Fall 9-14-2020

# Introducing the Self-Cleaning FiLtrAtion for Water quaLity SenSors (SC-FLAWLeSS) system

Aashish Sanjay Khandelwal
*University of New Mexico - Main Campus*

Aashish Sanjay Khandelwal

*Candidate*

Department of Civil, Construction & Environmental Engineering

*Department*

This thesis is approved, and it is acceptable in quality and form for publication:

*Approved by the Thesis Committee:*

Dr. Ricardo Gonzalez-Pinzon, Chairperson

Dr. David Van Horn

Dr. Mark Stone

# INTRODUCING THE SELF-CLEANING FILTRATION FOR WATER QUALITY SENSORS (SC-FLAWLESS) SYSTEM.

**by**


**AASHISH S KHANDELWAL**

**B.E. CIVIL ENGINEERING 2016**
**MUMBAI UNIVERSITY**
**MUMBAI, MH, INDIA**


THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

**Master of Science**
**Civil Engineering**

The University of New Mexico
Albuquerque, New Mexico

**December, 2020**

## Acknowledgements

Foremost, I would like to express my sincere gratitude to my advisor Dr. Ricardo Gonzalez Pinzon, for the continuous support of my graduate study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor.

I also acknowledge research professor David Van Horn for helping me develop the foundation of this work and professional resources to complete this research. Thank you for sharing your unique expertise and experience with me in our discussions, planning, and completion of this work.

I want to thank Dr. Mark Stone for your invaluable help in my thesis. I would also like to thank Post-doctoral fellow Peter Regier and Grad student Justin Nichols of the Ricardo Gonzalez Pinzon Hydro-systems lab for your generous efforts and ideas used to complete this work.

I graciously thank Rikk Smith of the UK Environment Agency for your generous sharing of the best practices for nutrient monitoring. I want to thank Dave Stahlke of Sea-Bird Scientific for sharing the information for reconfiguring the analyzer to fit with SC-FLAWLeSS system. I want to thank Mark Wallace from Campbell Scientific, helping me to design a reversible power circuit. Thank you to all the office and laboratory staff who contributed to the purchase process and documentation in this work.

## Introducing the Self-Cleaning FiLtrAtion for Water quaLity SenSors (SC-FLAWLeSS) system


By

**Aashish Khandelwal**

**MS Civil Engineering**

**Master of Architecture**


**ABSTRACT**


Sensor-based, semi-continuous observations of water quality parameters have become critical to understanding how changes in land use, management, and rainfall-runoff processes impact water quality at diurnal to multi-decadal scales. While some commercially available water quality sensors function adequately under a range of turbidity conditions, other instruments, including those used to measure nutrient concentrations, cease to function in high turbidity waters (> 100 NTU) commonly found in large rivers, arid-land rivers, and coastal areas. This is particularly true during storm events, when increases in turbidity are often concurrent with increases in nutrient transport. Here, we present the development and validation of a system that can affordably provide Self-Cleaning FiLtrAtion for Water quaLity SenSors (SC-FLAWLeSS), and enables long-term, semi-continuous data collection in highly turbid waters. The SC-FLAWLeSS system features a three-step filtration process where: 1) a coarse screen at the inlet removes particles with diameter > 397 μm, 2) a settling tank precipitates and then removes particles with diameters between 10-397 μm, and 3) a self-cleaning, low-cost, hollow fiber membrane technology removes particles ≥ 0.2 µm. We tested the SC-FLAWLeSS system by measuring nitrate sensor data loss during controlled, serial sediment additions in the laboratory and validated it by monitoring soluble phosphate concentrations in the arid Rio Grande river (NM, USA), at hourly sampling resolution. Our data demonstrate that the system can resolve turbidity-related interference issues faced by in-situ optical and wet chemistry sensors, even at turbidity levels >10,000 NTU.

**Table of Contents**

List of Figures------------------------------------------------------------------------------------------------viii

List of Tables--------------------------------------------------------------------------------------------------ix

Introduction-------------------------------------------------------------------------------------------------1

Motivation ---------------------------------------------------------------------------------------1

Research knowledge and gap-----------------------------------------------------------------3

The SC-FLAWLeSS system----------------------------------------------------------------------------5

Overview---------------------------------------------------------------------------------------5

Working----------------------------------------------------------------------------------------7

Validation and Optimization-------------------------------------------------------------------------11

Lab Validation------------------------------------------------------------------------------11

Field Validation-----------------------------------------------------------------------------14

Importance of filtration--------------------------------------------------------------------17

Comparison with existing technology-----------------------------------------------------------19

Conclusions & future direction-------------------------------------------------------------------23

Appendices------------------------------------------------------------------------------------------25

References------------------------------------------------------------------------------------------33

**List of Figures**

*Figure 1: Optical sensor flow path in headwater (top) vs large rivers (bottom) --------------------3*

*Figure 2: Physical layout of the SC-FLAWLeSS system, with components labeled as C1-C8 (cf. Table 1). ------------------------------------------------------------------------------------------------7*

*Figure 3: - Circuit wiring for the SC-FLAWLeSS system. ------------------------------------------8*

*Figure 4: SC-Flawless hourly cycle.-------------------------------------------------------------------10*

*Figure 5: Figure 5. Boxplot comparing nitrate readings from an optical nitrate sensor measured at different turbidity levels. ----------------------------------------------------------------------------12*

*Figure 6: Time series collected during co-deployment of a HydroCycle PO4 analyzer coupled to the SC-FLAWLeSS filtration system in the Rio Grande. Time series for ~1 month (August – September) of data collected through numerous high turbidity events.------------------------------16*

*Figure 7: Boxplot comparing turbidity values for major rivers across the USA for 2018. -------18*

**List of Tables**

*Table 1: SC-FLAWLeSS system component description.*-----------------------------------------------*9*

*Table 2: Time sequence of the SC-FLAWLeSS for 1-h filtration cycles.*-----------------------------*10*

*Table 3: Comparison of three commercially available filtration systems and the SC-FLAWLeSS.*-

----------------------------------------------------------------------------------------------------------19

***Introduction:***

**Motivation**

The rapid development of water quality sensors in the last decades, a period now called the "renaissance of hydrology" (Gabrielle, 2019), has enabled us to quantify the concentrations of multiple analytes (solutes and state parameters such as pH and temperature) at sub-hourly time scales. From these time series, we have gained unprecedented knowledge about the highly dynamic coupling-decoupling of terrestrial and aquatic ecosystems and surface water-groundwater interactions. High temporal resolution data have also allowed us to identify sites and times with disproportionally high interactions between environmental compartments and biogeochemical activity, i.e., hot spots and hot moments that control biological behavior, abiotic-biotic interactions and, thus, the transport and fate of contaminants, nutrients, and key inorganic elements that mediate biogeochemical cycles (e.g., Kirchner et al. 2004; Krause et al. 2015; Neal et al. 2012; Summers et al., 2019).

