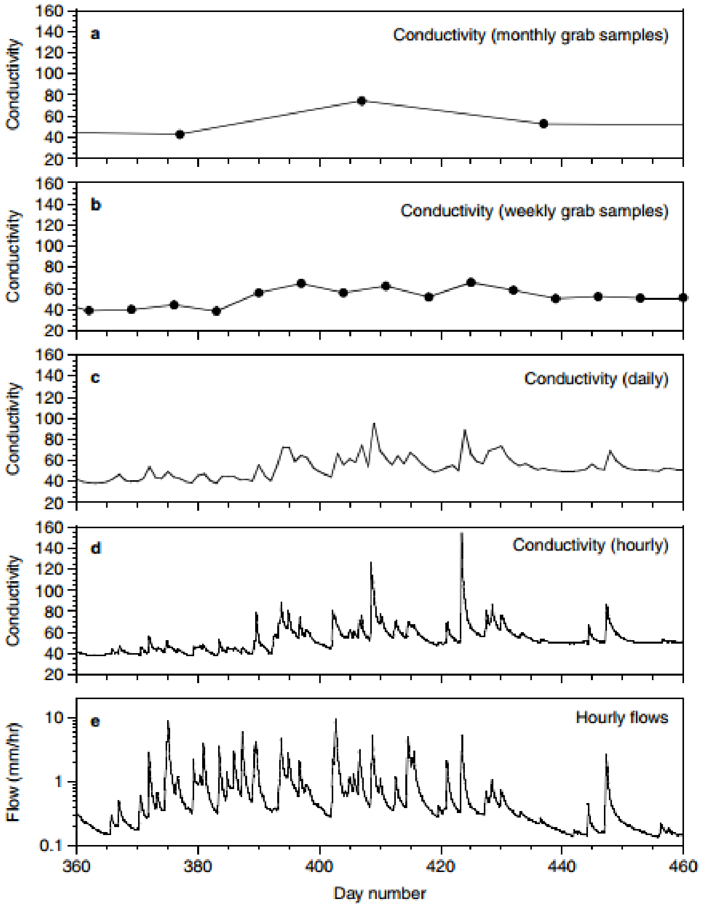


Figure 1. Temporal resolution comparison for electrical conductivity relative to flow (Kirchner et al., 2004)

The low temporal resolution of such monitoring schemes provides an imprecise representation of system behavior. Additional studies have shown that the error associated with these contemporary monitoring methods can be several times greater than the expected restoration effect (F Birgand, Appelboom, Chescheir, & Skaggs, 2011). From a mathematical perspective, Birgand at al. (2017) and Howden et al. (2018) have suggested that these discrete concentration indicators, used in contemporary water quality monitoring, are equivalent to ‘derivative’ indicators, which are subject to high coefficients of variation. As a result and unless their full variability taken into account, concentrations are inherently not robust indicators (F. Birgand, Howden, Burt, & Worrall, 2017; Howden, Birgand, Burt, & Worrall, 2018). ‘Integrative’ indicators that (mathematically) integrate or cumulate derivative indicators are inherently more robust to detect trends.

We have therefore proposed to use cumulative loads as robust indicators, which entails integrating over time both concentration and velocity data measured at high frequency. The proposed frequency, 15-minute intervals, has been found to be frequent enough to capture the temporal variations occurring within the reach (Lin, 2017). Sampling at high frequency has already shown potential to track pollutant patterns not possible with infrequent sampling. Multiple studies have used in-situ spectrometer to collect high frequency, 30-minute interval, samples with results that underscore the need for high temporal resolution data. Morandi et al., (2014) suggest that increased number of samples collected with a high sampling frequency produces an increase in statistical power to detect ecological changes in mitigation and restoration project (Morandi et al., 2014). We affirm the need for a three-fold shift in restoration monitoring is required to determine, with increased certainty, the effect of stream restoration on water quality. The three changes being: (1) monitoring restorations, (2) monitoring pre- and post-restoration, and (3) monitoring at high frequency.

The method used to detect the bulk water quality effect of the stream restoration of The Canal uses a “paired-watershed” approach – a method often applied in hydrology (Andréassian, Parent, & Michel, 2003; Bosch & Hewlett, 1982; Hornbeck, Adams, Corbett, Verry, & Lynch, 1993; Stednick, 1996). The paired-watershed approach differs, however, from the traditional approach because instead of pairing spatially separate watersheds, the watersheds in our case are nested, corresponding to three stations along the restored section. Three monitoring stations were constructed, along the unrestored reach and after the restoration was completed, at the beginning (CLUP), the middle (CLMD), and at the end (CLDN). From here on, these stations are referred to as CLUP, CLMD and CLDN. The three stations along the reach monitored water quality both pre- and post-restoration. CLUP functions as the control for the paired watershed study while CLMD and CLDN functioned as 'treatment stations'. We compared the cumulative loads passing through each station to the cumulative load passing through the reference station. We hypothesize that the degree of inflection of the double mass curves of the post-restoration curve form the pre-restoration curve should be indicative of the restorations effect on bulk water quality (Figure 2).

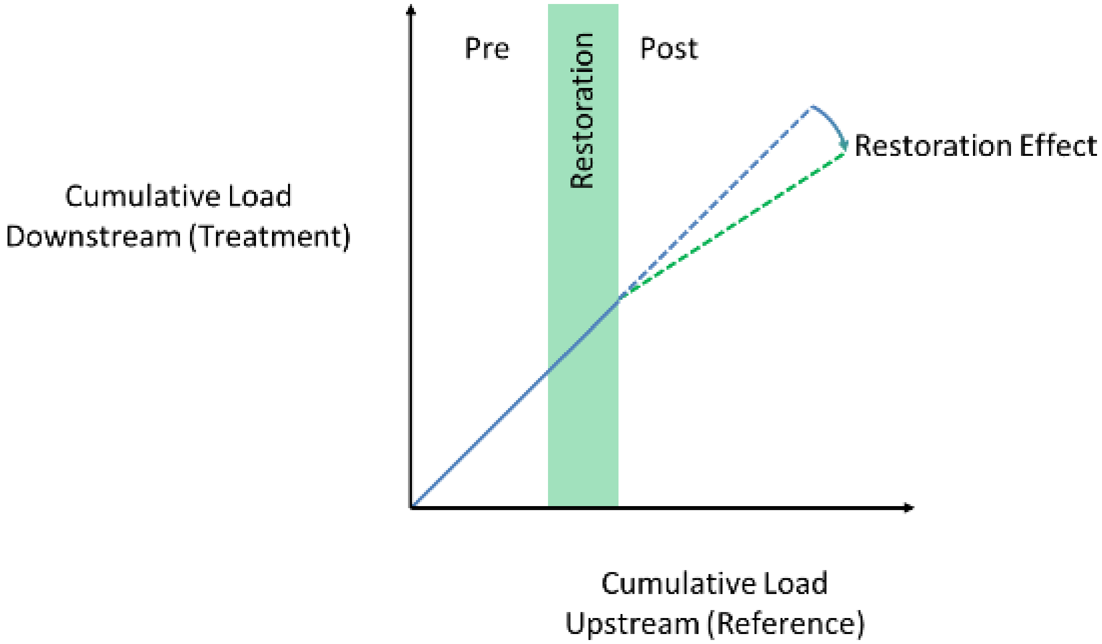


Figure 2. Hypothetical double mass curves. Projected pre-restoration double mass curve (blue), post-restoration double mass curve (green) and the restoration effect.

However, this method relies on two other hypotheses. Firstly, that nutrient additions corresponding to the nested watersheds between stations do not change significantly between the pre- and post-restoration periods. Secondly, that the magnitude of the bulk water quality effect has to be several times larger than the monitoring uncertainties.

Lin (2017) has shown that conventional sampling methods can generate errors in annual loads in the order of, e.g. ± 30% for nitrate for monthly sampling (Lin, 2017). Applying these results on the cumulative loads at CLUP and CLDN (Figure 3A) for example, we can draw the “angles” of uncertainty corresponding to annual loads ± 30%. However, to detect a water quality effect the uncertainty “angles” have to be several-fold smaller than the estimated effect (Figure 3B). Uncertainty “angles” smaller than the measured effect are reasonable, as Lin et al. (2017) found that uncertainties for some parameters to be as low as, e.g. ± 3% for nitrate (Lin, 2017). In an effort to reduce the uncertainty in water quality monitoring, it is essential that we measure flow and pollutant concentration as accurately as possible. To do so we have opted for high frequency Doppler based flow measurements in controlled wooden sections, and high-frequency concentration measurements using in-situ spectrophotometers.

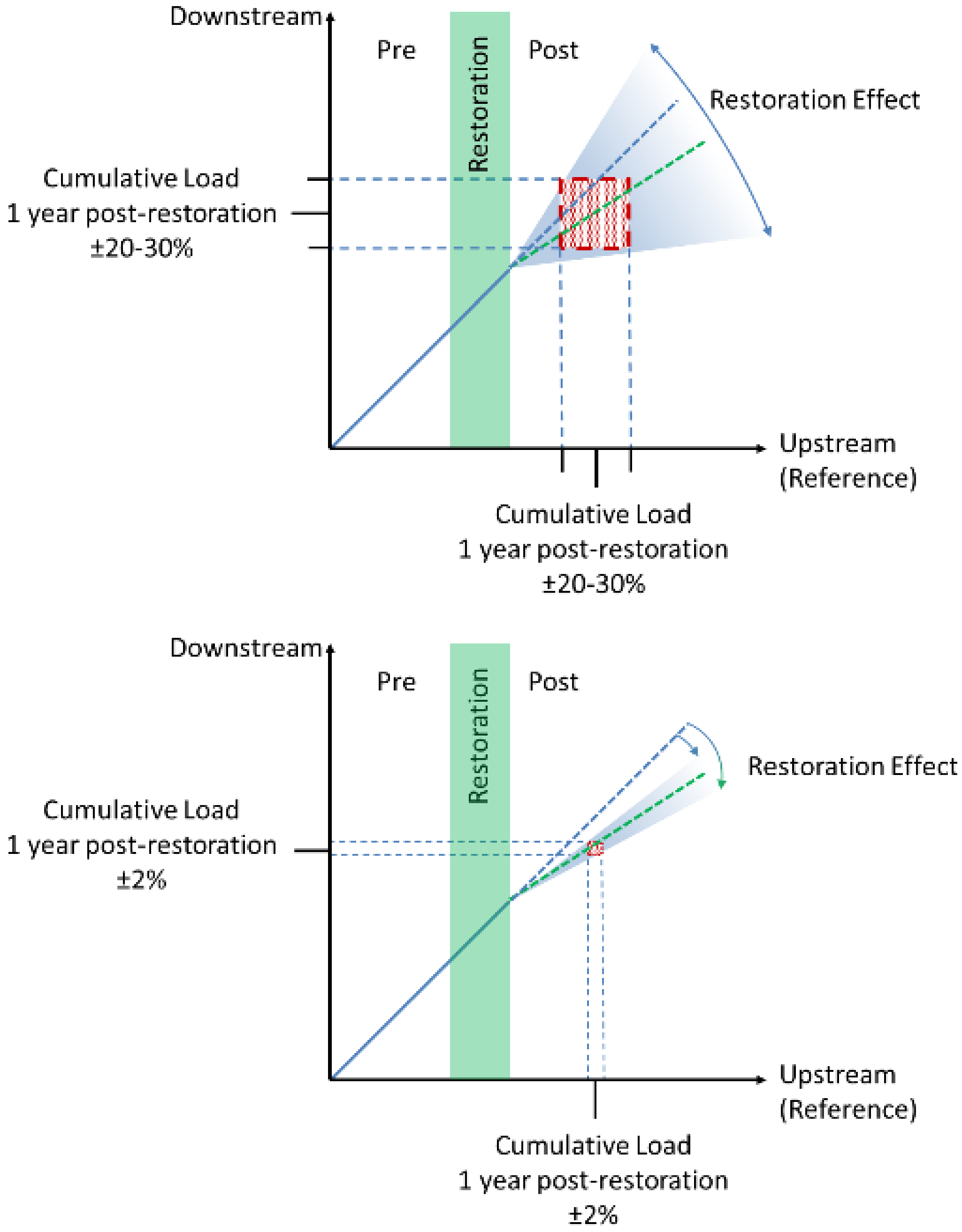


Figure 3. Top hypothetical double mass curves and cumulative load error ranges using conventional sampling techniques (A) and bottom high frequency sampling (B). Projected pre-restoration double mass curve (blue) and post-restoration double mass curve (green).

1.3 Hypotheses and goals

We hypothesize the following:

- that it is possible to monitor a restored stream effectively using high frequency in-situ UV-Vis spectrophotometry;

- that combined with high frequency velocity and flow data that it is possible to construct double mass curves for the post-restoration period using concentration calibration method established during the pre-restoration monitoring period;
- that it is possible to quantify the restoration effect between pre- and post-restoration by comparing cumulative volumes and loads of DOC and nitrate passing through station relative to a reference station; and
- that it is possible to determine the treatment effect of the restoration per unit length of stream.

The objectives for this study are:

1. Quantify the restoration effect using double mass curves from data collected pre- and post-restoration for DOC and nitrate through the reach;
2. Identify the timing and the chronology of the apparent water quality benefits and identify the drivers of the observed effects
3. Derive guidelines for future monitoring of stream restoration

1.4 Methods

Site Description

As mentioned previously, the location chosen by the NCDOT for the compensatory mitigation of TIP R-2554 is on the NCFS Claridge Tree Nursery. The Claridge nursery is located in Wayne County North Carolina, just west of the city of Goldsboro. One of the prominent features at Claridge is “The Canal”, a 2,206-meter-long agricultural ditch that runs approximately north south through the nursery. Over the course of 12 months beginning in the fall of 2015, a private environmental consulting firm under the direction of the NCDOT conducted a priority 2 restoration of The Canal. The entire mitigation project consists of three parts, the primary stream reach M1 (formerly The Canal), and two unnamed tributaries UT1 and UT2 as seen in figure 1. A third unnamed tributary (UT3) flowed into the reach between CLMD and CLDN but was not altered as part of the restoration. These sections are 2,456, 230 and 541 meters, respectively. To create the new meandering channel and 19-meter-wide floodplain for Section M1 construction crews excavated the surface surrounding the agricultural ditch by a depth of approximately 2.5 meters. Construction crew performed the same process for UT1 and UT2 but added no meandering channel, leaving the channels to self-design as the restoration matured.

Station Selection & Infrastructure

Once the restoration construction was completed, BAE personnel constructed monitoring stations on site. Post-restoration monitoring of the canal used three sampling stations similar to those used during the pre-restoration phase. We followed the same approach as the pre-restoration phase. Trapezoidal wooden sections were installed in the channel with an effort to keep the shape as close as possible to the geometry of the channel on the bottom and against the banks, to minimally impede the flow. Station locations were selected in areas as linear as possible and where there was the lowest chance of downstream scour. BAE personnel constructed CLUP and CLDN stations close (10 – 15 m) to the beginning and end of the restored reach (M1). We built CLMD approximately 1,670 m downstream of CLUP, just downstream of the two unnamed tributaries (UT1, UT2) that flowed into M1. Figure 4 indicates the locations of the monitoring stations along the reach.

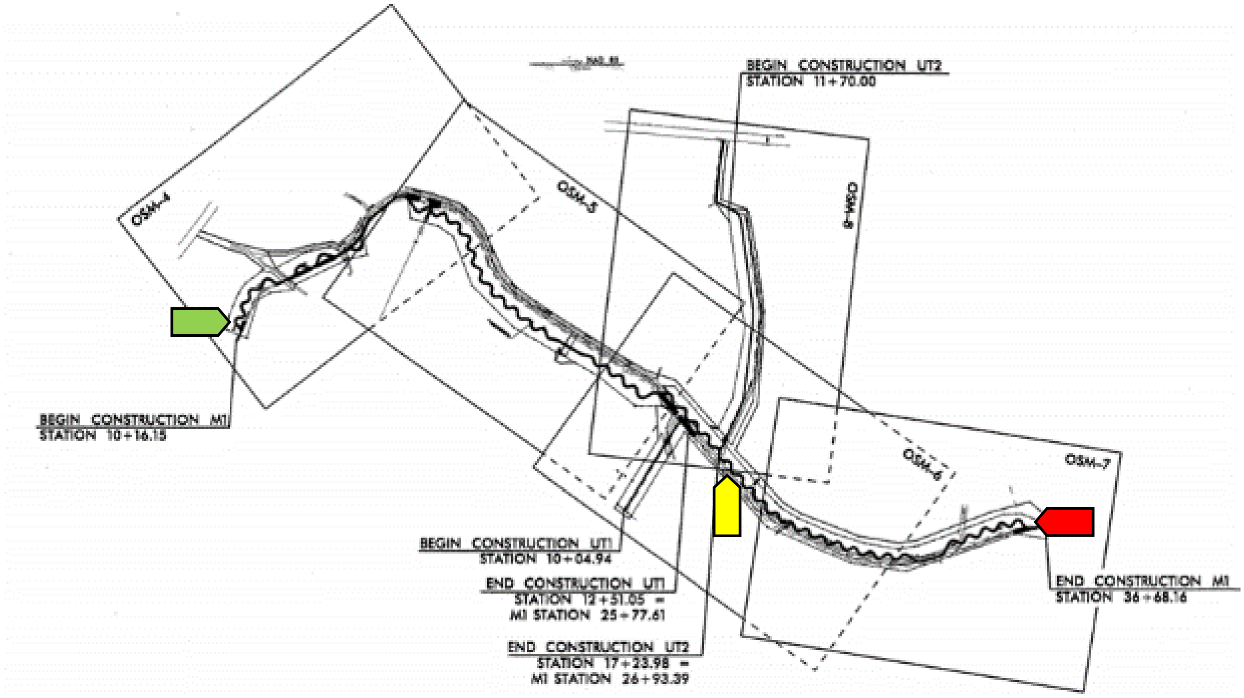


Figure 4. Plan view of the stream reach M1, UT1 and UT2. Monitoring stations CLUP (green), CLMD (yellow) and CLDN (red)

Figure 5. CLUP station with raised platform

Figure 6. CLMD station with raised platform

Figure 7. CLDN with raised platform

The trapezoidal wooden sections are used to create as laminar flow as possible in a wetted cross-section of precisely measurable area. Belenky and Birgand pre-fabricated the wooden sections as much as possible in Weaver Laboratories prior to installation to reduce build time and ensure uniformity of construction. Proper installation required that we excavate the streambed by a depth roughly equal to the height of the wooden sections bottom to bring the section about 5 cm above the channel bottom to limit sedimentation. Five-foot sections of rebar, set at an angle, anchored the bottom of the trapezoid to the streambed. Brackets and lag bolts clamped the rebar to the interior members of the bottom.

Station installation began in August of 2016 and was due to finish by mid-October. However, on October 8th 2016, Hurricane Matthew destroyed the CLDN station, the only operational station at the time, pushing the completion of all stations into early 2017.

Flow Calculations

In lowland areas, and because of variable downstream control, the stage-discharge relationship tends to be unstable and may change during events and over time (François Birgand, Lellouche, & Appelboom, 2013). Consequently, the measurement of the stage only to calculate flow cannot be applied reliably for our conditions. Instead, we have used acoustic Doppler velocity meters (ADVMs) installed in the trapezoidal wooden structures, to measure water velocity and stage. The known channel geometry provided by the section reduces the uncertainty in determining discharge through the monitoring station (Robinson & Chamberlain, 1960) . The ADVMs are mounted to the bottom of the downstream end of the wooden sections, where flow is most laminar. The ADVMs also log stage and temperature in addition to measuring velocity through the section.