Some in-situ water quality sensors which record basic parameters function properly over a range of turbidity values. However, instruments that use microfluidics to perform wet chemical analyses (e.g., HydroCycle PO4 by Sea-Bird Scientific) and those that measure UV absorbance across a standard flow path including nitrate and fluorescent or colored dissolved organic matter (f/cDOM) sensors (e.g., SUNA V1 by Sea-Bird Scientific and EXO fDOM by YSI), are highly susceptible to elevated turbidity. This limits the utility of these sensors in large rivers, arid-land rivers, and coastal areas, where increased in-channel and lateral flows bring and re-suspend fine sediments that physically clog, interfere or block the communication between sensor components responsible for signal emission and reception. This status quo and other logistical challenges associated with conducting research in larger fluvial subsystems have contributed to fundamental knowledge gaps regarding the mechanistic behavior of nutrient and organic matter dynamics along fluvial networks (i.e., from headwaters to the ocean), such as the role of physical characteristics, the impact of resource supply, quality, and stoichiometric constraints (the molar ratios of essential limiting nutrients including C, N and P), and how these factors vary over time and space, considering anthropogenic disturbance regimes (Aguilera et al., 2013; González-Pinzón et al., 2015, 2019; Hall et al. 2013; Marcé & Armengol, 2009; Mortensen et al. 2016; Tank et al. 2008).

Optical and wet-chemistry sensors can be affected by a variety of matrix effects such as turbidity (Downing et al. 2012; Lee et al. 2015; Saraceno et al., 2017), organics and inorganics (Johnson & Coletti, 2002; Pellerin et al., 2013; Snyder et al. 2018; Zielinski et al., 2011), air bubbles, water temperature (Watras et al., 2011), pH fluctuations, and biofouling (Pellerin et al., 2013). Of these, high turbidity is the main interference and causes false positives or lack of signal detection (Pellerin et al. 2016). While high turbidity issues could be addressed through mechanical solutions (e.g., filtration, wipers), correction algorithms (e.g. Downing et al., 2012; Saraceno et al. 2017) or both (Pellerin et al. 2013), current commercial filtration systems lack one or more desirable qualities for long-term aquatic monitoring, where sites are often remote, funding is limited, and site-specific logistics require customization for proper function.

Here, we introduce the SC-FLAWLeSS system, an innovative, do-it-yourself (DIY) filtration system to improve in-situ data collection in high-turbidity systems. We designed the SC-FLAWLeSS to be low-cost (both to build and maintain), simple to construct, easy to customize, and portable. After testing the system in the laboratory with serial turbidity additions, we validated its use in the Rio Grande River, near Albuquerque (NM, USA), under flow conditions that exceeded turbidity values of 10,000 NTU multiple times during the 2018 summer monsoon season. Our findings suggest that the SC-FLAWLeSS is a simple, cost-effective alternative to current commercial filtration systems, and holds great promise to improve data quality for in-situ monitoring of turbid aquatic systems.

**Existing knowledge and research gap.**

Large Rivers have not been studied from a nutrient dynamic perspective as compared to small streams. Most of the research have done on the between small streams and intermediate size ranging from first order to fifth order rivers. The changes of river from first order to fifth order occur within first 200 km of river length, whereas the remaining higher order of large rivers flow for remaining thousands of kilometers (Tank et al. 2008). This focus on low order streams is due to logistical and technological constraints inherent in working in large rivers.

Thus, little is known about how nutrient dynamics vary along the river continuum, promoting an over-reliance on knowledge gained from headwaters, despite a vast knowledge base that documents how stream structure and function changes throughout watersheds and along the river continuum (Bouwman et al., 2013, Vannote et al., 1980). Furthermore, since anthropogenic impacts to streams increase as stream order increases, research on headwater streams likely inadequately describes human impacts to instream nutrient dynamics including waste water inputs, dams and reservoirs, and how these impacts impair downstream aquatic ecosystems (Kiel and Cardenas, 2014; Gomez-Velez and Harvey, 2014).

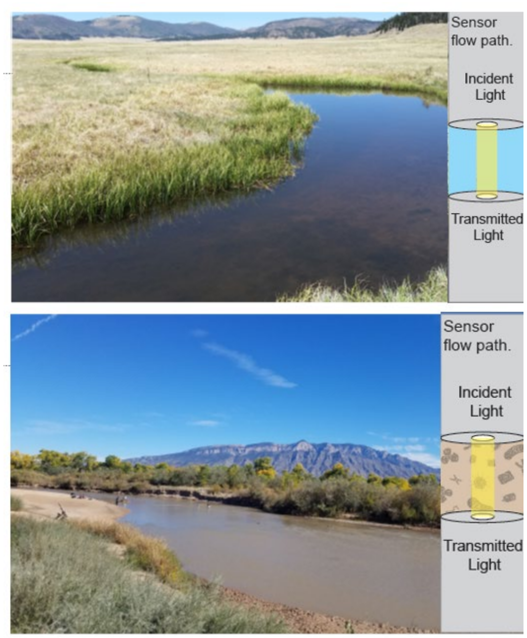


Figure 1. Sensor flow path in headwater (top) vs large rivers (bottom)

Long-term observations of nutrient load are critical to better understanding how changes in land use, management, and precipitation are impacting water quality. Monitoring nutrients in a large river's such as Rio Grande is a cumbersome and expensive process. Water quality indicators including physical, chemical, and biological properties are majorly monitored in two ways, one is traditional way of collecting discrete samples from the field and then analyzing in the laboratory which is a labor intensive and time consuming process thus not feasible for long term continuous monitoring (Duff and Triska, 2000, n.d.). Another way is emerging, by using in-situ optical sensors which offer high temporal resolution & is much more feasible for water quality database on a regional scale (Haylock et al., 2008). Currently, there are no economically viable technologies that can measure nutrients in big rivers, which could answer the critical question; even though, a good amount of research is being made to develop better sensors.