ADVMs used in this study function by sending out bursts of ultrasonic sound beams in multiple directions through the water column. Particles traveling through the path of the beam reflect the sound back at the instrument, albeit with a frequency shift. This frequency shift is what the instrument uses to calculate the velocity of particles within the beam. The sound beams are directed left and right of center as well as fore and aft from the device (SonTek/YSI, 2011; SonTek, 2015). Lin (2017) has found that the latter velocities were more stable and used as index values to calculate flow (Lin, 2017). Measuring flow using the Doppler principle works best under laminar flow conditions, hence the importance of constructing the trapezoidal wooden section for each station where flow was already somewhat laminar and make it more laminar. Because storm events carried more particles from which the ultrasonic bursts could bounce, these events provided especially smooth flow measurements. Measurements are poorer during times of low velocity and high stage, where the amount of reflected sound from moving particles was relatively small and became blurred by noise from, e.g., fish or wind ripples at the stream surface. Because of these considerations, we closely scrutinized the velocity data and analyzed it for smoothing and outlier removal. I describe the methods to correct for noise later on.

The measured stage and the known geometry of the trapezoids were used to determine the wetted cross-sectional area. Cross-sectional average velocities through each section were calculated using the 'index velocity' method at each station (F. Birgand et al., 2005; ISO 15769, 2010; Morlock, Nguyen, & Ross, 2002). To do so a 'velocity rating curve' was derived from a linear regression between manual mean velocities and the sensor velocities for the same time-stamp. Manually measured mean velocities were calculated from manual gauging obtained during bi-weekly maintenance visits using the velocity area method (ISO 748, 1997). Flow was calculated from the product of the cross-section average velocity (V) and the wetted cross-sectional area (A) (Equation 1).

$$Q = V * A \qquad \text{(Equation 1)}$$

To ensure that the calculated flow rate through the wooden section was as accurate as possible, we had to rout all flow through the section. This includes flow events where stage rises to inundate the floodplain. To restrict flow across the floodplain to pass only through the section, a floodplain curtain was erected across the floodplain (Figure 8). Extending from the upstream mouth of the wooden section, upstream and outward toward the terrace, the polypropylene curtain funnels water on the floodplain through the wooden section. Held upright by 2x4s driven into the floodplain and one foot of the curtain buried below the elevation of the floodplain to prevent water from short circuiting below the curtain and causing erosion. During high or "flashy" rain events, it is expected that the floodplain curtain may be overtopped or knocked over. The curtains are used as release valves and the flow measurements at these times are unreliable.

Figure 8. Image of the trapezoidal wooden section and the floodplain curtain at CLMD during construction

High Frequency Water Quality Measurements and Water Sampling

Spectrophotometers were used at each monitoring station to collect light absorbance data of the water passing through each station. These spectrophotometers are capable of capturing absorbance values in the 220 to 742.5 nm wavelength range across a 5 mm path length. Similar to flow, absorbance values are used as 'index values' or input to 'water quality or absorbance rating curves' to calculate concentrations. The instrument comes stock with an absorbance-rating curve, known as the 'global calibration', to measure Nitrate (NO_3), Dissolved Organic Carbon (DOC), and turbidity.

Previous research has shown, however, that it is possible to create superior rating curves on site, referred to as 'local calibrations', to correlate the absorbance values at different wavelengths to known pollutant concentrations. These local calibrations are been derived for Total Kjeldahl Nitrogen (TKN), Total Suspended Solids (TSS), Total Phosphorus (TP), Phosphate (OPO_4), and salinity in addition to Nitrate, DOC and turbidity (J R Etheridge et al., 2014). Light absorbance data is best correlated to known pollutant concentrations with the use of a partial least square regression (PLSR) (J R Etheridge et al., 2014; Lepot et al., 2016; Lin, 2017). The sampling method used to collect the local calibration data is discussed in following sections.

Discrete water sampling for establishing water quality rating curves

Discrete samplers are commonly used for concentration-based water quality studies. Using a discrete sampling scheme, an automated sampler can only collect as many discrete samples as it has bottles available before the bottles need to be changed. In this study, automate samplers were programmed to sample at 14-hour intervals allowing 24 samples (maximum number of samples per sampler) to be collected over the two-week intervals. Unacidified samples were transferred to a cooler during bi-weekly maintenance visits to the site and returned to Weaver Laboratories for analysis by the Environmental Analysis Laboratory. To create as best a local calibration for the spectrophotometers as possible, Lin (2017) has shown that it is best to have stratified concentration samples as well as samples stratified across the bi-weekly monitoring period. Stratification across time is beneficial when correcting for fouling of the spectrophotometer optics.

In situ spectrophotometers installation and maintenance

Submersible spectrophotometers are subject to chemical and biological fouling and this has to be dealt with. The spectrophotometers were installed under surf boards (Figure 5 to Figure 7) equipped with mechanical wipers that scrubbed the optics before each measurement. This dramatically reduced the extent of the fouling between two consecutive field visits. During maintenance visits conducted every two weeks, manual cleaning was performed. For that, the "dirty" absorbance values were measured in DI water and air and saved. Lenses were then cleaned with 5% hydrochloric acid (HCl) and a cleaning brush. Absorbance was measured between multiple iterations of cleaning until the absorbance values reached acceptable values (less than 10 m^{-1} across the spectrum) or remained constant and saved again. Lenses were considered clean if the absorbance for the fingerprint began between 0 and 14 and declined to a value below four in the 750 nm wavelength range (J R Etheridge et al., 2014; Flemming, 2011; Whelan and Regan, 2006)

Monitoring System Designs

After hurricane Matthew and a large event in April 2017, all equipment was hosted onto wooden platforms raised about 2 meters above the floodplain (Figure 5 to Figure 7). Two metal monitoring boxes protected electronic equipment and the automatic samplers. Power was supplied with two 12V Flooded Marine Battery installed in parallel for winter and recharged by a 120 Watt solar panel and 10A charge controller. The automated samplers were wired to a dedicated 12V marine battery with their own solar panel and charge controller. This system was robust enough to allow 14-hour sampling intervals even during a streak of cloudy weather.

Data Collection and Site Maintenance

A two-person team conducted data collection and site maintenance every two weeks. They serviced each station one at a time, starting downstream and working their way upstream. The team downloaded data from all instruments, transferred the discrete water quality samples to pre-labeled coolers and reloaded the discrete samplers with clean sampling bottles. Site maintenance includes physical and chemical cleaning of equipment, instrument calibration and upkeep and vegetation control during the growing season. It was important to regularly inspect and service equipment because a single piece of equipment failing at best creates a data gap for that station and in the worst-case scenario for the entire monitoring period.

Table 3. Sampling Scheme Summary

Generic Name	UV-Vis Spectrophotometer	Discrete Sampler	Grab Samples	Doppler Velocity Meter
Purpose	Spectral Data	Local Calibration of Spectral Data	Degradation study of Discrete Samples	Velocity & Stage

Frequency	15 minutes	14 hours	2 weeks	15 minutes
Analyzed for	NH_4^+, TKN, TSS, DOC, TP, PO_4,	NH_4^+, TKN, TSS, DOC, NO_x, TP, PO_4	NH_4^+, TKN, TSS, DOC, NO_x, TP, PO_4	Flowrate

Lab analysis

When selecting samples for analysis by the Environmental Analysis Laboratory (EAL) in BAE, we chose samples distributed regularly across the 2-week period to stratify samples temporally. Sudden increases in either velocity measured by the ADVM or spectrophotometer absorbance qualified samples for preferentially analysis in addition to the standard temporal spread. This kind of preferential sample selection creates greater concentration stratification of samples (Lin, 2017). For EAL to analyze the samples for ammonium, orthophosphates, and DOC we refrained from acidifying the samples. Instead, we conducted a sample degradation study (details below). Back in a laboratory environment, the samples were separated into two aliquots. The first aliquot required 140 ml of each discrete samples to be filtered in order to obtain a 40 ml filtered solution. The Environmental Analysis Laboratory in Weaver Laboratories used the 40 ml filtered solution to determine NH_4-N, NO_3-N/NO_2-N, PO_4-P, and DOC in each sample. EAL analyzed the remainder of the discrete sample for TKN, TP and TSS. The EAL is supervised by Faculty Advisor Dr. Jay Cheng and managed by Research Operations Manager Dr. Cong Tu. Table 4, shown below, lists the EPA method used by the EAL to analyze each analyte.

Table 4. Analyte and EPA methods used by the EAL

Analyte	Method	Detection Limit (mg/l)
TKN	Standard Methods 4500-Norg B, Bran & Leubbe Autoanalyzer III	0.03
NH_3	EPA Method 351.2	0.01

NO_3^-	EPA Method 353.2	0.01
TP	EPA Method 365.4	0.03
PO_4-P	EPA Method 365.1	0.01
TSS	EPA Method 160.3	0.5
DOC	EPA Method 415.1 with Teledyne Tekmar Apollo 9000, 0.45 µm filter	0.01

Degradation Study

Distance to the site, 52 miles, limited ease of access to the site and directly affected the monitoring setup. Due to the distance, we could not transport the discrete samples back to D.S. Weaver Laboratories on a daily basis. This in combination with refraining from acidifying the discrete water quality samples required us to conduct a sample degradation study. The degradation study consisted of three pairs of grab samples taken at each of the monitoring stations during bi-weekly maintenance visits. The first of each pair, labeled “Station_Name, Date, GS-A”, was returned to Weaver Labs and refrigerated while the second grab sample, “Station_Name, Date, GS-B”, was left inside the discrete sampler and collected during the following maintenance visit. A pair T-Test determined if there was any concentration difference between GS-A and GS-B (i.e. if there was a difference between samples brought back to the lab immediately and those left in the samplers for two weeks).

Method to calculate concentrations from absorbance data

We predicted high-frequency concentration data using the absorbance values, collected by *in-situ* UV-Vis spectrophotometers, as index data. The spectrophotometers (Spectro::lyser from S::CAN®) measure the absorbance of light in water for 256 wavelengths from 220 to 750 nm, covering the UV to the visible range. For each measurement, 256 absorbance values where obtained creating an absorbance spectrum, also referred to as fingerprint. The S::CAN ®

spectrophotometers used in this study are equipped with a ‘global calibration’, a method used to correlate the absorbance data with parameters known to absorb light (e.g. DOC, nitrate and TSS). While the ‘global calibration’ functions well to calculate parameter concentrations, more precise calibrations can be achieved using Partial Least Square Regression (PLSR). PLSR models were established for each parameter by coupling fingerprints with laboratory concentrations measured from discrete samples. Applying PLSR to the absorbance data has also been proven to predict concentrations of parameters that do not absorb light (J R Etheridge et al., 2014). The regressions we created using PLSR concentration data from discrete water quality samples stratified temporally and across a range of concentrations in order to provide the best possible calibration (Lin, 2017).

Calculating Nutrient Loading, Cumulative Loads and Cumulative Volumes

Cumulative load (L) passing through each station were calculated by multiplying the measured pollutant concentration (C) at a given time (t) with the flow rate (Q) through the wooden section at the same instance. In this study, the time (t) is the 15-minute measurement interval of the instruments.

$$L = \int C(t) * Q(t)\, dt \qquad \text{(Equation 2)}$$

Data pre-processing and gap filling for missing data

The method proposed to quantify water quality benefits of stream restoration relies on the ability to obtain as continuous data as possible. However, because of equipment failure and sometimes human errors, data were sometimes obviously erroneous and had to be corrected, and sometimes were completely missing, and had to be filled.

Flow Data Corrections

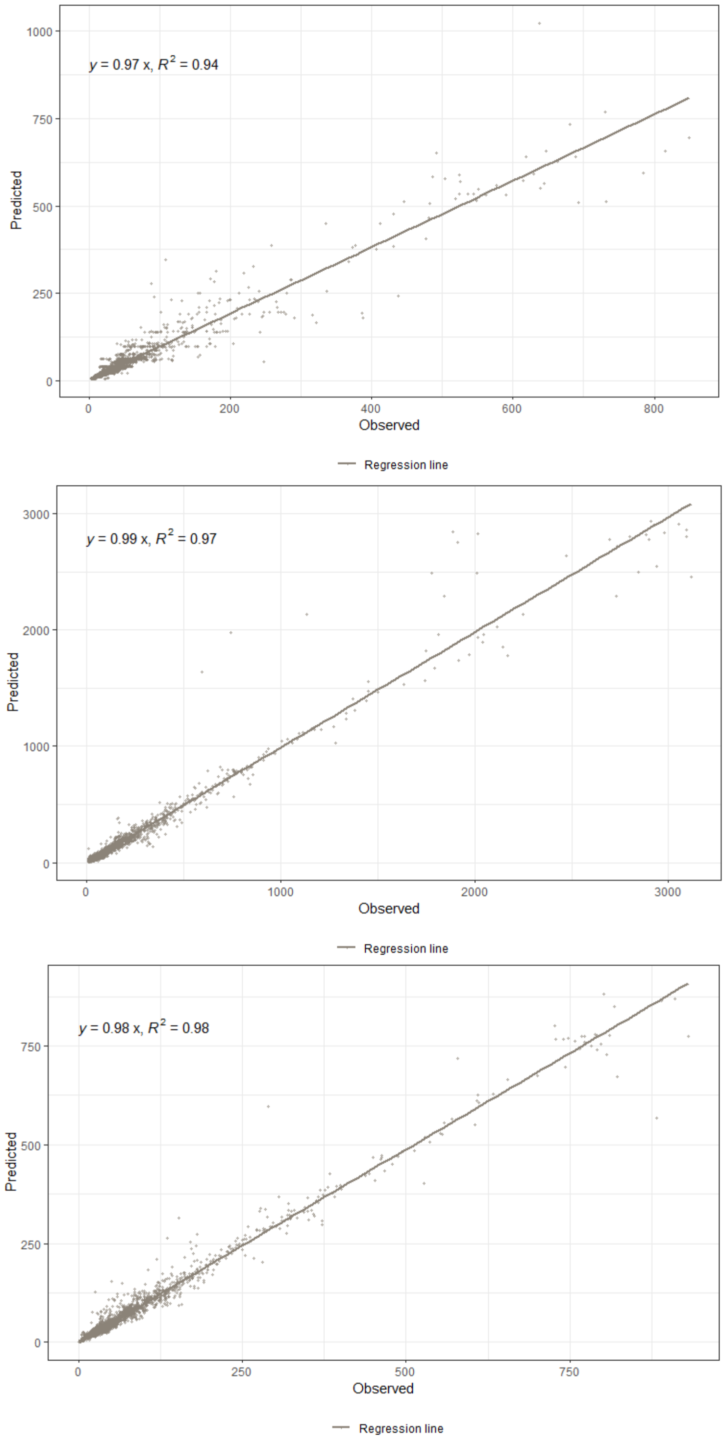
Doppler velocity meters work very well under laminar flow and for velocities greater than 10 cm. Velocity measurements, however, are subject to ‘noise’ in the data and also to ripples formed by the wind at the water surface, generating erroneous readings. Erroneous readings were removed and replaced from those calculated by a moving average method that used measurements deemed reliable.

For missing data, machine learning algorithms were used to correlate flow measured at one station from flow at the two others. Algorithm tested included linear regression, Boosted tree, Boosting machine, and K-nearest neighbors. The Boosted tree and K-nearest neighbors provided the best algorithms (Figure 9).

Spectral and concentration data corrections

Because of equipment malfunction, spectral data were not always available, or gave obviously erroneous readings (e.g., spikes and troughs in the global calibration time series discorrelated with flow variations). The latter were detected and excluded using R and the Aquarius software.

Similarly to missing flow data, machine learning algorithms were used to correlate concentrations at one station with flow and concentrations of the two others. Extreme gradient boosting and K-nearest neighbors provided the best algorithms for nitrate and DOC (Figure 10 and Figure 11).



CLUP ~ CLMD + CLDN
Best model: Boosted tree

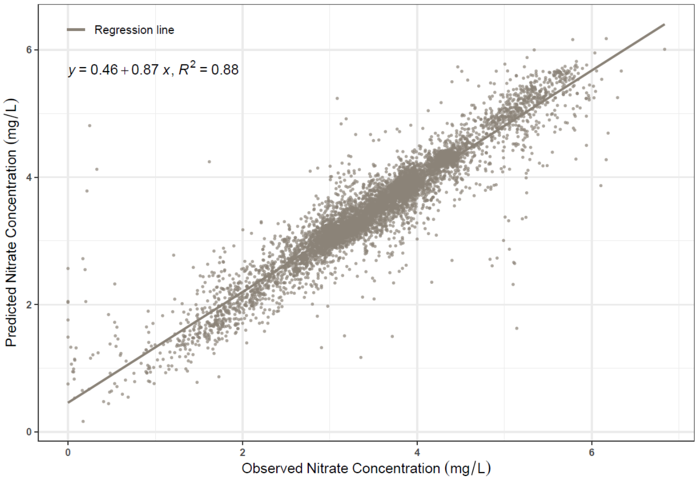
CLMD ~ CLUP + CLDN

Best model: K-nearest neighbors

CLDN ~ CLUP + CLMD

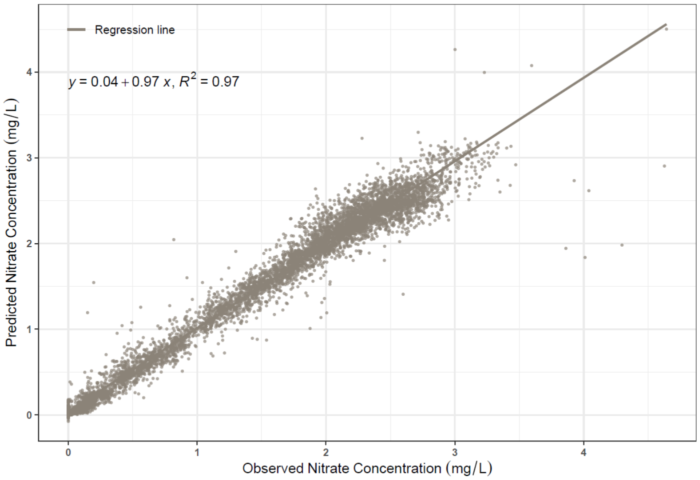
Best model: K-nearest neighbors

Figure 9: Regressions obtained using machine learning algorithms between flow rates of the two other stations. These regressions were used to fill in missing flow data



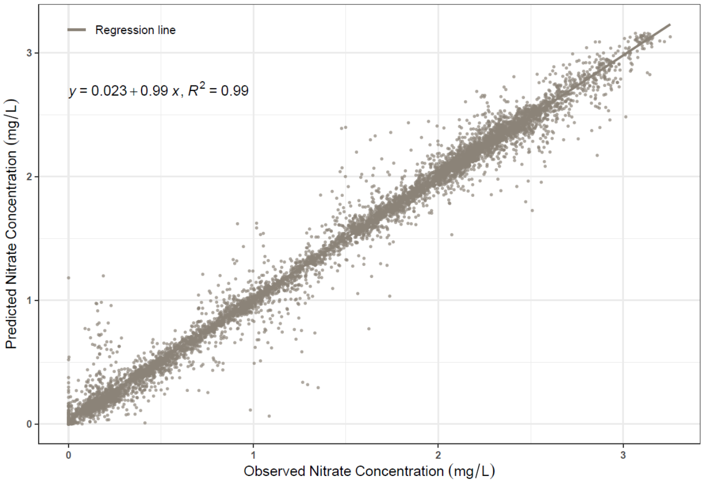
Nitrate_up ~ flow_up + flow_md + flow_dn + nitrate_md + nitrate_dn