In order to accurately quantify long term nutrient loading, lab analysis seems to be unfeasible as it will requires constant manual effort and high costs. The current sensors present a challenge of running smoothly in high turbid water of large rivers. The current cost to purchase the optical sensors alone is expensive ($15k -20k) and other overhead cost for instrument service and maintenance cost open the questions for the need for continuous data. Even after carefully identifying the need for continuous data there is a challenge with existing sensors to tackle the interferences to achieve the required quality of data. The data accuracies need to evaluate in order obtain the gap between the true data and the data through sensors that may be influenced by matrix interferences. Thus, little is known about how nutrient dynamics vary along the river continuum, promoting an over-reliance on knowledge gained from headwaters, despite a vast knowledge base that documents how stream structure and function changes throughout watersheds and along the river continuum (Bouwman et al., 2013, Vannote et al., 1980).

Furthermore, since anthropogenic impacts to streams increase as stream order increases, research on headwater streams likely inadequately describes human impacts to instream nutrient dynamics including wastewater inputs, dams and reservoirs, and how these impacts impair downstream aquatic ecosystems (Kiel and Cardenas, 2014; Gomez-Velez and Harvey, 2014). . To meet the objective of this project is to quantify water quality parameters and nutrients in the Rio Grande near Albuquerque through high- resolution monitoring system like, the SC-FLAWLeSS system will offer a vast possibilities for monitoring solutes in turbid aquatic systems.

### ***The SC-FLAWLeSS system:***

#### **Overview**

The SC-FLAWLeSS features a three-step filtration process where: 1) A coarse screen at the inlet removes particles with diameters >397 μm, 2) a settling tank precipitates and then removes particles with diameters between 10 and 397 μm, and 3) a self-cleaning filtration membrane uses low-cost, hollow fiber membrane technology to remove particles ≥ 0.2 μm. This set up enables long-term, high-frequency data collection from in-situ sensors sensitive to turbidity interference.

From up- to down-flow, the SC-FLAWLeSS system consists of the eight major components (Table 1 and Figure 1). In our descriptions, specific brand information is provided for informational purposes and does not constitute any recommendation or endorsement.

**Table 1.** SC-FLAWLeSS system component description.

| Component | Example | Description |
|---|---|---|
| C1 |  | 12-VDC inline submersible pump by Grainger (Item no: 3TNJ2) with a maximum capacity of 302 L/h and suction head of 4.6 m. This pump features a coarse screen made of 304 stainless steel 30 mesh to exclude coarse suspended sediments > 0.4 mm diameter and a pumping line of 0.95 cm diameter. |
| C2 |  | Conic settling tank produced by Den Hartog Industries (Manufacturer part no SPBM003-RT) with a capacity of 11.4 L made from UV stabilized medium density polyethylene, which allows the settling of suspended sediments. The tank dimensions are 30.5 cm L x 17.8 cm W x 35.6 cm H, with a 0.5 cm nominal wall thickness. It has a 1.9 cm spin weld fitting at the bottom, 1.9 cm overflow outlet at the 11.4 L level mark and 12.7 cm lid for maintenance. |
| C3 |  | Solenoid valve produced by Hardware Factory Store (Model number: SLV-12-03) with a 1.9 cm diameter that allows flushing of sediments from the settling tank. |
| C4 |  | Hollow fiber membrane to filter out particles ≥0.2 µm in diameter. The filter pore size traps most of the suspended particulates in the water. For this, we used a LifeStraw® hollow fiber filter. |
| C5 |  | Reversible peristaltic pump to pull water from the settling tank, and to back-flush the hollow fiber membrane. The pump used was a Masterflex L/S Compact 12-VDC drive; @540 rpm using Masterflex L/S peroxide-cured silicone tubing. |
| C6 |  | Cylindrical tank of 1.9 L, produced by Hanna Instruments, to store filtered water, which can be used to feed or house the analyzer or sensor. Plastic barbed couplings were used to connect the tubing to the tank and provide leak prevention. |
| C7 |  | Sensor or analyzer. The wet chemical analyzer HydroCycle $PO_4$ by Sea-Bird Scientific was used in our field test for phosphate monitoring but note that virtually any sensor can be coupled to the SC-FLAWLeSS. |
| C8 |   | The circuitry controlling the SC-FLAWLeSS involves reversible polarity of the current using two solid state relays (SSR) and a double pole-double throw (DPDT) relay. SSRs are connected to low-power COM ports controlled by a datalogger (Campbell Scientific CR1000), while a third COM port controls the DPDT relay. We used SSRs produced by Galco (D1D07) and DPDT relays produced by IDEC (RJ2V-C-D5). |

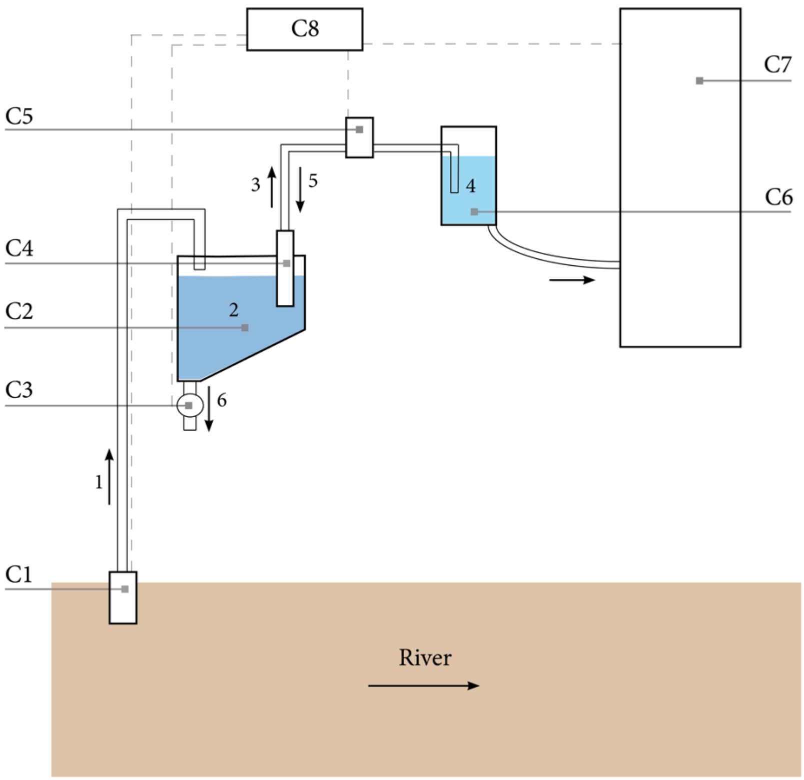


**Figure 2.** Physical layout of the SC-FLAWLeSS system, with components labeled as C1-C8 (cf. Table 1), and flow arrows associated with the filtration steps described in working.

**The SC-FLAWLeSS system: Working.**

Below, we describe the filtration steps of the SC-FLAWLeSS, referring to the components C1-C8 described in Table 1 and Figure 1.

**Filtration Step 1:** C1 is connected to C2. The pumping schedule is specified in the data logger program and implemented through a 5V COM port that magnetizes a solid-state relay (SSR) to close the circuit between the battery and the pump (Figure 2). Because disaggregation of particles via physical agitation from the pump could lead to dissolution of particle-bound nutrients, we used a slimline pump rather than an impeller pump which both reduces power needs and minimizes turbulence.

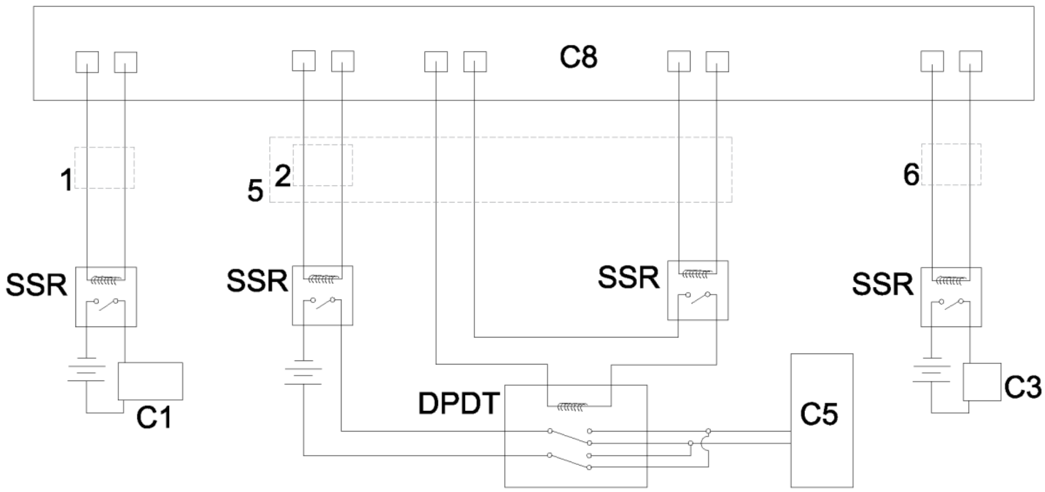


**Figure 3.** Circuit wiring for the SC-FLAWLeSS system. SSR: Solid State Relay. DPDT: Double pole double throw relay. C1: River pump. C5: Reversible pump. C3: Solenoid Valve (cf. Table 1). Dashed lines indicate activation of the COM port with respect to the sequence. Flow sequence steps are numbered, matching numbered steps in working section.

**Filtration Step 2:** As water is brought into the SC-FLAWLeSS system with the submersible pump C1, it enters the settling tank C2, which has a conic shape to prevent the accumulation of the sediments at the bottom of the tank and diverts all the sediments towards the spin weld fitting. The solenoid valve C3 is connected to the spin weld fitting to regulate the flushing of the settling tank (see Filtration Step 6). Using the controlling board C8, the SC-FLAWLeSS system initially flushes any residual water by pumping 22.7 L of water to the settling tank when the solenoid valve C3 is open. After flushing, C3 is closed and sediments are allowed to settle. The settling time may be varied according to filtration needs. For reference, we used 20 minutes of residence time to filter water from the Rio Grande river, which has an average turbidity level of 100 NTU (see Supplemental Information for details). The gravity-driven settling process in the tank results in the separation of sediments, which sink to the bottom, providing a clarified surficial layer at the top of the water column. The system was located beneath a low concrete bridge to shelter it from sunlight and minimize any potential of temperature-driven changes in microbial nutrient utilization, and also to protect the setup from the rain, wind and animals.

**Filtration Step 3:** After the retention time in the settling tank has elapsed, the pump C5 pulls the top layer of clearer water from the settling tank C2 through the filter membrane C4. The schedule of this pump for the forward flow is controlled through the SSR system, similar to the inline pump (Figure 2).

**Filtration Step 4:** The water exiting the filtration membrane C4 is collected in a filtered water tank, C6, which is connected to the sensor/analyzer and to one overflow outlet at the 1.9 L level mark. The capacity of C6 is sized according to the water demand/size of the sensor/analyzer and the back-flushing requirement for the hollow fiber membrane C4.

**Filtration Step 5:** Once the clean tank C6 is filled with filtered water, the sensor/analyzer starts to collect data. When it finishes, the reversible pump C5 is operated in the reverse direction to pump filtered water and back-flush the filtration membrane C4. The sensor/analyzer can run in standalone mode or be attached to the SC-FLAWLeSS system programmer, C8. The membrane C4 is sturdy enough to withstand back-flushing, greatly prolonging filter life and decreasing maintenance required to clean or replace clogged filters.

**Filtration Step 6:** The final step for completing one full cycle of the filtration system is the activation of the solenoid valve, C3. After the back-flushing of the filtration membrane C4, the solenoid valve C3 is activated to gravity-flush the settling tank C2. After this, C3 is deactivated, and the SC-FLAWLeSS system is ready for the next filtration cycle. C3 is scheduled and operated through an SSR system in a similar way to the operation of the inline pump.