Best model: Extreme gradient boosting



Nitrate_md ~ flow_up + flow_md + flow_dn + nitrate_up + nitrate_dn

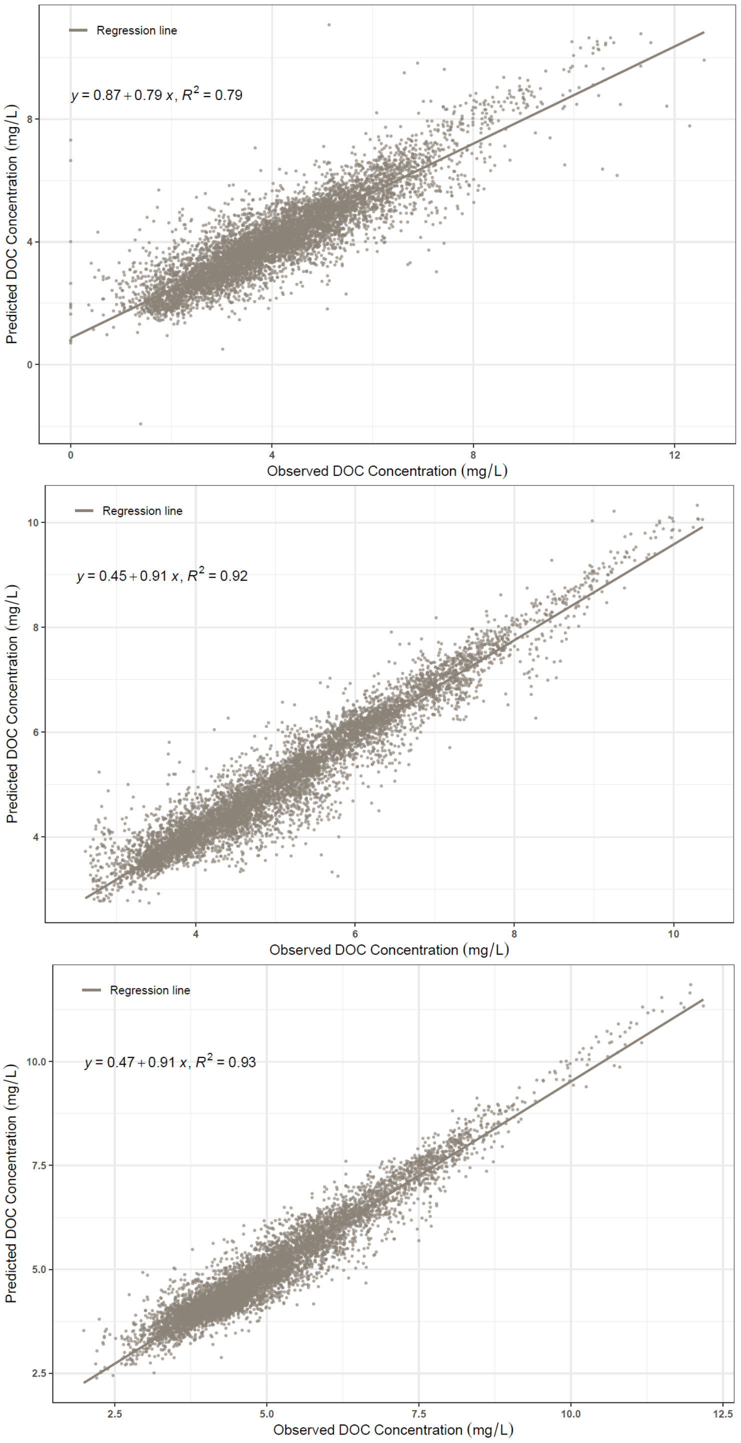
Best model: Extreme gradient boosting



Nitrate_dn ~ flow_up + flow_md + flow_dn + nitrate_up + nitrate_md

Best model: K-nearest neighbors

Figure 10: Regressions obtained using machine learning algorithms between nitrate concentrations at one station and flow rates and nitrate concentrations at the other two stations. These regressions were used to fill in missing nitrate concentration data



DOC_up ~ flow_up + flow_md + flow_dn + DOC_md + DOC_dn

Best model: K-nearest neighbors

DOC_md ~ flow_up + flow_md + flow_dn + DOC_up + DOC_dn

Best model: K-nearest neighbors

DOC_dn ~ flow_up + flow_md + flow_dn + DOC_up + DOC_md

Best model: K-nearest neighbors

Figure 11: Regressions obtained using machine learning algorithms between nitrate concentrations at one station and flow rates and nitrate concentrations at the other two stations. These regressions were used to fill in missing nitrate concentration data

1.5 Results and Discussion

Monitoring conducted by Lin (2017) yielded consecutive data from 26 November 2013 until 23 March 2015, for all three monitoring stations (Lin, 2017). Monitoring conducted by Belenky from January 2017 until January 2018, yielded consecutive data for all three monitoring stations for a roughly 6-month period from 18 June 2017 until 5 January 2018. Monitoring conducted by Hang yielded consecutive data from 6 January 2018 to August 26 2019.

Index velocity ratings to calculate flow

The core of the flow measurement technique used is the ability to create velocity rating curve between the ADVM velocities and the cross-section mean velocities in the wooden flumes. Over time the channel configuration upstream the flumes changed because of changes in the channel configuration (difference between pre- and post-restoration, with totally different flumes built), changes in sediment deposition and upstream vegetation. As a result, we expected the rating curves to change over time. Results show that over time the relationship between the sensor velocity and the cross-section average velocity did change significantly among the different phases and the students monitoring flow (Table 5).

Table 5. Comparison of the correction factors derived from the index velocity ratings from Pre- and Post-Restoration.

	Pre-Restoration (Lin)		Post-Restoration (Belenky)		Post-Restoration (Hang)	
	Correction Coefficient	R^2	Correction Coefficient	R^2	Correction Coefficient	R^2
CLUP	97.57%	0.9858	74.52%	0.9947	87%	0.96
CLMD	93.02%	0.9889	77.75%	0.9961	81%	0.98
CLDN	98.91%	0.9838	83.03%	0.9929	89%	0.97

The rating curves for the Post-restoration (Hang) are illustrated in Figure 11 below.

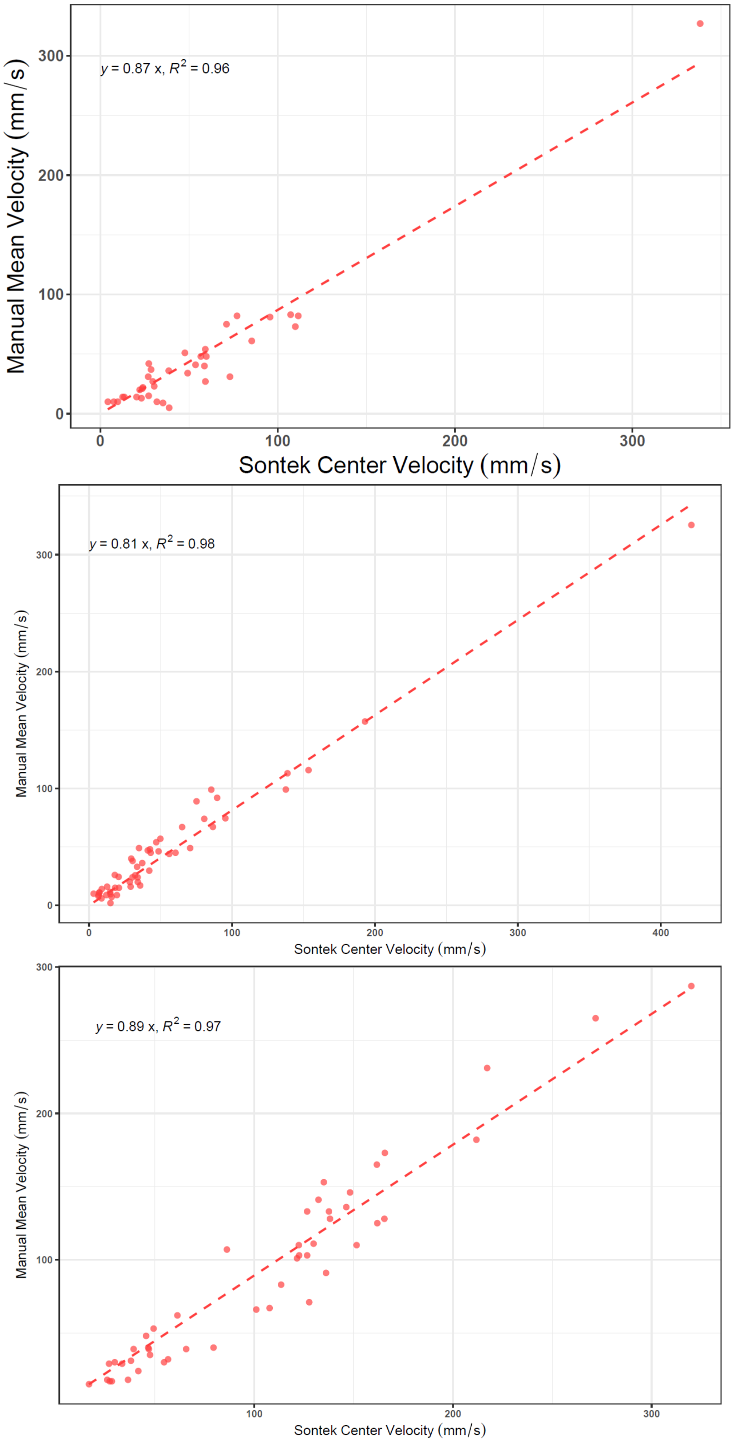


Figure 12. Raw Sensor Velocity versus Mean Channel Velocity (a) CLUP; (b) CLMD; (c) CLDN (top to bottom)

Gap filling and smoothing of flow data

The approach described in the method section above was able to reconstruct flow data where it was missing at each of the stations. Figure 13 illustrates the type of flow results that were obtained thanks to the regressions derived to fill in missing data (blue curve to fill in missing data). Figure 13 also illustrates the capacity of the velocity smoothing methods used to generate flow data with very little noise.

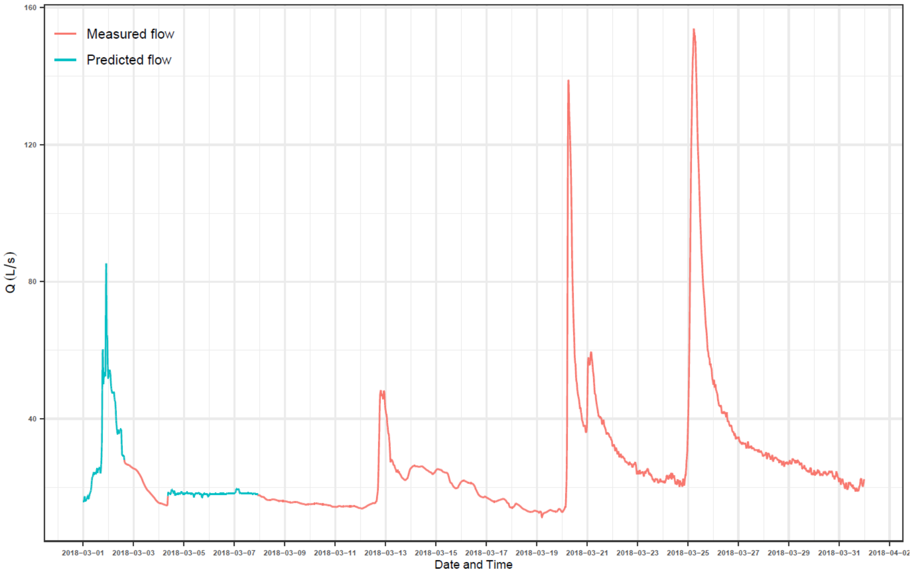


Figure 13: Reconstructed hydrograph at the upstream station using the methods to fill in flow data that was missing in March 2018

Degradation Study Results

The degradation study conducted shows that there were no statistically significant differences between the samples grabbed and put on ice versus those grabbed and left in the samplers for two weeks (Table 6). As a result, we concluded there the concentrations obtained from discrete automatic samples could be used for our analyses.

Table 6. Results of the paired T-test used to test for degradation between GS-A and GS-B for Spring/Summer (top) and Fall/Winter (bottom). Alpha = 0.05

Station		**TKN**	**NH_4-N**	**NO_3-N**	**TP**	**PO_4-P**	**TSS**	**DOC**
Spring and Summer								
CLUP	Mean A	1.20 ±0.60	0.047 ±0.042	1.51 ±1.77	0.27 ±0.23	0.012 ±0.0052	19.1 ± 36.0	4.06 ±1.74
	Mean B	0.93 ±0.18	0.042 ±0.046	2.08 ±1.97	0.29 ±0.30	0.013 ±0.013	19.28 ± 35.8	4.14 ±1.32
	p-val	0.3929	0.7452	0.1547	0.8922	0.9551	0.8559	0.9279
	Mean of differences	0.2715	0.0040	-0.568	-0.0120	-0.0003	-0.1825	-0.0775
CLMD	Mean A	0.972 ±0.66	0.044 ±0.048	1.28 ±1.78	0.068 ±0.048	0.006 ±0.0089	7.362 ±12.267	4.692 ±1.541
	Mean B	0.888 ±0.17	0.026 ±0.021	0.59 ±0.45	0.082 ±0.067	0.006 ±0.0055	9.22 ±14.95	4.436 ±0.536
	p-val	0.8291	0.3301	0.4507	0.2262	1.00	0.8534	0.7615
	Mean of differences	0.0840	0.0180	0.6880	-0.0140	0.00	-1.8580	0.256
CLDN	Mean A	1.353 ± 0.588	0.0433 ±0.067	0.7 ±0.685	0.1067 ±0.045	0.02 ±0.035	10.71 ± 12.39	5.42 ±0.97
	Mean B	0.756 ±0.271	0.01 ±0.01	0.883 ±0.764	0.1833 ±0.0666	0.0067 ±0.012	22.31 ±30.74	4.833 ±0.125
	p-val	0.3551	0.4226	0.1354	0.08583	0.6349	0.3908	0.4199
	Mean of differences	0.4067	0.0330	-0.1833	-0.0767	0.0133	-0.1161	0.5867

Station		**TKN**	**NH_4-N**	**NO_3-N**	**TP**	**PO_4-P**	**TSS**	**DOC**
Fall and Winter								
CLUP	Mean A	1.17 ±1.25	0.06 ±0.04	3.31 ±0.69	0.30 ±0.73	0.022 ±0.019	2.19 ±1.89	3.59 ±1.70
	Mean B	0.87 ±0.53	0.082 ±0.06	3.31 ±0.52	0.12 ±0.20	0.025 ±0.022	2.54 ±2.04	3.81 ±1.75
	p-val	0.4606	0.3083	0.9813	0.4378	0.7418	0.5992	0.6755
	Mean of differences	0.30	-0.0191	-0.0042	0.1817	-0.0025	-0.3525	-0.2192
CLMD	Mean A	1.59 ±1.39	0.083 ±0.087	2.13 ±0.96	0.081 ±0.066	0.019 ±0.0302	0.9967 ±1.066	3.998 ±0.766
	Mean B	0.76 ±0.44	0.068 ±0.060	2.35 ±1.07	0.195 ±0.448	0.0175 ±0.021	0.9775 ±1.292	3.587 ±1.253
	p-val	0.1053	0.4873	0.5917	0.3722	0.7774	0.9698	0.2773
	Mean of differences	0.8320	0.0150	-0.2217	-0.1140	0.0017	0.0192	0.4110
CLDN	Mean A	1.081 ±0.222	0.0475 ±0.0349	1.699 ±0.704	0.0536 ±0.04	0.02 ±0.024	0.6863 ±0.899	3.975 ±0.938
	Mean B	1.244 ±0.418	0.0825 ±0.0305	1.740 ±0.645	0.0575 ±0.0378	0.0225 ±0.034	0.7087 ±1.39	4.054 ±0.825
	p-val	0.4286	0.0509	0.687	0.8419	0.7406	0.966	0.8251
	Mean of differences	-0.1625	-0.0350	-0.0413	-0.00375	-0.0025	-0.0225	-0.0788

Discrete Sample Summary

Table 7. Summary of the discrete samples collected during the monitoring period

	TKN	**NH_4-N**	**NO_3-N**	**TP**	**PO_4-P**	**TSS**	**DOC**
CLUP							
No. Samples	184	184	184	184	184	184	184
Mean ± SD	1.04 ±0.76	0.08 ±0.08	3.08 ±0.85	0.25 ±0.76	0.02 ±0.04	4.61 ±10.85	3.99 ±1.63
Minimum	-0.09	0.00	0.15	0.00	0.00	0.00	1.84
Maximum	5.12	0.78	4.99	7.53	0.38	93.44	9.98
CLMD							
No. Samples	191	191	191	191	191	191	191
Mean ± SD	1.10 ±0.74	0.10 ±0.48	1.54 ±1.01	0.13 ±0.2	0.02 ±0.03	4.42 ±9.59	4.88 ±1.54
Minimum	0.05	0.00	0.00	0.00	0.00	0.00	0.66
Maximum	6.71	6.61	4.36	1.61	0.24	74.07	9.27
CLDN							
No. Samples	139	140	140	139	140	139	140
Mean ± SD	1.10 ±0.4	0.08 ±0.11	1.37 ±0.76	0.11 ±0.12	0.02 ±0.03	5.60 ±13.34	5.15 ±1.65
Minimum	0.37	0.00	0.00	0.00	0.00	0.00	1.84
Maximum	2.42	1.18	4.09	0.49	0.14	101.43	19.05

Predicted concentrations using PLSR Analysis and Summary

Similarly to the observations about the flow data relationships, we expected the PLSR models derived during pre-restoration and during the two post-restoration phases to change over time. As a result, the models to predict concentrations over time changed. Additionally, the spectro::lyser instruments had to be changed at times, necessitating creating PLSR models per instrument. We also found that for the middle station, it was best to divide PLSR models seasonally into Spring and Summer, vs. Fall and winter. The regressions of the PLSR model found for the post-restoration (Hang) period are illustrated in Figure 14 and Figure 15 below.