**Table 2** provides an example of our current set-up, which allows instrument readings every hour. However, note that this set-up can be customized to match data frequency requirements and sensor capabilities.

| Sequence | Time HH:MM | Activity |
|---|---|---|
| 1 | 0:00 | River Pump (C1) Start. |
| 2 | 0:01 | River pump stop and, flushes and fill up the settling tank (C2). |
| | 0:21 | Settling Process takes place for 20 min. |
| 3 | 0:23 | Reversible pump (C5) pulls water through the membrane filter (C4). |
| | 0:27 | Reversible pump stops filling the filtered chamber (C6). |
| 4 | 0:27 | Analyzer (C7) starts. |
| 5 | 0:50 | Analyzer stops and reversible pump start back-flushing membrane filter (C4). |
| 6 | 0:52 | Activation of solenoid valve (C3) flushes the settling tank. |
| | 1:00 | Solenoid valve stops and is ready for the next filtration cycle. |

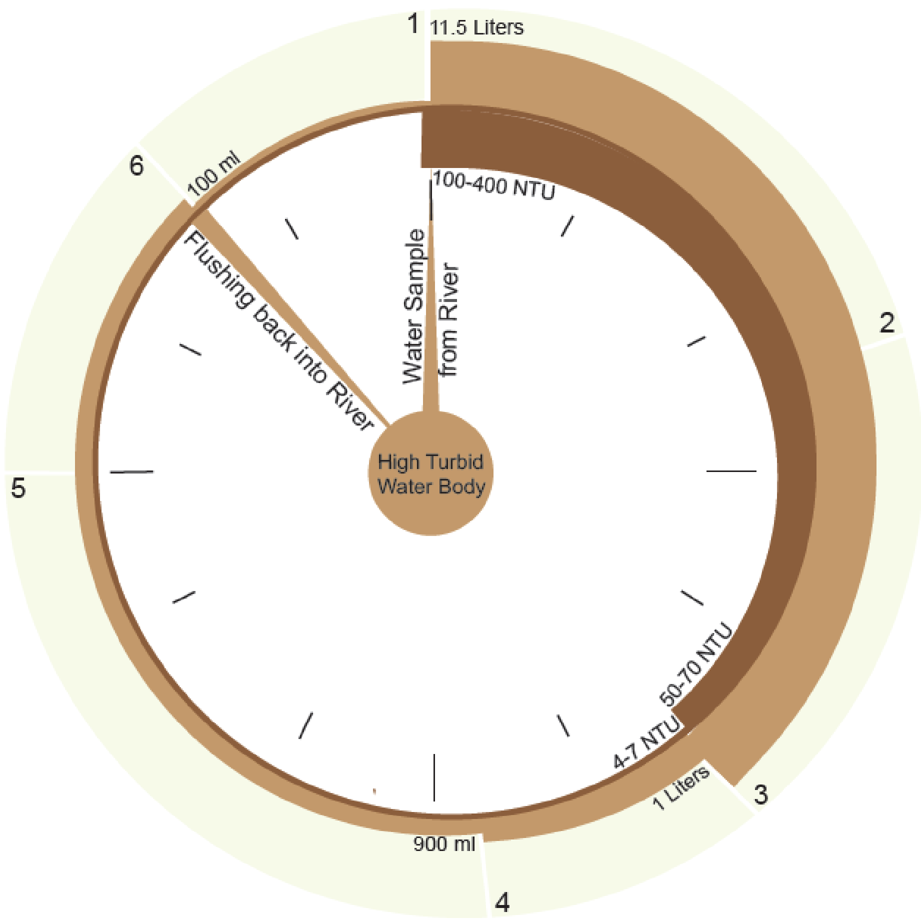


**Figure 4:** SC-Flawless hourly cycle. Light brown indicating the quantity of sampled water flowing through system wrt to time and dark brown indicating the turbidity values wrt to time (cf. Table 2).

*The SC-FLAWLeSS system: Optimization and validation*

## Laboratory optimization and validation of SC-FLAWLeSS

We tested the individual and integral performance of all the components of the SC-FLAWLeSS in the laboratory using high-turbidity water (1150 FNU) from the Rio Grande, near Albuquerque. Here, turbidity is reported in FNU (Formazin Nephelometric Units) instead of NTU (Nephelometric Turbidity Units), as FNU are reported by YSI sondes used for lab and field experiments, and by USGS monitoring sites. We note that FNU is equal to NTU for YSI instrumentation (YSI Technical Note T627). While all the laboratory optimization steps are discussed in detail in the Supplemental Information, we summarize here the main findings, particularly those related to the settling and filtration steps.

We investigated the effects of increasing turbidity conditions on sensor readings in a controlled laboratory setting by measuring nitrate with a SUNA V1 optical sensor (10 mm pathlength). The instrument was calibrated immediately prior to the experiment and, since the total run time for a lab experiment was 25 minutes, we expected negligible drift based on the manufacturer's specifications (0.004 mg/L/hr). For our test, we prepared a solution with nitrate concentration of 35.5 μM or 2 mg/L by adding $NaNO_3$ salt to ultrapure water, set the SUNA V1 sensor to read twice per second, and used an in-line pump to continuously agitate the water. Starting when no sediments were present, nitrate measurements were collected continuously for 5 minutes for each of five turbidity levels spanning a range of 0-1050 FNU. Each turbidity level was reached by sequential additions of previously dried river sediments from the Rio Grande. Figure 3 demonstrates the importance of filtration for in-situ instruments in several ways. First, at higher turbidity levels, potential sediment inputs of organic carbon could result in over-estimated nitrate values, as optical nitrate measurements are sensitive to organic carbon concentrations (Pellerin et al. 2013). Second, both variance and heterogeneity of the water column increased with higher turbidity conditions. Third, at higher turbidity levels, data loss consistently rises, indicating a decrease in data quality. The combination of altered mean values, increased noise, and data loss, reduce data quality during high turbidity conditions, which frequently coincide with storms that in many systems represent the most important periods for solute transport assessment and investigation (e.g., Raymond & Saiers, 2010).