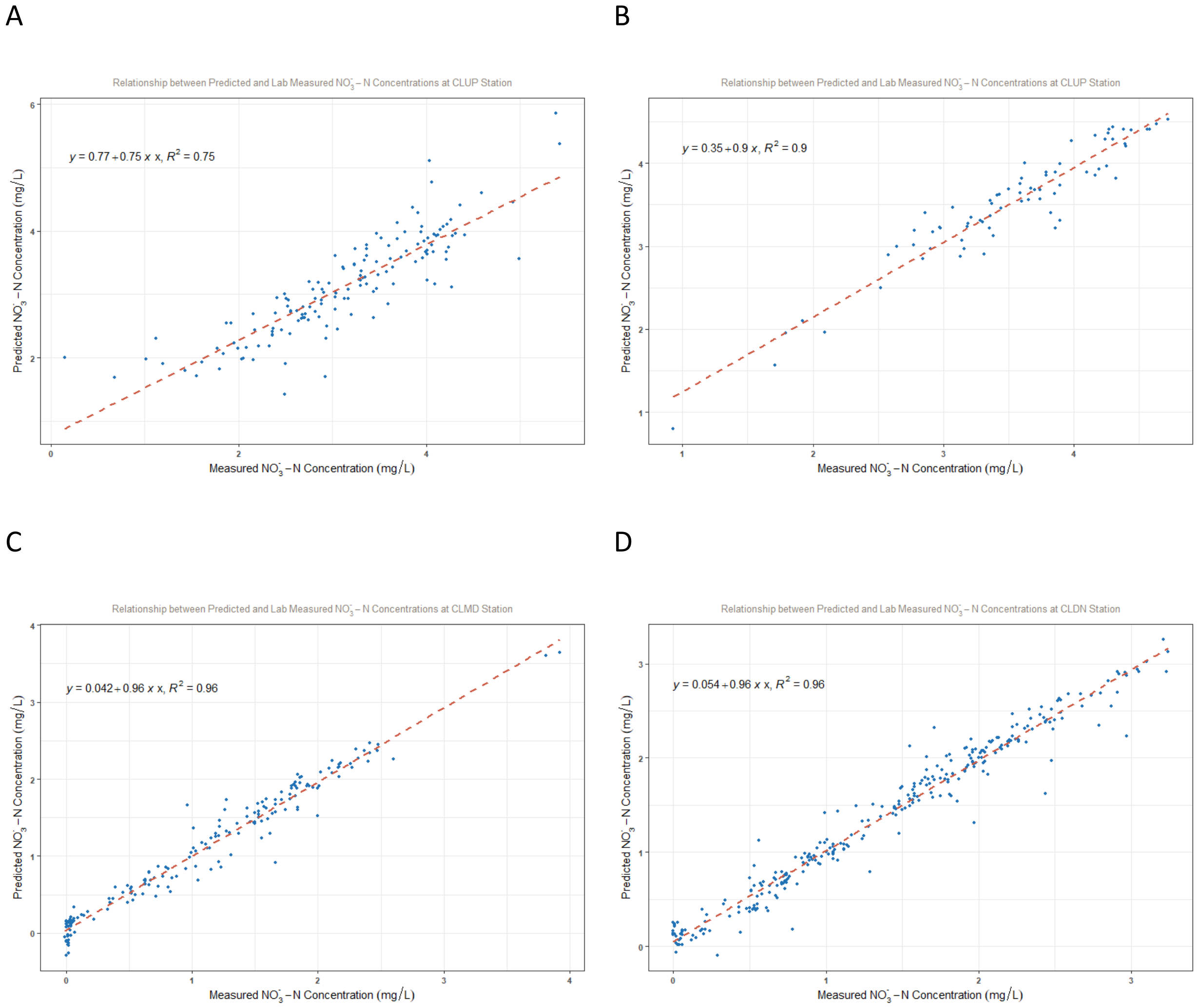


Figure 14: Goodness of fit between predicted vs. laboratory measured nitrate concentrations for the post-restoration (Hang) at the upstream station corresponding to two different instruments (A and B), corresponding to the Spring and Summer calibration at the middle station (C), and to the overall post-restoration period for the downstream station (D)

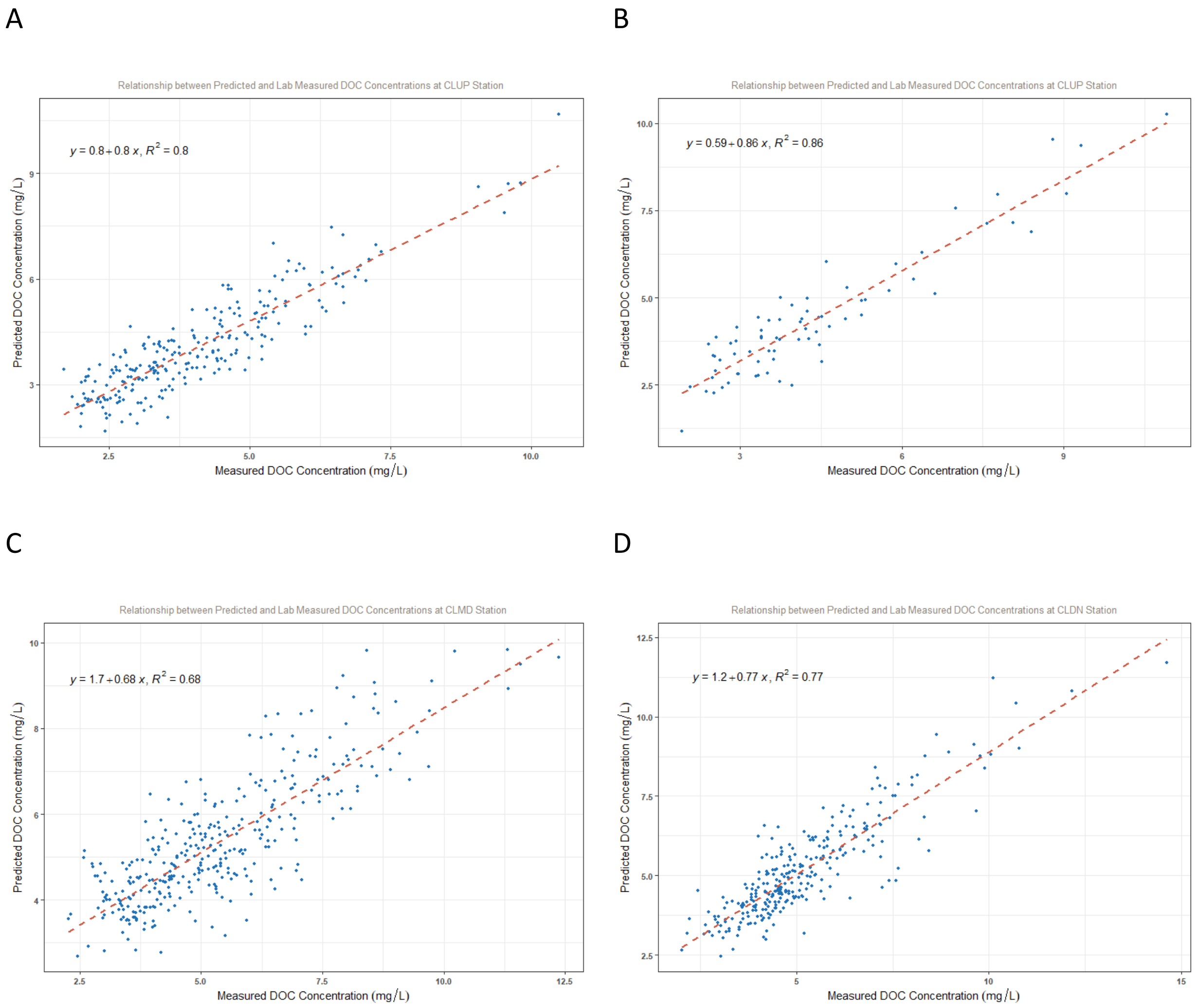


Figure 15: Goodness of fit between predicted vs. laboratory measured DOC concentrations for the post-restoration (Hang) at the upstream station corresponding to two different instruments (A and B), corresponding to the overall post-restoration period at the middle station (C), and the downstream station (D)

Continuity of flow across monitoring periods

In order to determine if there is an effect on water quality due to the restoration of The Canal, we first had to determine if there was a change in flow relationship between our monitoring stations and the reference before and after restoration. Changes in land use or land cover within the watershed and climatological variations have an impact on the flow relationships of the reach.

Results show that there was a 19% decrease in the expected flow at the middle station between the pre- and post-restoration periods. It is unclear whether this is the result of a monitoring problem, or whether this actually corresponds to water that would have a chance to bypass the stream, possibly through buried gravel channel which connection would have been opened thanks to the enlarging of the channel floodplain. The latter is possible as the water level was maintained artificially high during long periods of time because of debris dams that formed following large storms (Figure 16).

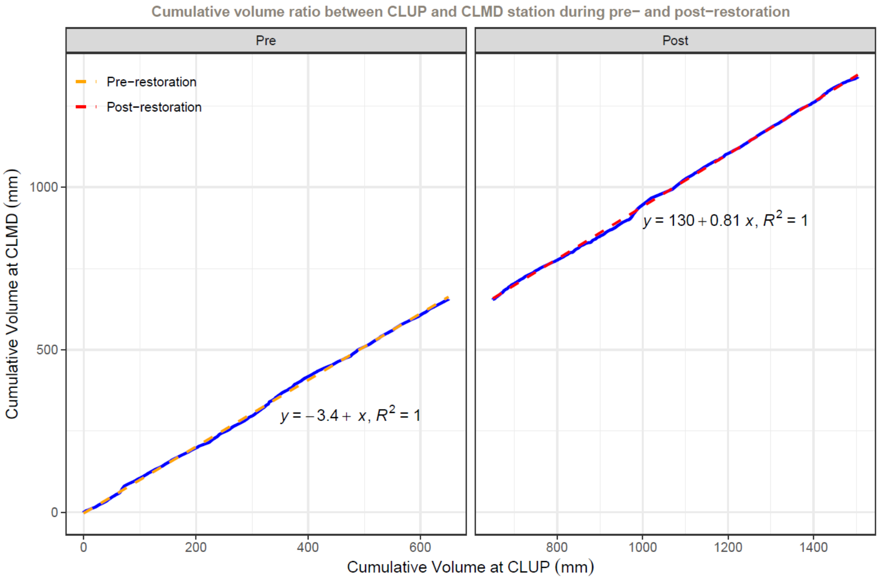


Figure 16: Cumulative volume at the middle station CLMD (mm) vs. cumulative volume at the upstream station CLUP (mm) for pre- and post-restoration periods showing a 19% decrease in the expected flow volume reaching the CLMD during the post-restoration period compared to the pre-restoration period

Conversely, there was an increase of similar magnitude (9 to 18%) in the relative flow volumes measured at the downstream station during the post-restoration period vs. the pre-restoration period. The large increase observed around the 1,000 mm flow volume mark during the post-restoration period corresponds to a large rainfall event due to hurricane Florence that connected the adjacent Little River to the restored stream, and added a lot of flow to the downstream station and that was unrelated to flow at the upstream station (Figure 17). Interestingly, this did not affect flow nearly as much at the middle station.

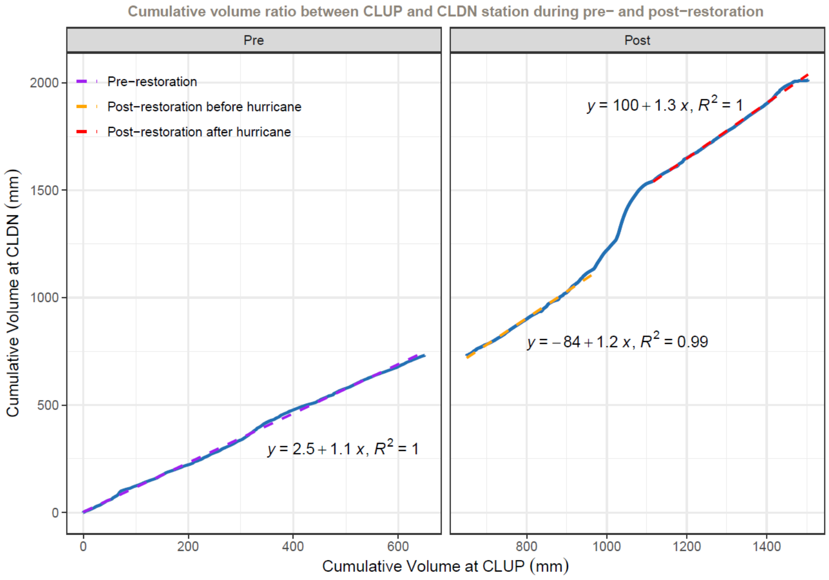


Figure 17: Cumulative volume at the downstream station CLMD (mm) vs. cumulative volume at the upstream station CLUP (mm) for pre- and post-restoration periods showing a 9% and 18% increase (before and after hurricane) in the expected flow volume reaching the CLDN during the post-restoration period compared to the pre-restoration period

Although these results are somewhat surprising, the buried old channels of the Little River provide an explanation for possible by-pass of the channel during the post-restoration period.

Stability of the overall nutrient inflow to the restored stream at CLUP

Although the overall method to assess the capacity of this stream restoration to benefit water quality relies on the changes in the relative export of nutrients at the middle and downstream station compared to the upstream one, it is interesting to observe whether the overall nutrient inflow to the restored stream changed dramatically over time. Results show a rather stable input of nutrients from the watershed upstream of the CLUP station to the restored stream reach. The slopes of the cumulative load curve expressed as a function of the cumulative flow volume quantify the overall flow-weighted concentrations. Despite inflections up and down, the general trend, it is remarkable to observe that the DOC load into the restored stream shows very little change (same regression slope value between pre- and post-restoration; Figure 18). The upward inflectionn from 950 mm to 1,100 mm corresponds to hurricane Florence and its aftermath.

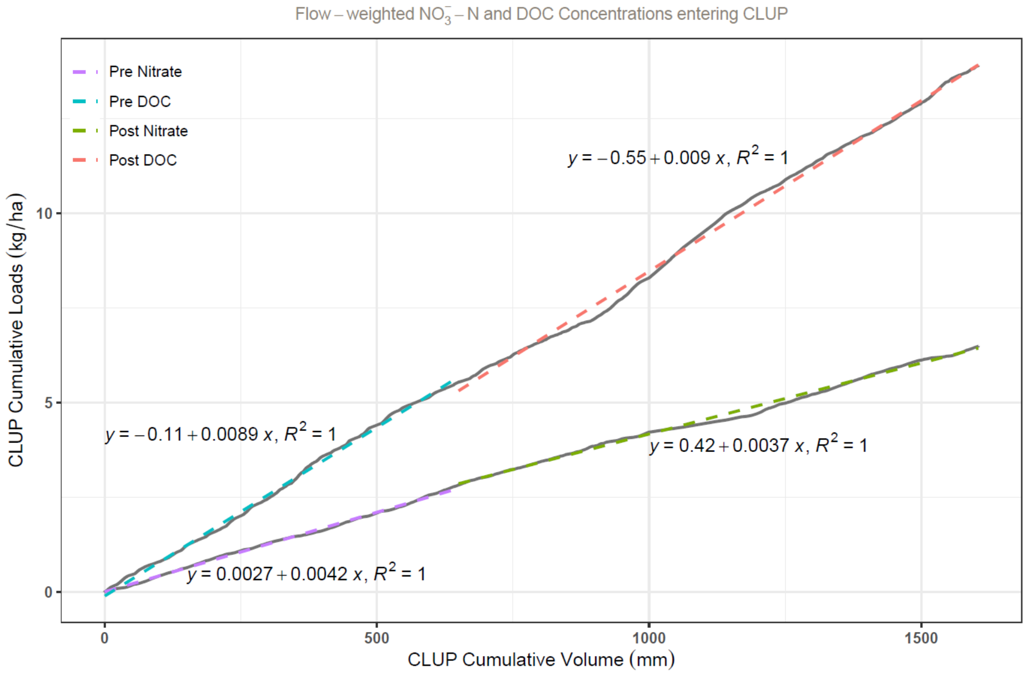


Figure 18: Nitrate and DOC cumulative loads expressed as a function of the cumulative flow for pre- and post-restoration periods showing almost no changes in the amount of DOC brought in the restored reach (as measured by the overall flow-weighted concentration estimated by the trend line) and a 12% decrease in the overall nitrate flow weighted concentration.

The flow-weighted concentrations for nitrate appeared to have decreased by about 12% during the post-restoration period, possibly because of hurricane Florence which tended to dilute nitrate concentrations from 950 mm to about 1,200 mm, and/or lower inputs in the watershed upstream the restored reach. This has no reason to influence the overall results on the quantification of the water quality benefits of the stream restoration.

Change in Cumulative NO3 Loading at CLMD and CLDN Relative to CLUP

The core of the quantification of the water quality benefits boils down to the overall inflection of the cumulative load at the treatment (CLMD and CLDN) stations compared to the reference station (upstream CLUP) as illustrated in Figure 2. All the minutia detailed in this report until now lead to the cumulative graph (Figure 19) from which much of the conclusions are drawn.

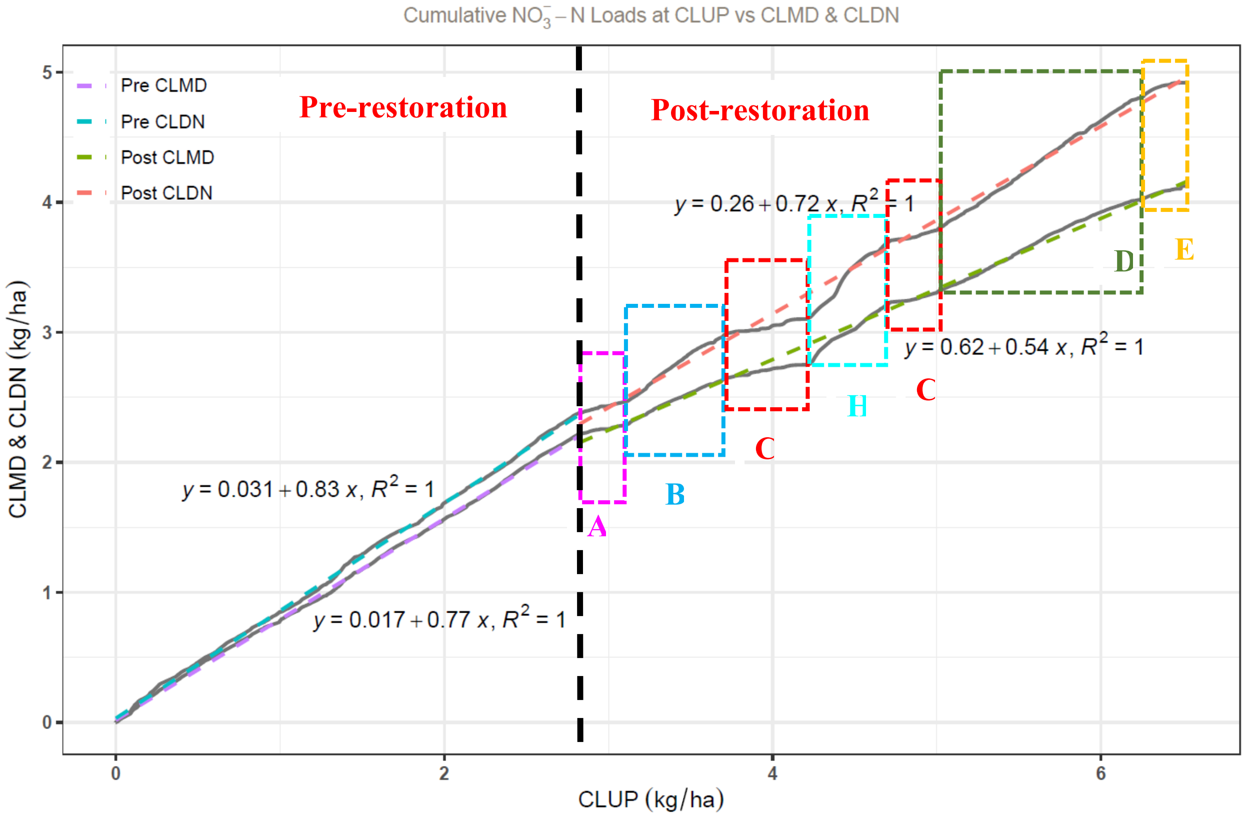


Figure 19: Cumulative nitrate load at the middle and downstream stations as a function of the cumulative load at the upstream station for pre- and post-restoration periods. Dotted frames represent identified seasonal trends. A: June to December 2017; B January to June 2018; C July to November 2018 with Hurricane Florence in mid September 2018 (H); D: December 2018 to May 2019; E: June to August 2019.