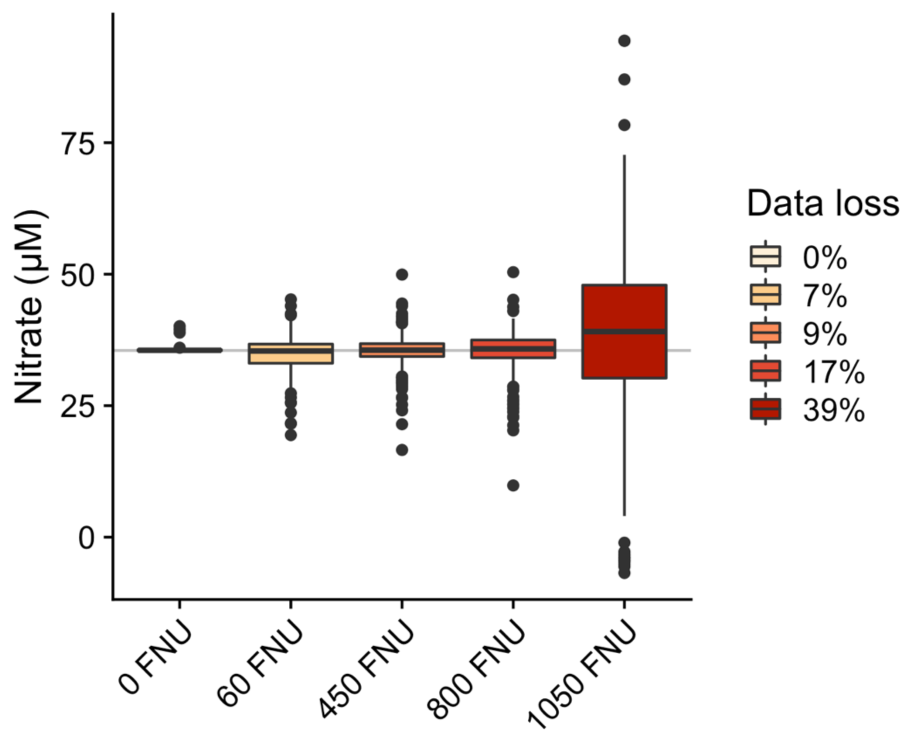


**Figure 5.** Boxplot comparing nitrate readings from an optical nitrate sensor measured at different turbidity levels. Nitrate levels were kept constant throughout the experiment, while turbidity was increased stepwise by sequential addition of sediments collected from Rio Grande surface water. Each box represents around 480 measurements, but many data collected were compromised (negative values, no data collected, etc.). The color shading each box indicates the percentage of data loss, ranging from 0% to 39%.

From the knowledge gained from Figure 3, we targeted the design of an affordable settling and filtration system capable of reducing data loss from optical and wet-chemistry sensors deployed in high turbidity water to values below 10%. For this, we first determined the optimal balance between shorter settling times (i.e., increased frequency of data collection) and lower turbidity (i.e., increased longevity of the membrane filter) by measuring turbidity as a function of time in a settling container. Our tests suggested that a settling time of 20 minutes was sufficient to remove ~70% of turbidity (see Supplemental Information). Next, we evaluated multiple filtration options and selected the commercially available LifeStraw®, which features a sterilizing grade filter with pore diameter of 0.2 μm, capable of providing low turbidity water to the sensor while removing 99% of bacteria, thereby reducing the potential for bio-fouling interference. Additionally, LifeStraw® filters are capable of backflushing, which increases their capacity and longevity while deployed. Finally, we conducted tests to select a sampling tank that minimizes air bubble formation due to oscillating and turbulent flow conditions occurring prior to sensor measurements (see Supplemental Information). Thus, the SC-FLAWLeSS was designed to achieve low turbidity levels and allow continuous, high-quality data collection regardless of suspended sediment conditions.

**Field validation**

To validate filtration performance of the SC-FLAWLeSS system in the field, we coupled it with a HydroCycle $PO_4$ sensor. During this activity, we used manufacturer standards (phosphate standard, ascorbic reagent, and mixed molybdate reagent), purchased in pre-filled, sealed cartridges which were installed on the instrument. Standards were run automatically by the instrument prior to every measurement. We replaced cartridges prior to expiration if not exhausted. We deployed the HydroCycle $PO_4$ sensor with SC-FLAWLeSS filtration in a fish bypass channel located along the Rio Grande, near the Albuquerque drinking water treatment plant and USGS gauge 08329918. At this location, the Rio Grande river is a 7$^{th}$ order stream and has an average discharge of 26 $m^3/s$; there, previous testing with the HydroCycle $PO_4$ sensor by the manufacturer determined that clogging of the stock HydroCycle filters at high turbidity levels typically occurred within 3-4 days. Besides the coupled SC-FLAWLeSS and HydroCycle $PO_4$ system, we co-deployed a YSI EXO2 water quality sonde measuring turbidity in FNU. Figure 4 presents discharge, turbidity and $PO_4$ data collected between August and September during the 2018 monsoon season (Figure 4A-C) and during a single extreme turbidity event in October, 2018 (Figure 4D).

During this field validation, the SC-FLAWLeSS successfully provided filtered water to the HydroCycle $PO_4$, as evidenced by nearly continuous data availability. To better contextualize the optimal performance and potential use of the SC-FLAWLeSS system with multiple instrumentation platforms, we highlight here that Pellerin et al. (2013) found incomplete transmittance of optical nitrate readings above 450 NTU. Likewise, Downing et al. (2012) noted that algorithms for turbidity correction of in-situ fDOM sensor data are not robust above 600 FNU. The HydroCycle $PO_4$ manufacturer guidelines state that even when the instrument is equipped with an upgraded filter (Filter Upgrade: PN SAS-542531), it can operate for 100 hours (~4 days) at 200 NTU, and 80 hours (~3.3 days) at 600 NTU when sampling at 1-h intervals. These thresholds are overlaid on Figure 4 for reference, and clearly demonstrate that significant portions of the dataset, including most storm events, would likely be compromised (poor data quality) or lost entirely without the SC-FLAWLeSS. The instrument-specific turbidity thresholds of 200, 450, and 600 NTU/FNU were exceeded in the time-series data in Figure 4B for 41%, 25%, and 22% of the dataset, respectively, representing significant loss of data, along with potential damage to instruments (i.e., clogging of plumbing, abrasion and burial of wiped sensors) if the SC-FLAWLeSS was not co-deployed. The HydroCycle $PO_4$ internally does a quality control analysis based on the upper and lower limits for high, suspect and low-quality data. In our field validation of the SC-FLAWLeSS, the HydroCycle $PO_4$ was able to collect high-quality data (i.e., 95% was designated as high quality), even throughout extended periods of very high suspended sediments (peak turbidity reached ~18,000 FNU during one event).