The first general observation from the nitrate double mass curves (Figure 19) is that there is a general inflection, as hypothesized, of the cumulative nitrate load at both the middle and downstream stations during the post-restoration period, compared to the pre-restoration period. The global inflection after three growing seasons (2017-19) shows that the restored stream exported about 30% less nitrate than expected at the middle station and about 13% less than expected at the downstream station.

The second general observation is that the double mass curve during the post-restoration period is subject to seasonal variations that were not apparent during the pre-restoration period (Figure 19). The double mass curves appear 'flatter' during the Summer and Autumn periods (A, C, and E in Figure 19), where the apparent nitrate export is about 60% lower than expected, and 'steeper' during the Winter and Spring periods (B and C in Figure 19), where the apparent nitrate export is about that expected from the pre-restoration period. Hurricane Florence that occurred in mid-September 2018 dramatically, and a bit artificially increased the loads at the middle and downstream stations relative to the upstream station, diminishing the overall water quality benefit of the stream restoration. The seasonality of the double mass curve suggests that processes occurring during the warmest months and when the vegetation is at its peak have a dramatic effect on nitrate retention in the restored reach.

Change in Cumulative DOC Loading at CLMD and CLDN Relative to CLUP

Contrary to what was observed for nitrate, outside of the effect of hurricane Florence (dotted frame H in Figure 20), there was no obvious seasonal variation in the double mass curve of DOC. This suggests that the export/retention processes of DOC was not affected nearly as much by vegetation and/or temperature as those of nitrate appear to be.

The overall balance of the DOC export shows a 30% decrease in DOC export at the middle station relative to what was expected, and, a 7% increase before, and a 7% decrease after hurricane Florence, for the downstream station, or a rather neutral balance at that station.

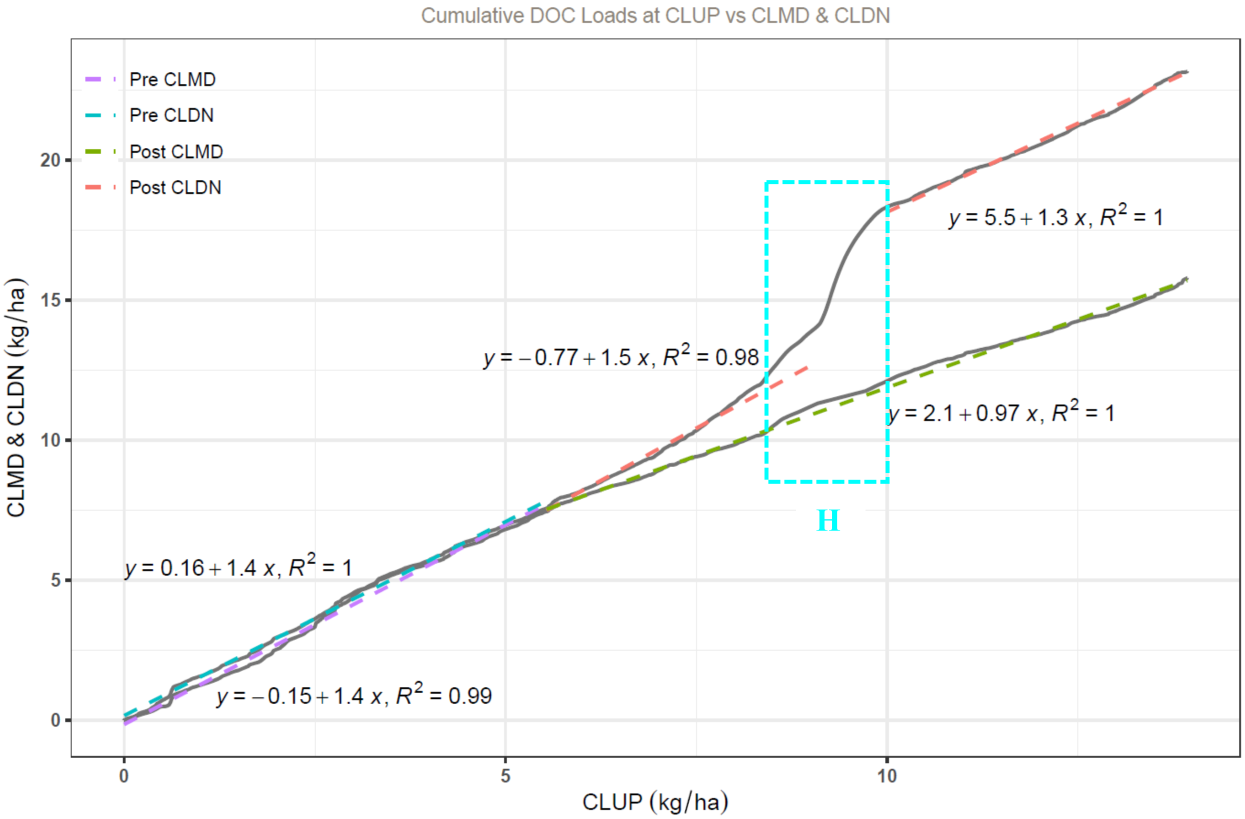


Figure 20: Cumulative DOC load at the middle and downstream stations as a function of the cumulative load at the upstream station for pre- and post-restoration periods. Dotted frame H represents the effects of Hurricane Florence that occurred in mid-September 2018.

Identification of the possible drivers for the water quality benefits observed

We cannot rule out possible land use/ land cover changes that might have occurred in the downtime between monitoring periods. Results from CLUP show that load-to-flow ratios for DOC and nitrate remain very similar pre- and post-restoration, indicating no significant changes in the export signature of sub-watershed I. Other than restoration and the by-pass, there are no obvious visible changes to sub-watersheds II and III. We know that the controlled animal feeding operation (CAFO) in sub-watershed II and the farm and post-processing facility in sub-watershed III were still active during monitoring, suggesting that there were no obvious reasons for the nitrate addition from these sources to suddenly stop.

In the same vein, we cannot rule out that the restoration was ineffective. The apportionment between the effect of possible land use changes (no obvious changes observed), and the effect of the restoration cannot be determined. However, it is possible to list all the potential effects of the restoration on water quality, and list whether there are corresponding observations.

The DOC removal processes in-stream include microbial respiration and algae and macrophyte assimilation. The DOC production processes include incomplete mineralization of both autochthonous and allochthonous organic matter, in the water column and the sediment. The latter corresponding to leaves and branches flowing from upstream into the restoration.

Nitrate removal processes in-stream include macrophyte and algae uptake and denitrification by water column biofilms and in the sediment, while the nitrate producing processes include nitrification of ammonium resulting from the mineralization of the organic matter.

The creation of the floodplain and of a new unshaded channel provided a new sand bottom channel and an abundance of light for algae and macrophytes. The consequences of the new sandy bottom, compared to the previous 'muck' between CLUP and CLMD, suggests that DOC production due to sediment diagenetic processes were initially halted, at least immediately post-restoration, and that in fact surface runoff on the newly formed floodplain likely initially increased the export of carbon as has been observed for the downstream station. The overall flooding of the area between the upstream and the middle stations for much of the post-restoration period may have quenched carbon export through surface runoff, and instead favored carbon sequestration in the new channel and on the floodplain. The retention of carbon at the latter part of the post-restoration period may be associated with the formation of vegetation on the floodplain, and to some extent in the channel, although to a lower degree than what was observed between the upstream and middle station.

However, the increase in light entering the channel post-restoration allowed widespread establishment of alligatorweed (*Alternanthera philoxeroides*) in low velocity areas across the entire channel. In higher velocity areas, macrophytic hummocks established themselves carrying their epiphytic algae, within the channel during the early post-restoration, which were eventually replaced by complete covering of the channel. The aquatic vegetation visibly more prevalent and more luxuriant than during the pre-restoration, all along the stream, most certainly played a role in nitrate uptake during all the Summer and Autumn seasons. It is also possible that the extra organic matter produced and trapped by the vegetation was in the end conducive to denitrification.

Additionally, increased local water velocities due to the minor in-stream blockages around the aquatic vegetation, might have increased hyporheic exchange (Francois Birgand, 2000; Findlay, 1995; Hill, 1988). Water directly in front of a vegetation block may be forced downward into the substrate and travel underneath the channel (Figure 22; longitudinal section), while water forced to flow around a vegetation block may enter the stream bank and join subsurface flow or in-stream flows (Figure 22; planer view). Preliminary data from two tracer studies conducted during the pre- and post-restoration periods suggest increased transient storage, supporting the hypotheses that transient exchange (hyporheic plus water column storage in macrophytic mats) has increased between the two periods (Danielle Winter, personal communication)

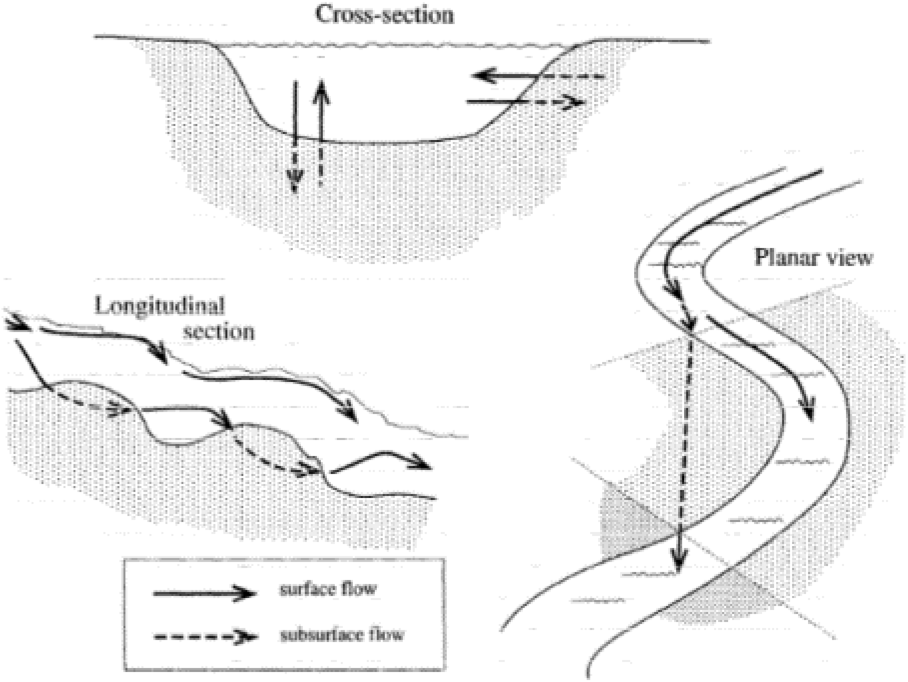


Figure 21. Diagram from Findlay (1994) demonstrating the exchange of water with the hyporheic zone in all three dimensions.

Major visible physical effects of the restoration

The excavation of the floodplain and the creation of the new channel has increased the linear length of stream from 2,206 m to 2,652 m, or a 20% increase (NEU, 2011). This increased the potential reactive surface area (banks and benthos) and possibly the residence time. The restoration also removed a large amount of vegetation that had been shading The Canal. Greater exposure to sunlight increases water temperatures, allowing for potentially increased microbial activity (Hill, 1988). The increase in light entering the channel post-restoration also allowed macrophytic vegetation to take root within the channel. Macrophytes facilitated a decrease of nitrate in stream by having generated biomass (Figure 23). Another possibility is that the restoration facilitated processes conducive to denitrification. The bacteria responsible for denitrification require (1) anaerobic conditions, (2) NO3 to be denitrified, and (3) readily available source of organic carbon (Knowles, 1982).

Figure 22. Alligatorweed covering the channel during the summer

The stream substrate, wetland tributaries, floodplain and riparian buffers of the restoration likely created anaerobic conditions needed for denitrification (Burt, Matchett, Goulding, Webster, & Haycock, 1999; Messer, Burchell, Grabow, & Osmond, 2012; Roley et al., 2012). Within the stream substrate, the majority of in stream microbial activity takes place in the first few millimeters of the stream (Francois Birgand, 2000). The interface of the water column and the stream bottom is a mixture of aerobic and anaerobic environments that allow obligate oxic or anoxic biotic and abiotic processes to occur (Findlay, 1995). The earthworks done during the restoration significantly altered the stream substrate. What was previously a "mucky" less permeable stream bottom heavy in organic matter had become more permeable sandy substrate in the early phase of the post-restoration phase. The stream substrates became very organic again after one growing season thanks to the vegetation trapping debris and dying off after the growing season. This created a dense, yet highly porous organic medium, creating great condition for denitrification to occur in anaerobic microsite, and for advective flow to penetrate and increase exchanges with streamwater.

The apparent consumption of DOC between CLUP and CLMD could be a result of the restoration removing the “mucky” stream bottom and leaving a sandy bottom. We believe the stream bottom is now exporting DOC at a greatly reduced rate rather than consuming DOC at a vastly greater rate. DOC is likely still being consumed, as to assume otherwise would be to say a large number of in-stream processes are no longer taking place, however we cannot apportion the amount of DOC being consumed or released to their respective processes. It is important to note that the area immediately upstream of CLDN was visibly higher in organic matter relative to the rest of the restoration further upstream which were left as sandy subsoil post-restoration. This last observation may explain why the DOC export at CLDN had apparently changed, although it decreased at CLMD. Some additional process had to compensate for the decrease in the upper part of the stream.

While the literature is split as to which process can be credited with the majority of nitrate removal from streams and with the data collected, we can only say that the apparent nitrate reduction in-stream is due to some combination of biomass production and denitrification. Similarly, it is difficult to a priori apportion the apparent changes in DOC and nitrate dynamics to land use/land cover or in-stream processes, despite having observed no obvious land use/land cover changes within the nested watersheds.

1.6 Recommendations for future stream restoration monitoring

Overall, this stream restoration has shown very significant abatement of nitrate export four years after restoration. Most nitrate abatement values reported for stream restorations are based on short term methods that only bring a very partial view of the mid-term trends. The first report by Belenky (2018) reported more than 60% nitrate abatement during the second growing season following restoration. Had the study stopped there, we would have reported much high water quality benefits than the longterm study has revealed later and where a more effective value is closer to 30%. This is still very high for a system that is continually flowing.

The major strength of our approach is that the indicator chosen (the double mass curve) is, by definition, a cumulative indicator. These have been shown to be a lot more robust as the random measurement errors tend to compensate each other, leaving the overall tendency apparent, provided that systematic errors have been reduced to a maximum. This method was able to unveil a mid-term tendency of nitrate disappearance and of carbon sequestration, with distinct drivers. The stream restoration at the Claridge nursery site has essentially created a flowing wetland favoring the very luxuriant growth of an aquatic vegetation in the channel and an aquatic/hydric vegetation in the floodplain. This had not been planned this way but hurricane Matthew and Florence have forged a new hydraulic functioning where the floodplain is almost always saturated with the water table at the ground surface in most places.

The strength of our approach came with considerably more monitoring efforts compared to infrequent sampling that has traditionally been the method chosen. This has been made relatively more difficult as we used state of the art, but yet still not fully robust technology that uses optics for water quality monitoring. This shows that obtaining continuosus flow and concentrations in stream is still far from simple and being able and is really a tour de force that the three graduate and one undergraduate students involved have managed to do.

Since this project has revealed a clear seasonality in the nitrate retention pattern, it might be possible to evaluate water quality benefits over shorter periods to characterize ‘summer’ and ‘winter’ benefits. Yet, taking the average of the two would not yield what we were able to observe.

Our ultimate recommendation for monitoring of stram restoation project is probably to find restorations that have a high potential for visible effects, and refrain from areas where there might be too many unknowns. Because we think that robust results came at the cost of very serious and meticulous monitoring, it might be best to monitor fewer projects but in great details, possibly following the approach we proposed.

1.7 Conclusions

This project is the first of this kind, that we know of, where a stream restoration project was monitored over six consecutive years, before, during, and after restoration. This has been possible thanks to the dedicated support from NC DOT, and particularly thanks to support of Mrs. Marissa Cox and Mr. John Kirby we believed in our approach. This has also been possible to the dedication of personnel and students, graduate and undergraduate, who have spent countless hours in the field under all but hurricane conditions, and afterwards in the lab and in their offices to analyze what they had found.

This priority 2 stream restoration and monitoring have taken place on the Claridge nursery canal, located within the larger floodplain of the Little River. This actually is important as the original design of the stream depth and the functioning of the built floodplain were changed by the forces of nature, namely hurricanes Matthew and Florence. As a result, obstacles formed along the channel, preventing water to drain efficiently, and the stream restoration has essentially created a flowing wetland with a very wet floodplain. This has resulted in the growth of a luxuriant aquatic and hydric vegetation in the channel and on the floodplain, which have had a profound effect on the water quality benefits.

From the beginning we made the hypothesis that a robust way to quantify the water quality benefits of this stream restoration was the use of cumulative nutrient load indicators. However, these indicators are not easy to obtain and required the use of state-of-the-art instruments capable of capturing flow and water quality on a near continuous basis over the long term.

After meticulous correction and all the necessary verifications, we were able to show that the restoration of the Claridge nursery canal, effectively creating a flowing wetland, was able to lower the nitrate loads by about 30% over three post-restoration consecutive years. This was accompanied by an overall carbon sequestration. The seasonality of the nitrate retention suggests that much of the nitrate unaccounted for was associated with the growth of vegetation, either through plant uptake and/or through denitrification associated with the release of organic matter from dead vegetation and the exchange conditions that they provided in the channel and with the floodplain. Increased residence time associated with the aquatic vegetation working as a filter time likely increased the capacity of the stream to retain nitrate. The capacity of the system to strip phosphorus could not be determined, however, because of the failure of the instruments to be able to measure phosphorus robustly.

The seasonality of the nitrate retention may suggest that shorter monitoring periods could be chosen to represent a ‘summer’ vs. a ‘winter’ effect. However, averaging these effects would not necessarily represent the effective benefits over the long term. Instead, we suggest that monitoring should focus on cumulative indicators used over the long term for projects for which there is a high potential for nutrient retention. Fewer projects may have to be monitored, but properly so.