While Figure 4A shows that during the field validation period there was only one major storm, Figure 4B shows that there were many very large turbidity events, where turbidity measurements greater than 100 FNU (considered a high turbidity environment by the HydroCycle $PO_4$ manufacturer) were present for 87% of all samples. Figure 4D shows an expanded view of an isolated storm event in October, where both the diel behavior of $PO_4$ and the relationship between turbidity and $PO_4$ are apparent. During periods of high turbidity associated with storm events, diel patterns in $PO_4$ are muted, and $PO_4$ concentrations generally decrease (Figure 4B and 4C), and this is particularly clear in Figure 4D when the semi-diel signature completely disappears, and $PO_4$ levels reach near-zero concentrations. Results in Figure 4D suggest stronger adsorption of $PO_4$ to sediments (e.g., Reddy & DeLaune, 2008; Watson et al., 2018) at higher sediment concentrations, which would not be observable for much for this period without the SC-FLAWLeSS, since the HydroCycle $PO_4$ functioning becomes suboptimal when turbidity is greater than 600 FNU, even with frequent instrument servicing (i.e., every 3-4 days).

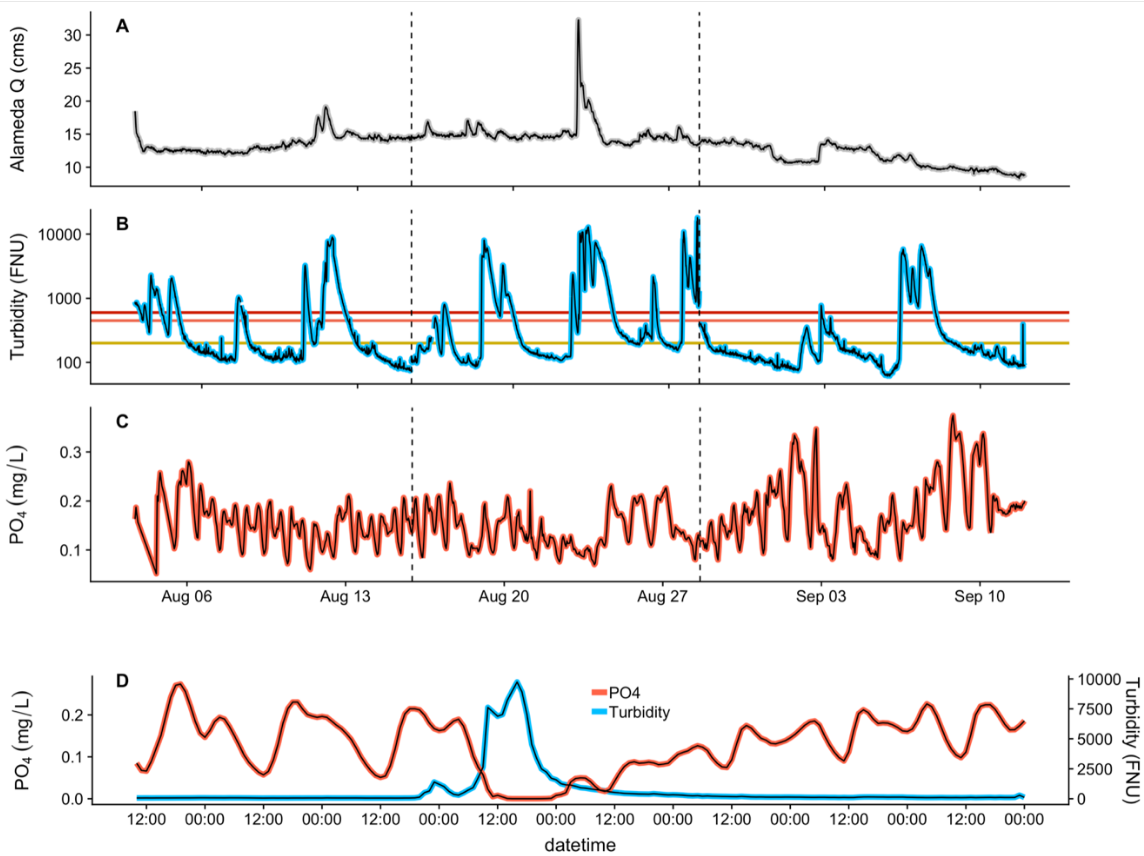


**Figure 6.** Time series collected during co-deployment of a HydroCycle $PO_4$ analyzer coupled to the SC-FLAWLeSS filtration system in the Rio Grande. Time series for ~1 month (August – September) of data collected through numerous high turbidity events are presented for A) discharge, B) turbidity and C) $PO_4$, where vertical lines in C indicate field visits, and yellow, orange and red horizontal lines indicate instrument-specific turbidity thresholds above which instruments are not robust, i.e., 200 FNU (e.g., HydroCycle $PO_4$ would last only 4 days sampling every hour before clogging), 450 FNU (incomplete transmittance of optical nitrate), and 600 FNU (fDOM sensor readings are unreliable). D) Time series for turbidity and $PO_4$ are overlain for a late-season storm (mid-October) where adsorption of $PO_4$ to sediments or dilution are evident.

## The importance of filtration

Sensor-based, semi-continuous observations of water quality parameters in large rivers have become critical to understanding how diurnal to multi-decadal changes in land use, management, and rainfall-runoff cycles impact water quality. However, as demonstrated in Figure 3, turbid conditions reduce data quality and increase data loss, limiting data available during important hydrologic events. Moreover, turbidity levels in aquatic systems are related to a complex array of factors (Vercruysse et al. 2017), including catchment characteristics (Chinchilla et al. 2019), non-linearities in wetting-drying cycles (Chen & Ju, 2014) and altered land use (Huey & Meyer, 2010), making it difficult to predict when turbidity interferences will compromise data quality or damage instrumentation (e.g., clogging or scratching of wiped optical sensors).