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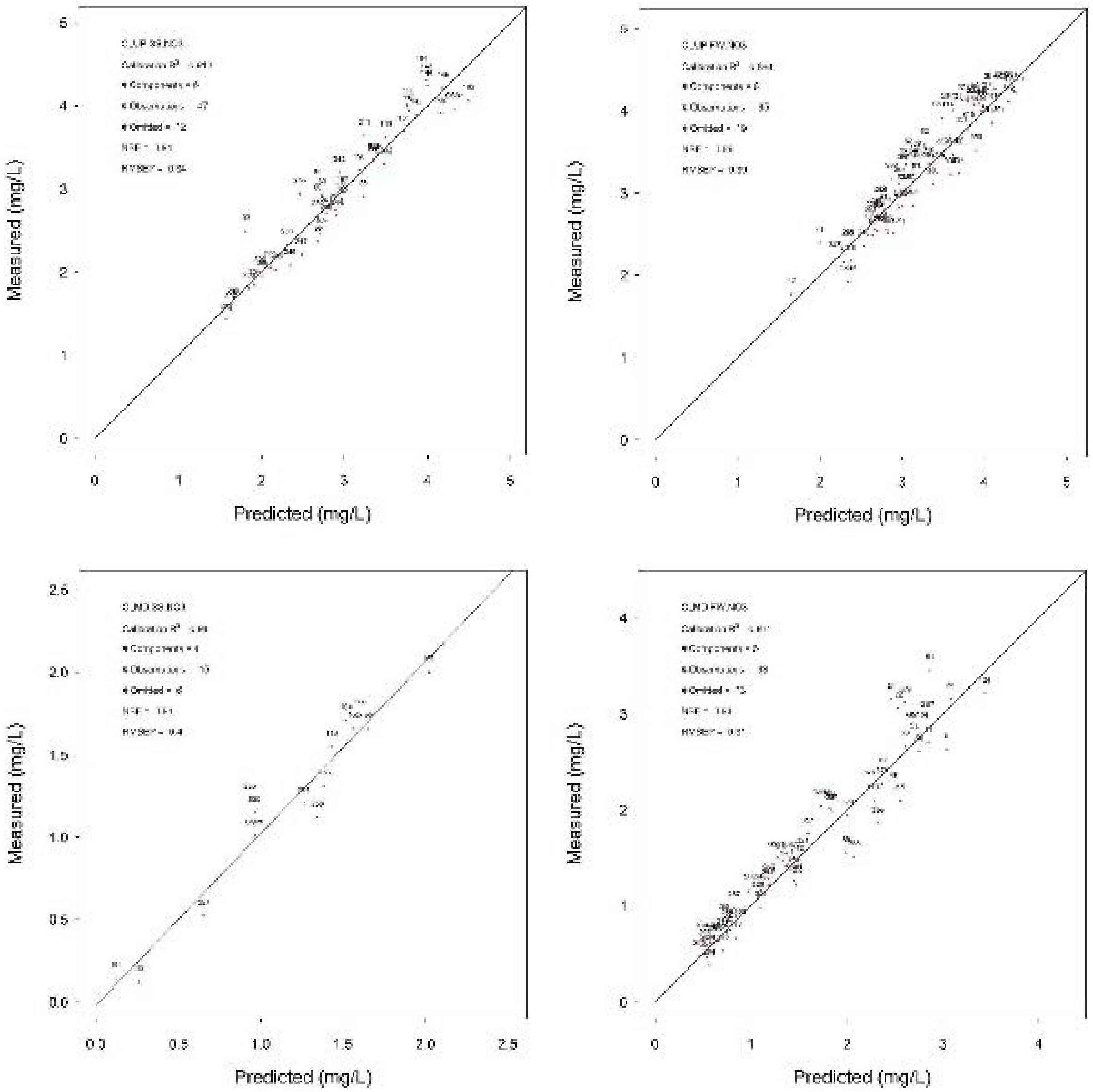
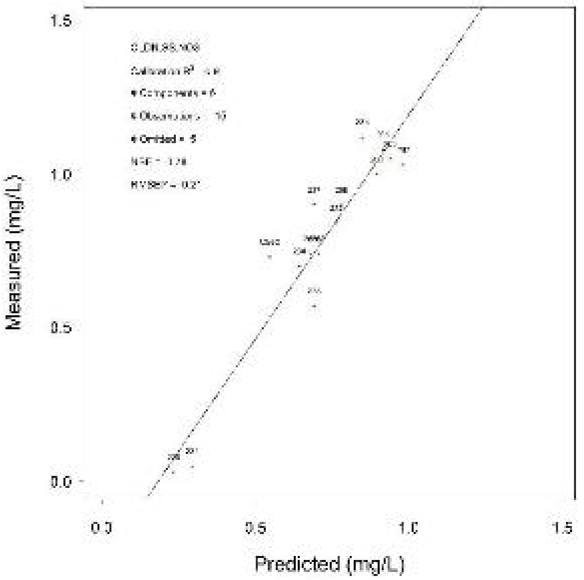
APPENDICES

Appendix A: Additional PLSR Calibration Plots

The following section contains all plots generated during the PLSR calibration for all seven parameters. The left column contains the regressions for the spring/summer period and the right column contains the fall/winter regressions. The three rows of plots between captions always correspond to CLUP, CLMD and CLDN. Each plot contains the R^2 value, number of components used in PLSR, number of observations/samples used, number of erroneous samples omitted, Nash-Sutcliffe coefficients and root mean square error of prediction.

Figure A 1 Regression relationships between measured nitrate concentrations from discrete sampling and predicted nitrate concentrations from PLSR calibrations; Spring/Summer (left column) and Fall/Winter (right column); CLUP, CLMD and CLDN (top to bottom)




Q_DN_SS_NO3
Calibration R^2
Components = 6
Observations = 15
Omitted = 5
NSE
RMSEP
Measured (mg/L)
Predicted (mg/L)
0.0
0.5
1.0
1.5

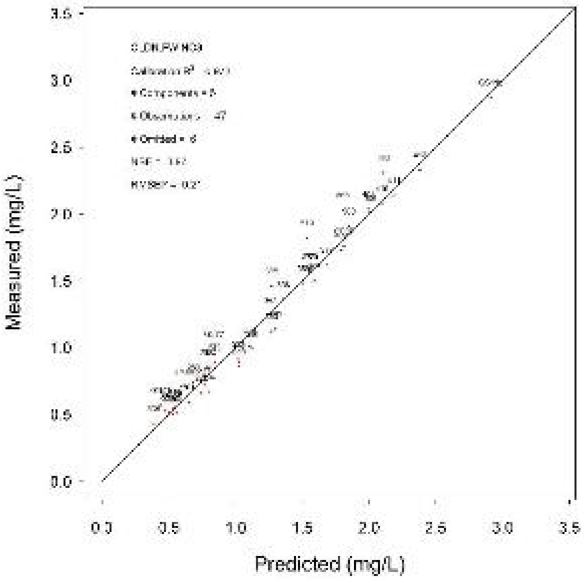
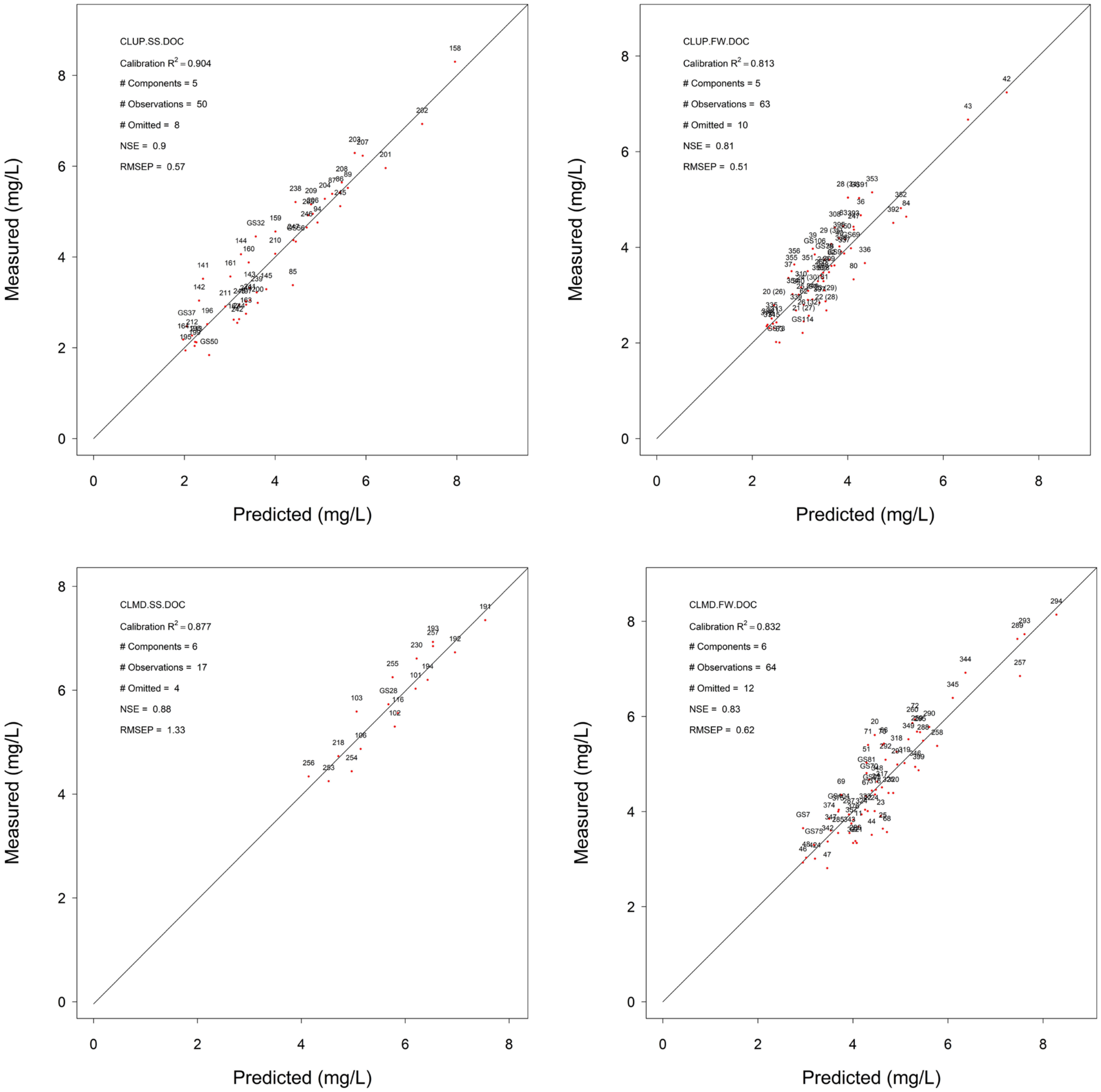
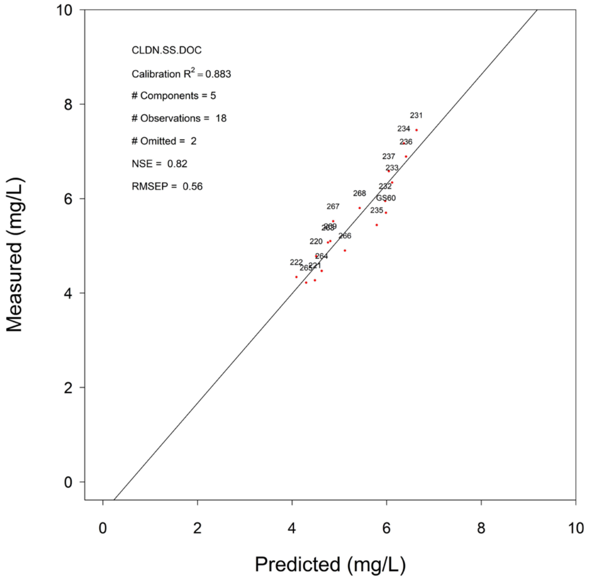

Q_DN_PV_NO3
Calibration R^2
Components = 5
Observations = 47
Omitted = 6
NSE
RMSEP
Measured (mg/L)
Predicted (mg/L)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Figure A 2 Regression relationships between measured DOC concentrations from discrete sampling and predicted DOC concentrations from PLSR calibrations; Spring/Summer (left column) and Fall/Winter (right column); CLUP, CLMD and CLDN (top to bottom)




CLDN.SS.DOC
Calibration $R^2 = 0.883$
# Components = 5
# Observations = 18
# Omitted = 2
NSE = 0.82
RMSEP = 0.56
Measured (mg/L)
Predicted (mg/L)
0
2
4
6
8
10
231
234
236
237
233
232
GS60
268
235
267
269
263
266
220
264
222
265
221

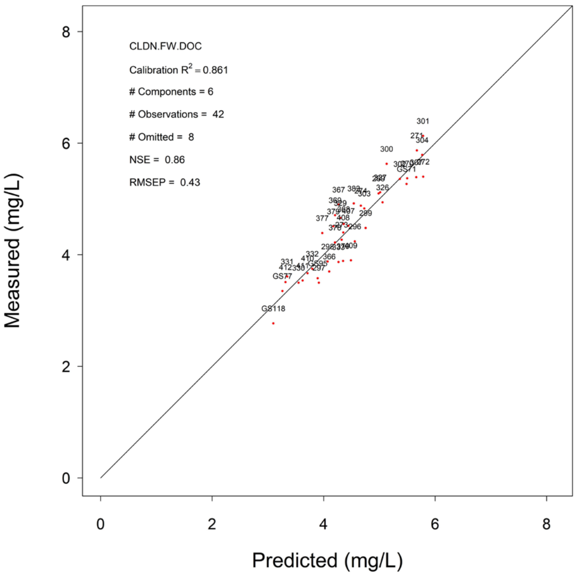
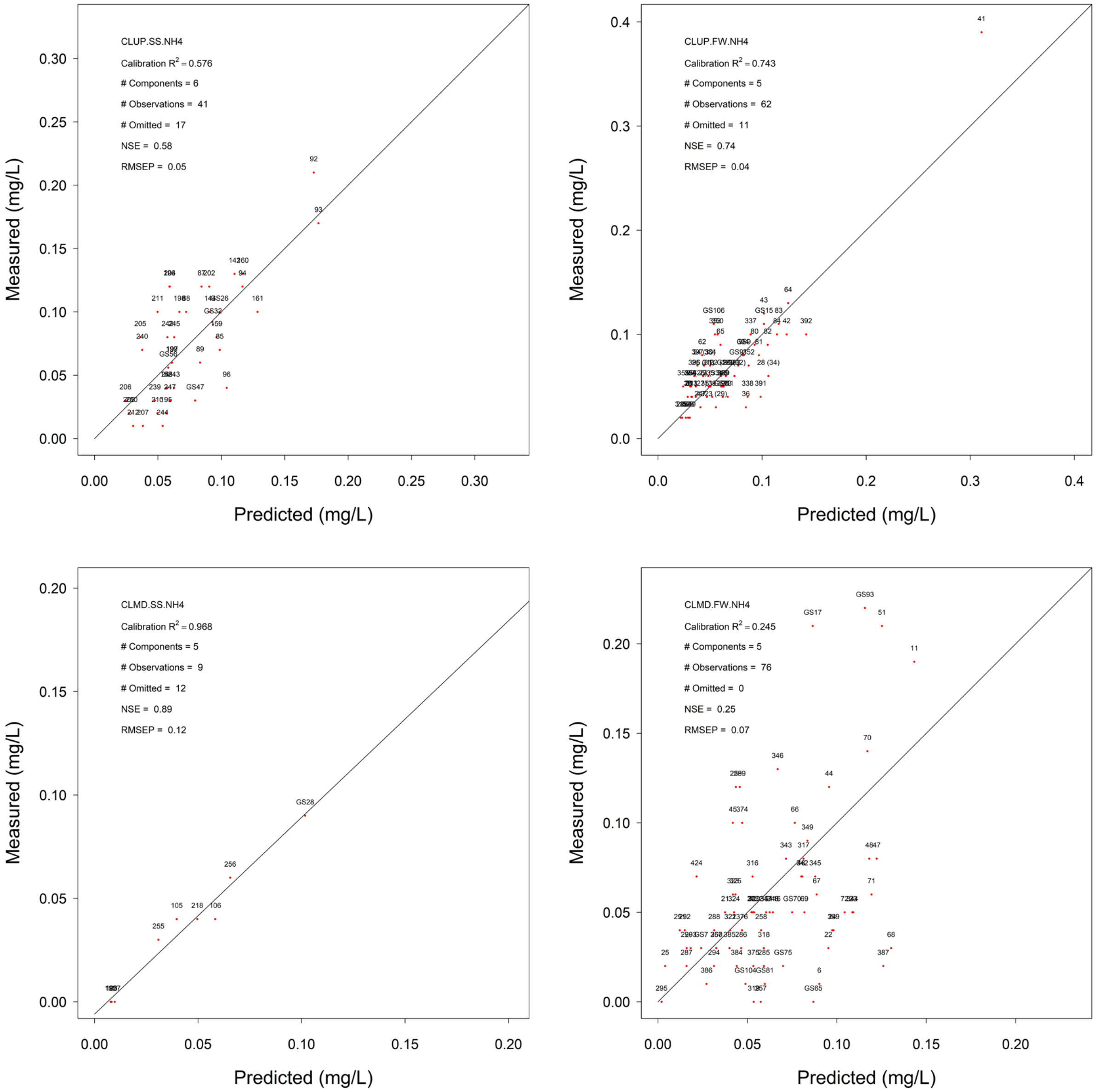
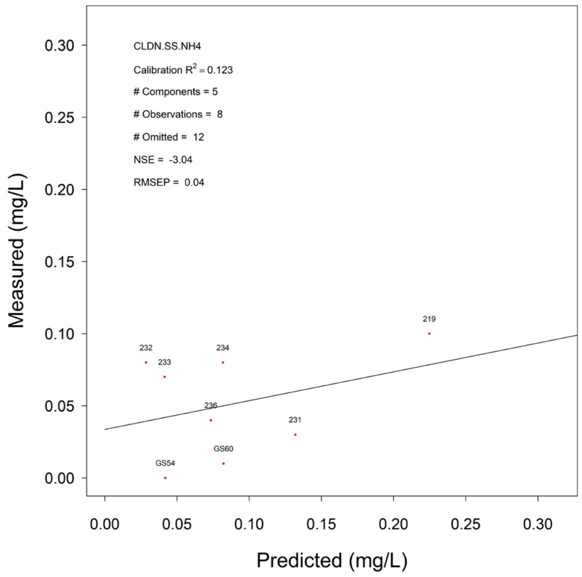

CLDN.FW.DOC
Calibration $R^2 = 0.861$
# Components = 6
# Observations = 42
# Omitted = 8
NSE = 0.86
RMSEP = 0.43
Measured (mg/L)
Predicted (mg/L)
0
2
4
6
8
301
304
300
GS71
367
326
377
299
332
410
366
331
GS77
GS118

Figure A 3 Regression relationships between measured ammonium concentrations from discrete sampling and predicted ammonium concentrations from PLSR calibrations; Spring/Summer (left column) and Fall/Winter (right column); CLUP, CLMD and CLDN (top to bottom)




CLDN.SS.NH4
Calibration $R^2 = 0.123$
# Components = 5
# Observations = 8
# Omitted = 12
NSE = -3.04
RMSEP = 0.04
Measured (mg/L)
Predicted (mg/L)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
219
232
233
234
236
231
GS60
GS54

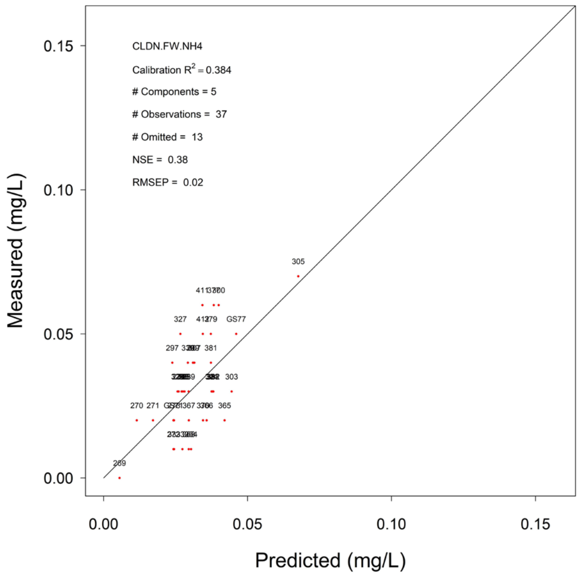
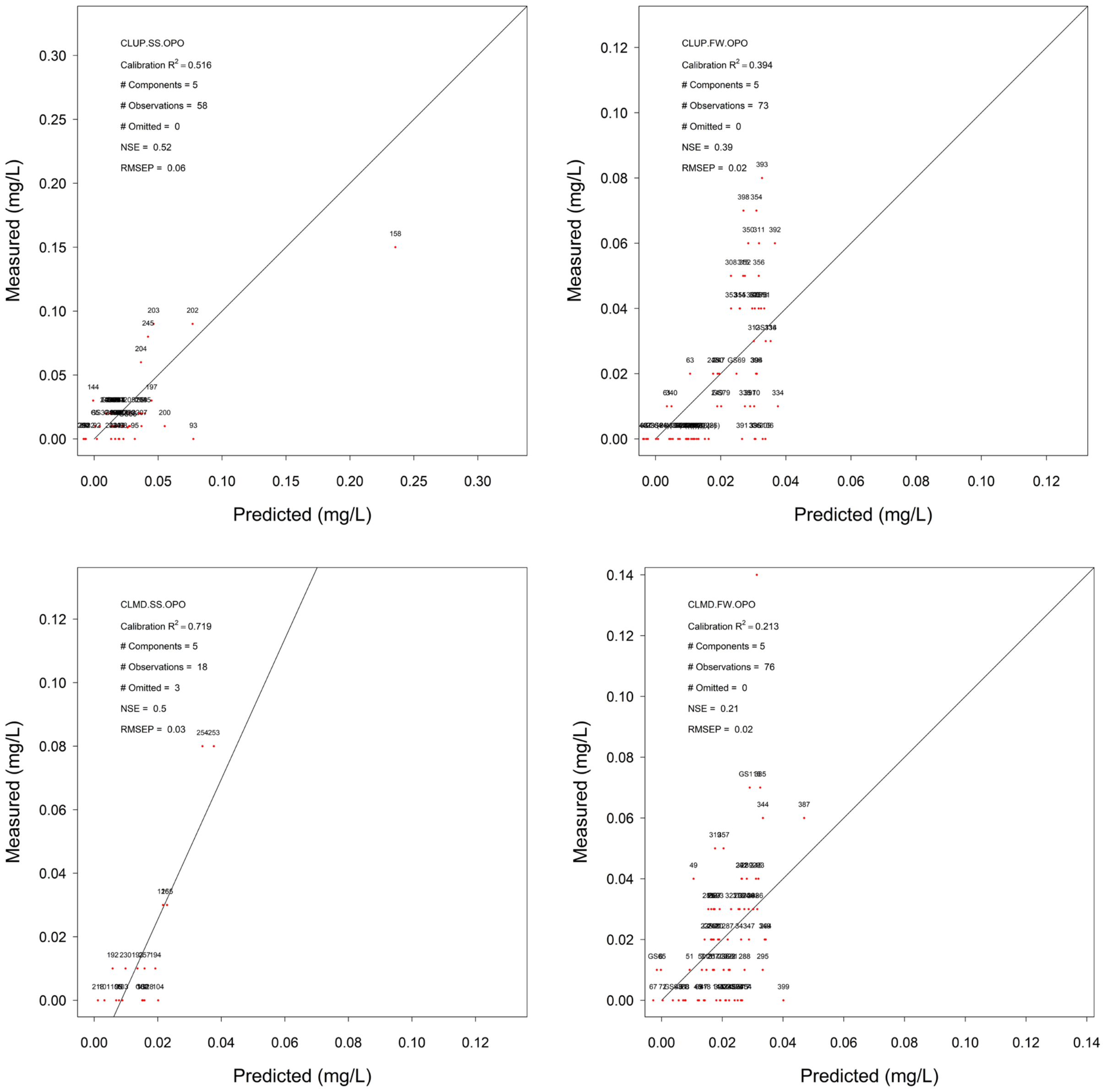
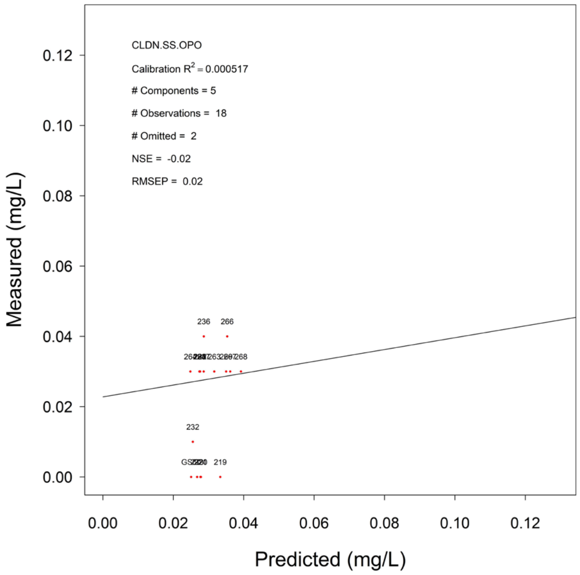

CLDN.FW.NH4
Calibration $R^2 = 0.384$
# Components = 5
# Observations = 37
# Omitted = 13
NSE = 0.38
RMSEP = 0.02
Measured (mg/L)
Predicted (mg/L)
0.00
0.05
0.10
0.15
305
327
279
GS77
297
381
303
270
271
367
365
269

Figure A 4 Regression relationships between measured phosphate concentrations from discrete sampling and predicted phosphate concentrations from PLSR calibrations; Spring/Summer (left column) and Fall/Winter (right column); CLUP, CLMD and CLDN (top to bottom)




CLDN.SS.OPO
Calibration $R^2 = 0.000517$
# Components = 5
# Observations = 18
# Omitted = 2
NSE = -0.02
RMSEP = 0.02
236
266
268
232
219
Measured (mg/L)
Predicted (mg/L)
0.00
0.02
0.04
0.06
0.08
0.10
0.12

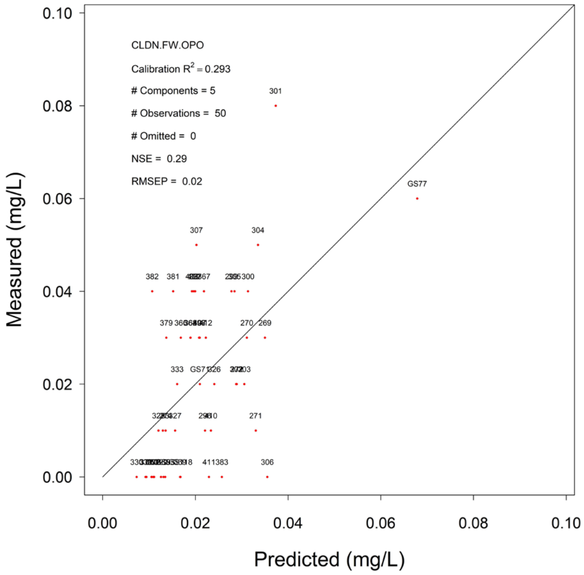
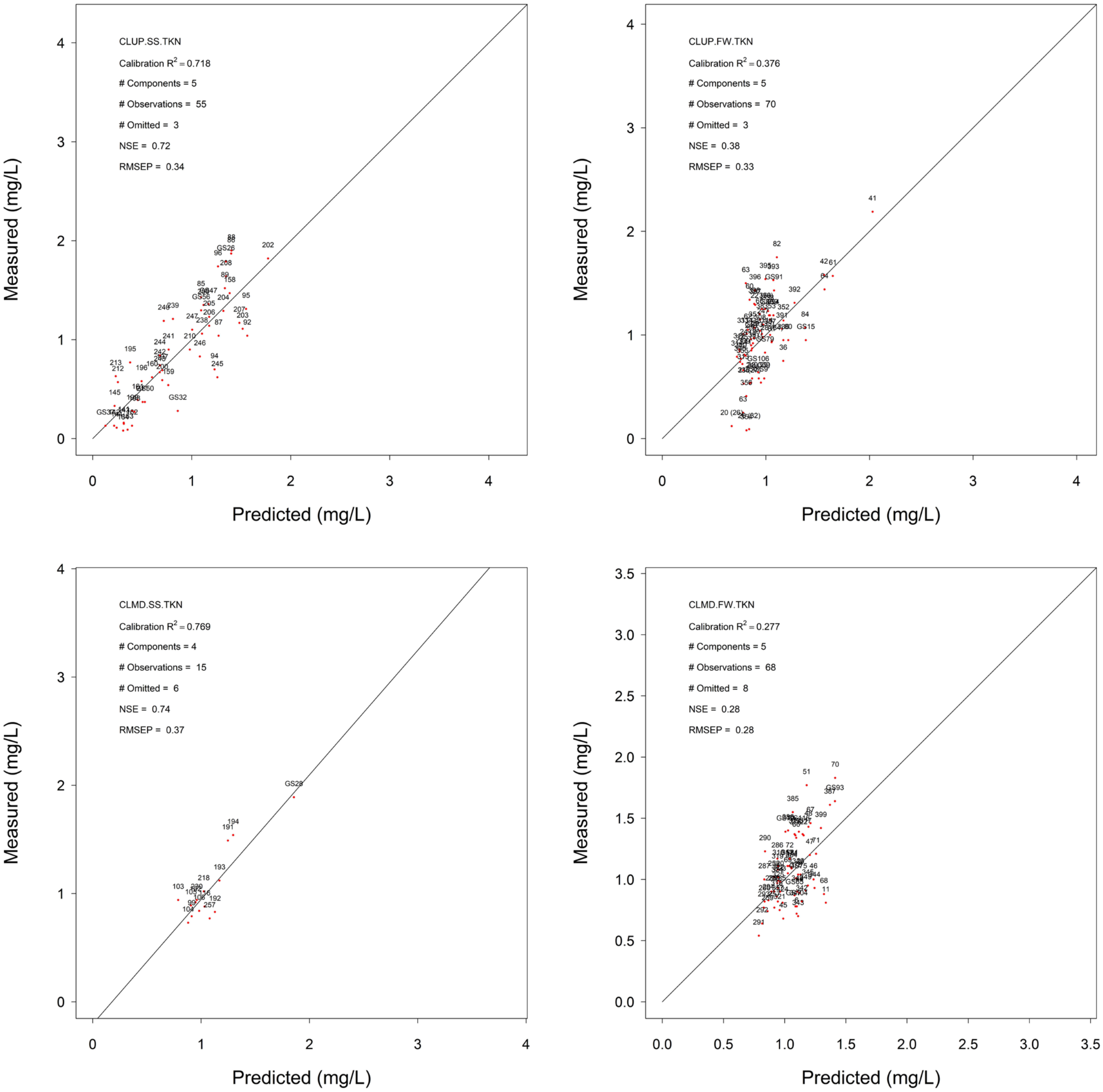
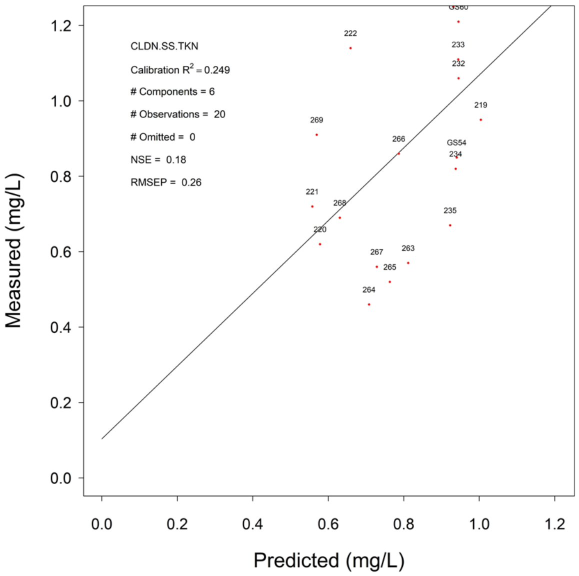

CLDN.FW.OPO
Calibration $R^2 = 0.293$
# Components = 5
# Observations = 50
# Omitted = 0
NSE = 0.29
RMSEP = 0.02
301
GS77
307
304
382
381
367
300
379
412
270
269
333
326
303
327
271
306
Measured (mg/L)
Predicted (mg/L)
0.00
0.02
0.04
0.06
0.08
0.10

Figure A 5 Regression relationships between measured total kjeldahl nitrogen concentrations from discrete sampling and predicted total kjeldahl nitrogen concentrations from PLSR calibrations; Spring/Summer (left column) and Fall/Winter (right column); CLUP, CLMD and CLDN (top to bottom)




CLDN.SS.TKN
Calibration $R^2 = 0.249$
# Components = 6
# Observations = 20
# Omitted = 0
NSE = 0.18
RMSEP = 0.26
Measured (mg/L)
Predicted (mg/L)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
GS60
222
233
232
219
269
266
GS54
234
221
268
235
220
267
263
265
264

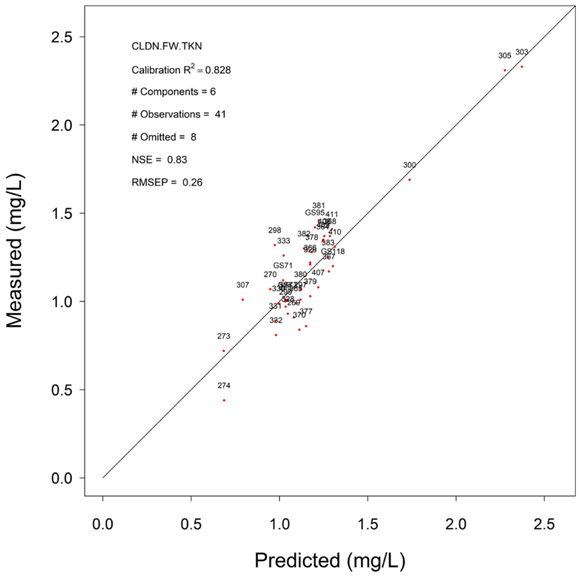
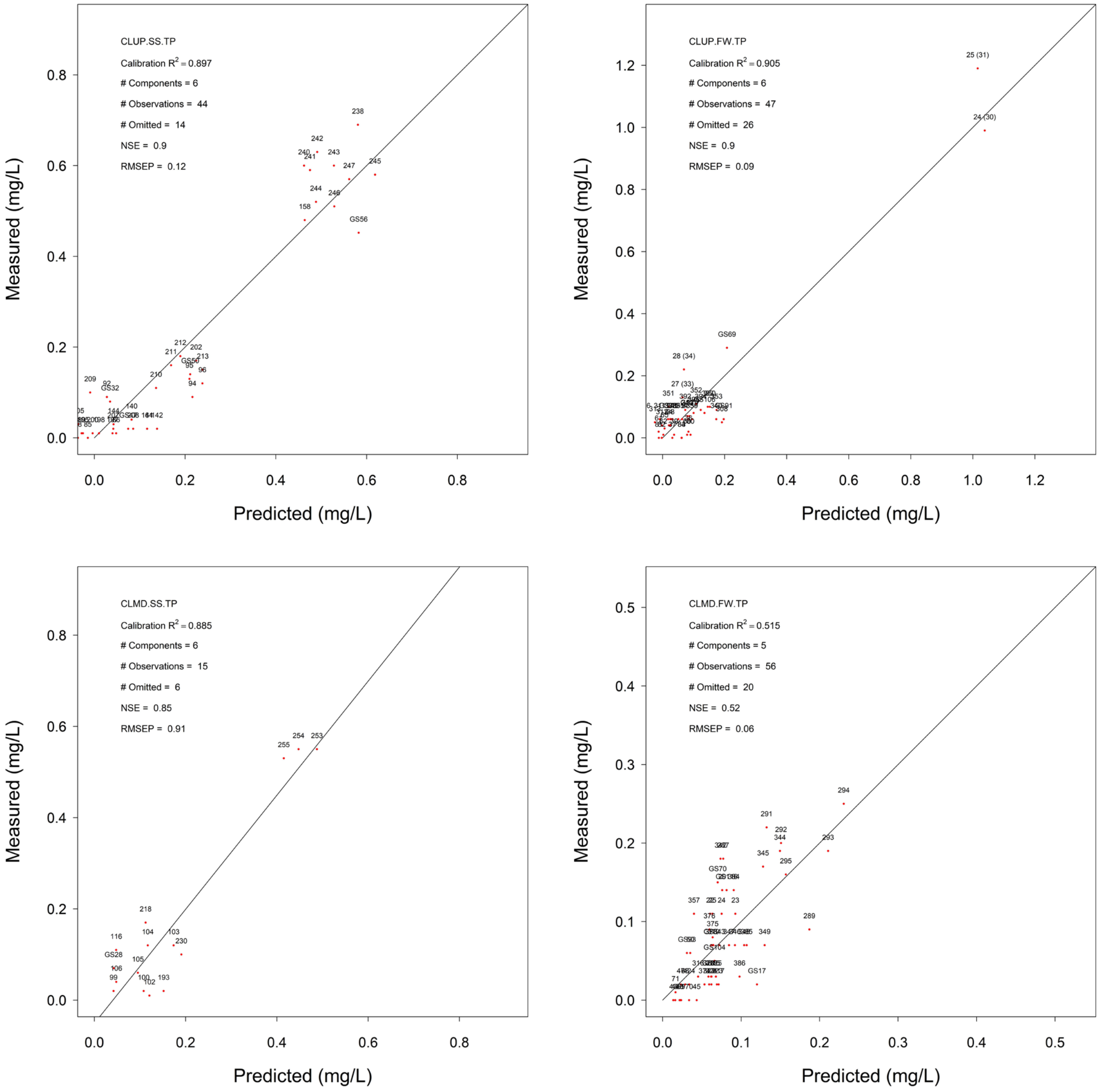
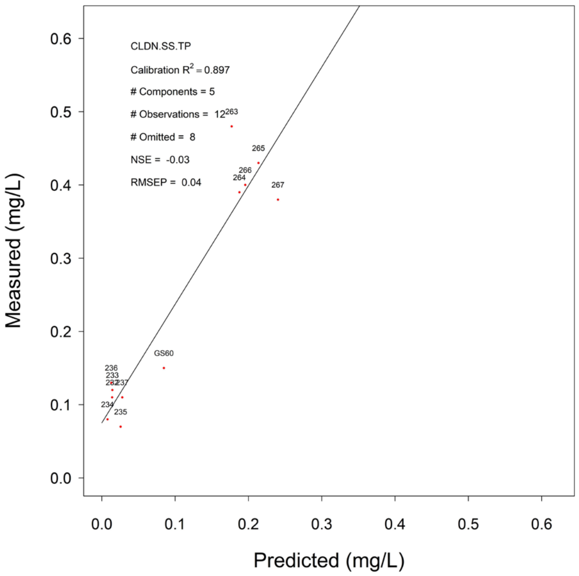

CLDN.FW.TKN
Calibration $R^2 = 0.828$
# Components = 6
# Observations = 41
# Omitted = 8
NSE = 0.83
RMSEP = 0.26
Measured (mg/L)
Predicted (mg/L)
0.0
0.5
1.0
1.5
2.0
2.5
305
303
300
381
GS95
411
298
333
382
378
410
383
GS71
270
380
407
379
307
331
377
370
332
273
274

Figure A 6 Regression relationships between measured total phosphorus concentrations from discrete sampling and predicted total phosphorus concentrations from PLSR calibrations; Spring/Summer (left column) and Fall/Winter (right column); CLUP, CLMD and CLDN (top to bottom)




CLDN.SS.TP
Calibration R^2 = 0.897
# Components = 5
# Observations = 12
# Omitted = 8
NSE = -0.03
RMSEP = 0.04
263
265
266
264
267
GS60
236
233
232
237
234
235
Measured (mg/L)
Predicted (mg/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6

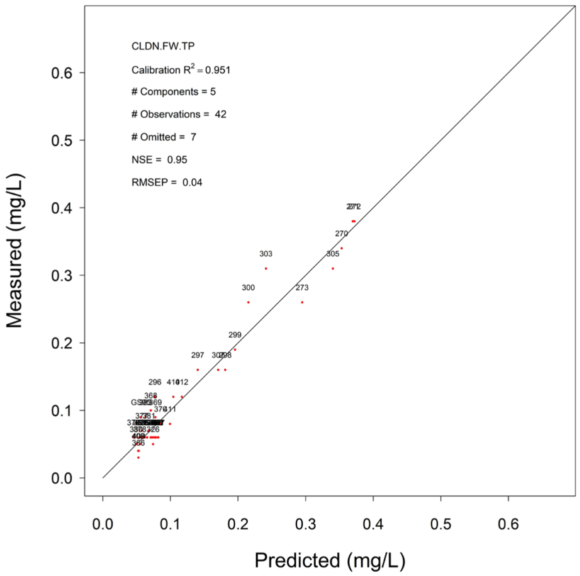
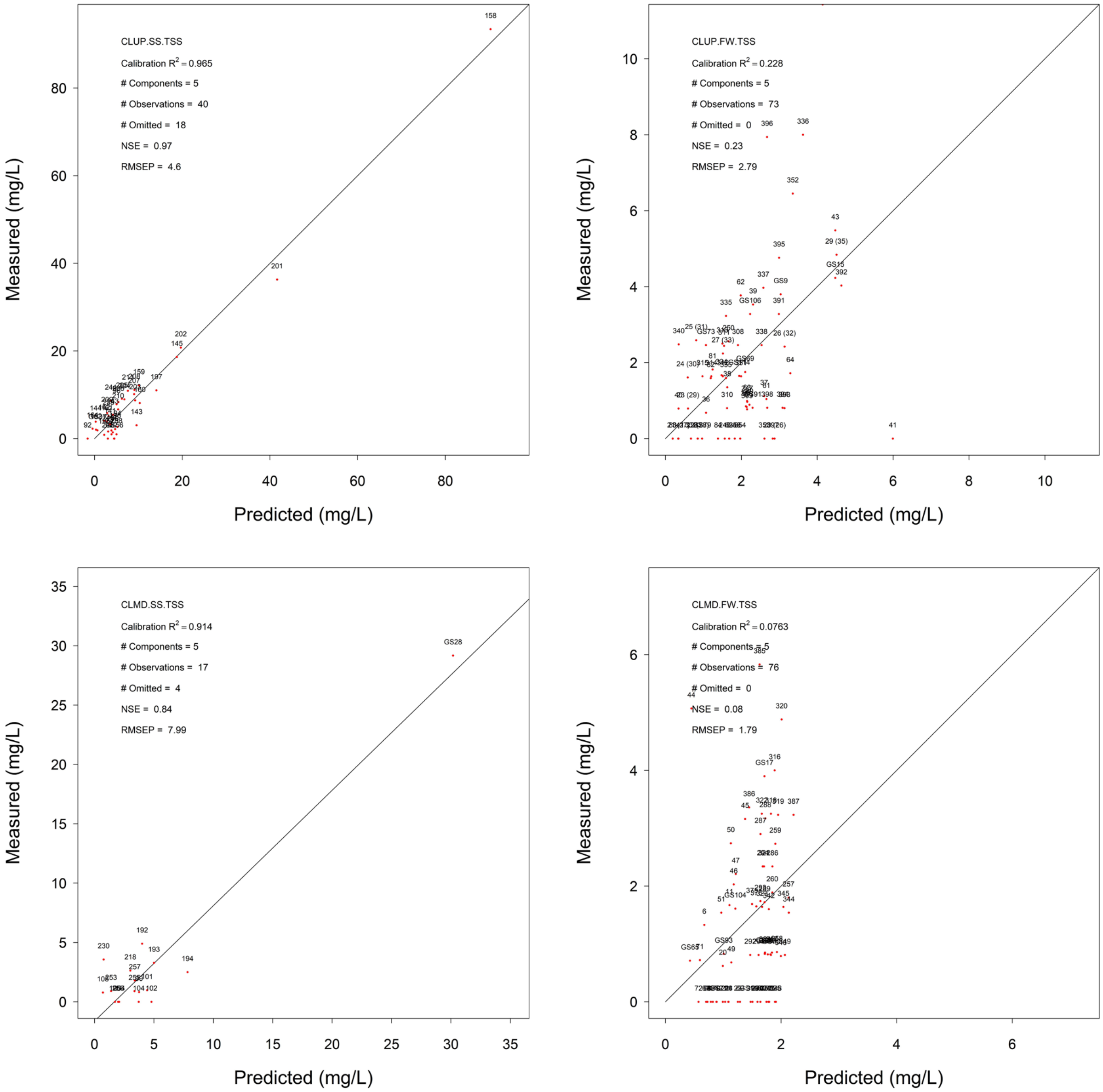
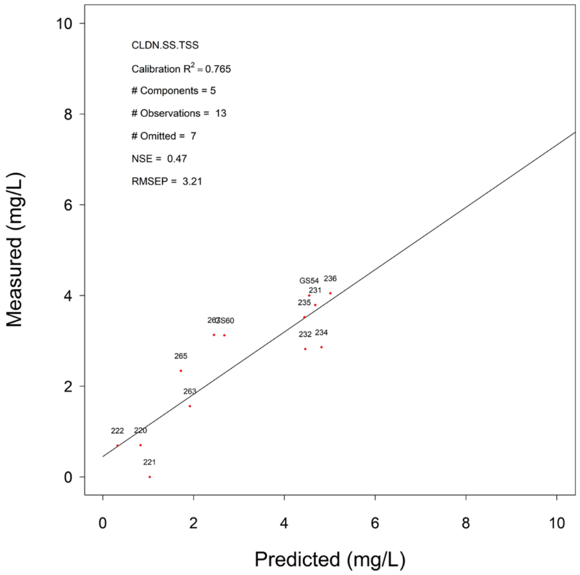
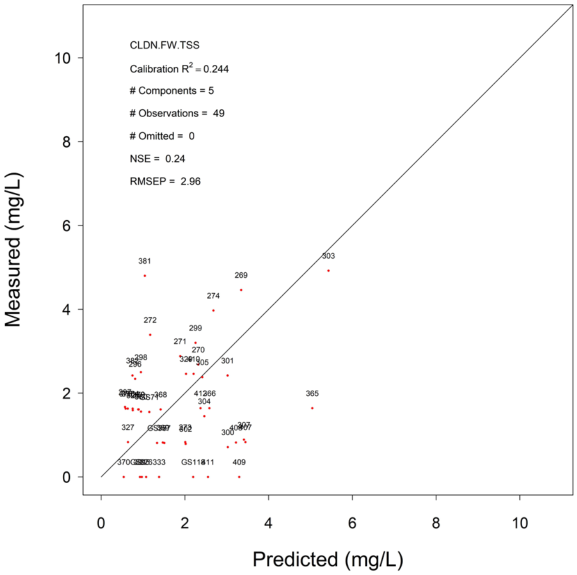

CLDN.FW.TP
Calibration R^2 = 0.951
# Components = 5
# Observations = 42
# Omitted = 7
NSE = 0.95
RMSEP = 0.04
272
270
303
305
300
273
299
297
298
296
410
412
368
369
311
Measured (mg/L)
Predicted (mg/L)
0.0
0.1
0.2
0.3
0.4
0.5
0.6

Figure A 7 Regression relationships between measured total phosphorus concentrations from discrete sampling and predicted total phosphorus concentrations from PLSR calibrations; Spring/Summer (left column) and Fall/Winter (right column); CLUP, CLMD and CLDN (top to bottom)

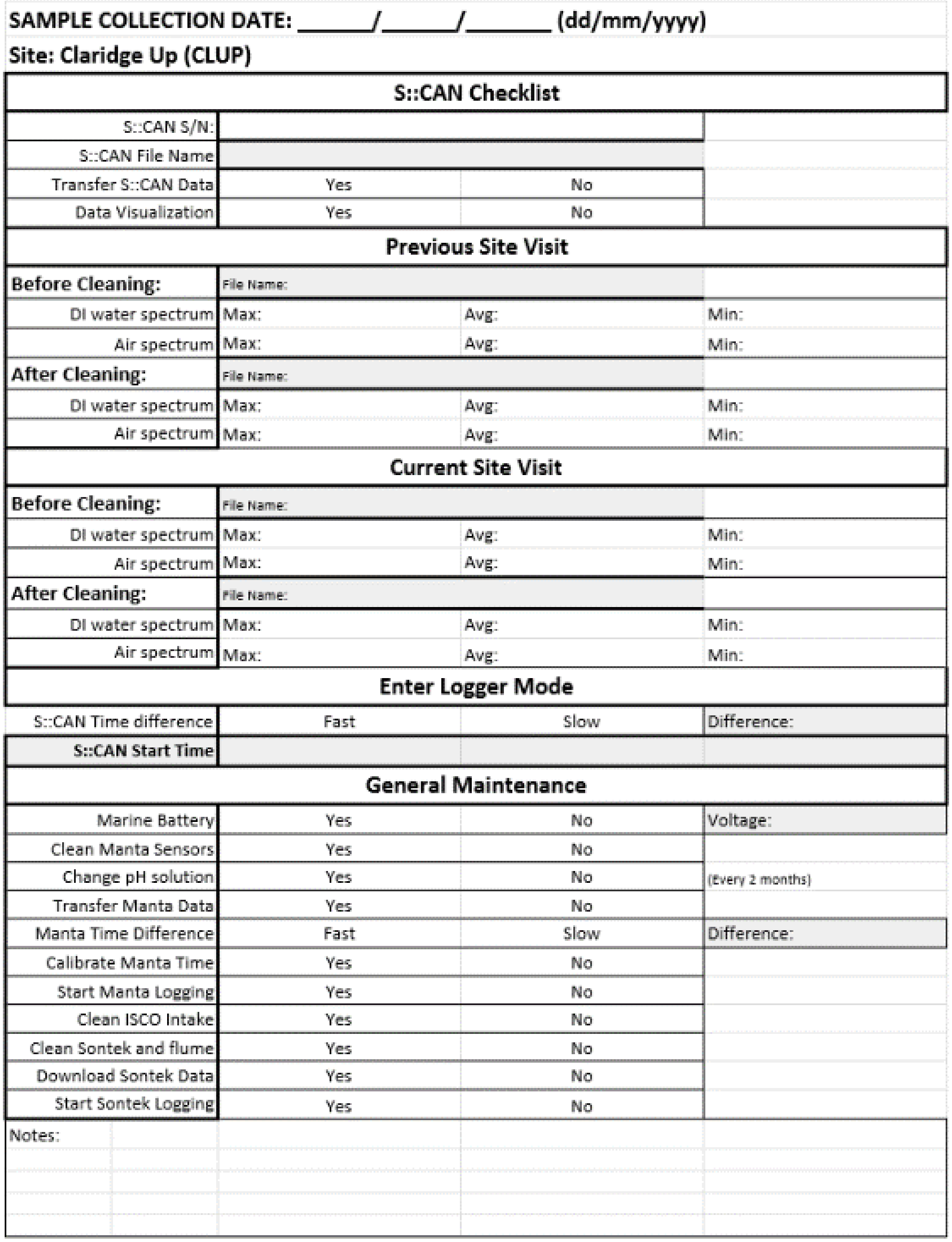



CLDN.SS.TSS
Calibration $R^2 = 0.765$
# Components = 5
# Observations = 13
# Omitted = 7
NSE = 0.47
RMSEP = 3.21
Measured (mg/L)
Predicted (mg/L)
0
2
4
6
8
10
GS54
236
231
235
GS60
232
234
265
263
222
220
221


CLDN.FW.TSS
Calibration $R^2 = 0.244$
# Components = 5
# Observations = 49
# Omitted = 0
NSE = 0.24
RMSEP = 2.96
Measured (mg/L)
Predicted (mg/L)
0
2
4
6
8
10
381
303
269
274
272
299
271
270
298
296
305
301
368
266
304
365
327
300
307
409
370
333
GS118
411

Appendix D: Site Visit Checklists and Datasheets

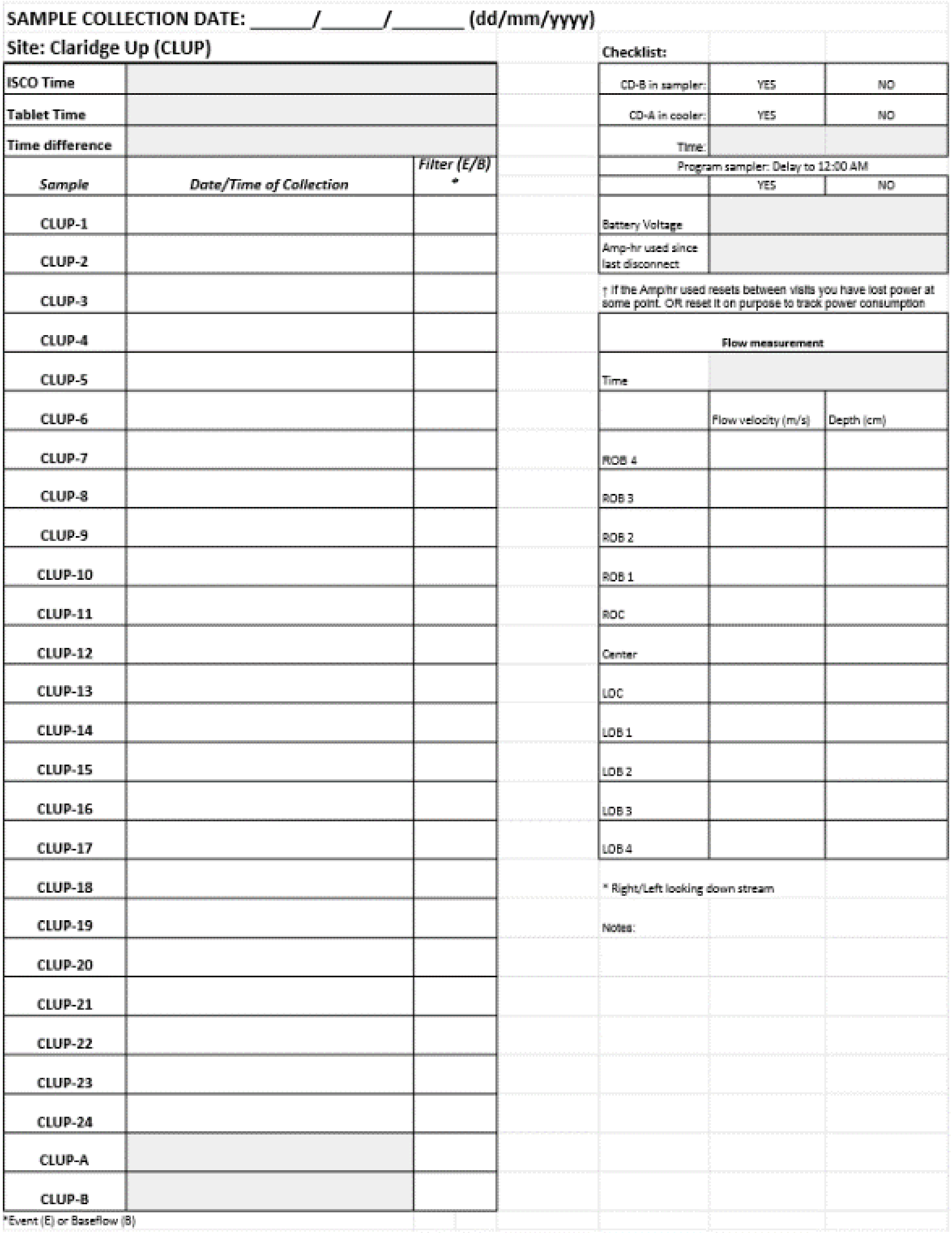
Fillable data collection sheets used during each field visit to ensure consistent data collection.



SAMPLE COLLECTION DATE: ______/______/_______ (dd/mm/yyyy)

Site: Claridge Up (CLUP)

S::CAN Checklist			
S::CAN S/N:			
S::CAN File Name			
Transfer S::CAN Data	Yes	No	
Data Visualization	Yes	No	
Previous Site Visit			
Before Cleaning:	File Name:		
DI water spectrum	Max:	Avg:	Min:
Air spectrum	Max:	Avg:	Min:
After Cleaning:	File Name:		
DI water spectrum	Max:	Avg:	Min:
Air spectrum	Max:	Avg:	Min:
Current Site Visit			
Before Cleaning:	File Name:		
DI water spectrum	Max:	Avg:	Min:
Air spectrum	Max:	Avg:	Min:
After Cleaning:	File Name:		
DI water spectrum	Max:	Avg:	Min:
Air spectrum	Max:	Avg:	Min:
Enter Logger Mode			
S::CAN Time difference	Fast	Slow	Difference:
S::CAN Start Time			
General Maintenance			
Marine Battery	Yes	No	Voltage:
Clean Manta Sensors	Yes	No	
Change pH solution	Yes	No	(Every 2 months)
Transfer Manta Data	Yes	No	
Manta Time Difference	Fast	Slow	Difference:
Calibrate Manta Time	Yes	No	
Start Manta Logging	Yes	No	
Clean ISCO Intake	Yes	No	
Clean Sontek and flume	Yes	No	
Download Sontek Data	Yes	No	
Start Sontek Logging	Yes	No	
Notes:			



SAMPLE COLLECTION DATE: ______/______/_______ (dd/mm/yyyy)

Site: Claridge Up (CLUP)

ISCO Time		
Tablet Time		
Time difference		
Sample	***Date/Time of Collection***	***Filter (E/B) ****
CLUP-1		
CLUP-2		
CLUP-3		
CLUP-4		
CLUP-5		
CLUP-6		
CLUP-7		
CLUP-8		
CLUP-9		
CLUP-10		
CLUP-11		
CLUP-12		
CLUP-13		
CLUP-14		
CLUP-15		
CLUP-16		
CLUP-17		
CLUP-18		
CLUP-19		
CLUP-20		
CLUP-21		
CLUP-22		
CLUP-23		
CLUP-24		
CLUP-A		
CLUP-B		

*Event (E) or Baseflow (B)

Checklist:

CD-B in sampler:	YES	NO
CD-A in cooler:	YES	NO
Time:		
Program sampler: Delay to 12:00 AM		
	YES	NO
Battery Voltage		
Amp-hr used since last disconnect		

† If the Amp/hr used resets between visits you have lost power at some point. OR reset it on purpose to track power consumption

Flow measurement		
Time		
	Flow velocity (m/s)	Depth (cm)
ROB 4		
ROB 3		
ROB 2		
ROB 1		
ROC		
Center		
LOC		
LOB 1		
LOB 2		
LOB 3		
LOB 4		

* Right/Left looking down stream

Notes:

Appendix E: Data Processing Flow Chart