Figure 5 presents turbidity data collected by in-situ instrumentation in major rivers across the United States for the 2018 calendar year. Based on average turbidity values, only 3 of the 9 rivers shown have average turbidity values above 100 FNU (equal to 100 NTU). However, the percentages of turbidity values >100 FNU, presented at the top of Figure 5, are high for several rivers, including the Mississippi River, which is the largest river in the USA (13.9%). For the HydroCycle $PO_4$, the threshold of 200 FNU is regularly (>5%) exceeded by the Arkansas, Missouri, Rio Grande at US550, San Juan, and Yellowstone (9.2%, 15.0%, 10.6%, 36.3%, and 21.3%, respectively). For the SUNA V1, the threshold of 450 FNU is regularly exceeded by the Rio Grande at US550 and the San Juan (7.8% and 21.7%, respectively), both of which are arid-land rivers. Both of these rivers also regularly exceed the 600 FNU threshold for YSI sondes (7.3% and 15.7%, respectively). Moreover, we note that these turbidity values represent the full calendar year. In many systems, winter flows are low, have low turbidity, and represent a disproportionally small percentage of annual discharge and annual nutrient and pollutant loads. During snowmelt and rainy periods, discharge, nutrient and pollutant inputs, and turbidity all generally increase. Therefore, instruments deployed in rivers during these periods, particularly in semi- and arid regions but also in major rivers across the nation, are at risk of collecting low quality data. Since these data inform management strategies and are used to verify the compliance of allowed discharges and total maximum daily loads, filtration systems such as the

SC-FLAWLeSS can provide affordable, simple and customizable solutions to improve data quality of in-situ instrumentation.

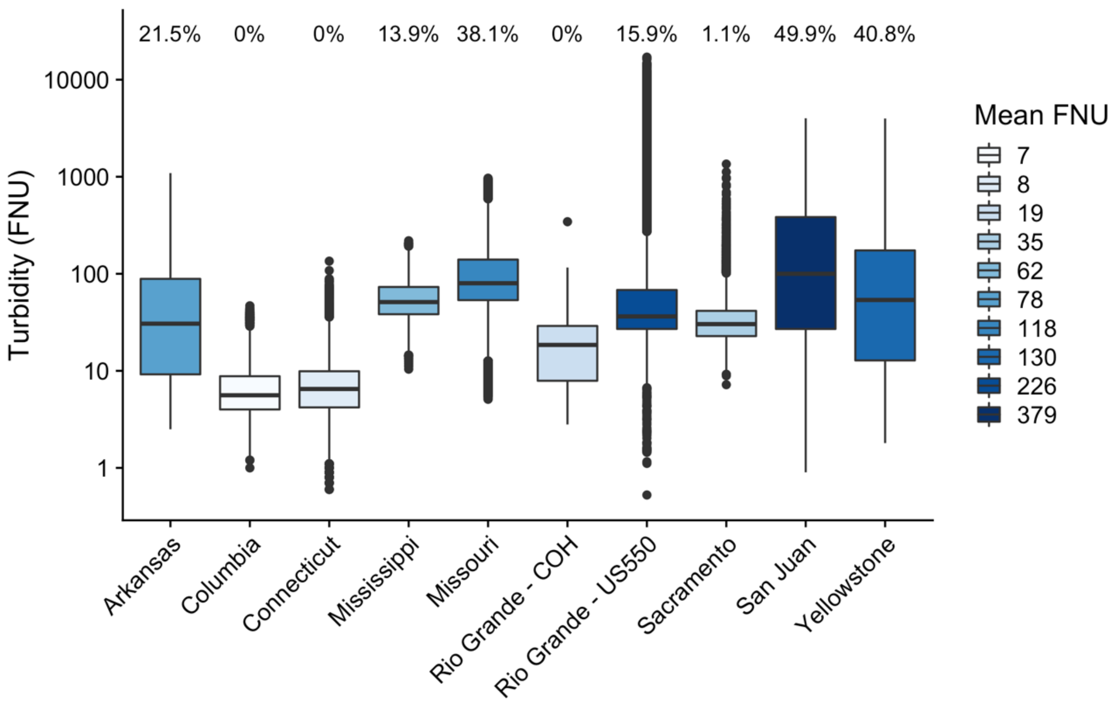


**Figure 7.** Boxplot comparing turbidity values for major rivers across the USA for 2018. Boxes are color-coded by mean turbidity values, with the percent of data above 100 NTU (indicating turbid waters) presented above each box.

### *The SC-FLAWLeSS system: Comparison with existing technology*

Optical sensors and wet-chemistry analyzers do not operate properly in high turbidity waters because fine particles block signal propagation and clog moving parts and filters. To solve these issues, commercial companies are customizing water quality sensors to have shorter path lengths and minimize the impact of high turbidity conditions, but these solutions come with the tradeoff of reduced sensitivity/higher detection limits (Pellerin et al., 2013). On the other hand, commercial sensor makers have developed filtration systems that tend to be expensive ($2,300-

$3,000 USD), require frequent cleaning, have high energy demands, have large power requirements and depend on additional infrastructure (AC power, air compressors or pumps), making them ill-suited for aquatic monitoring sites located in remote or difficult to access locations.

We developed the SC-FLAWLeSS system to be adaptable, versatile, and capable of efficiently filtering a wide range of suspended materials at customized flow rates that match the filtration needs of specific sensors. In developing the SC-FLAWLeSS system, we sought to satisfy all the following conditions: 1) low cost, 2) low maintenance, 3) low power requirements, 4) self-cleaning capacity, 5) compact design, and 6) easy automation. To provide a more quantitative context, Table 3 compares three commercially available filtration solutions for in-situ instrumentation and the SC-FLAWLeSS.

**Table 3.** Comparison of three commercially available filtration systems and the SC-FLAWLeSS.

| Developer | Rotor Flush | Xiamen Kelungde Env. Engineering Co., Ltd | Sea-Bird Coastal for HydroCycle | Our team |
|---|---|---|---|---|
| **Part** | RF100AN | CZGL-15 | Filter Upgrade: PN SAS-542531 | SC-FLAWLeSS |
| **Filter Specification** | Polyproplen, acetal with nylon filter | Porous AISI 316L stainless steel | Ultra-high-molecular-weight polyethylene thermoplastic | 'U' shaped hollow fiber micro tubes |
| **Filter Pore Size** | 60 µm | 1–10 µm | 5–10 µm | 0.2 µm |
| **Power** | AC 230v or 110v 50 Hz or 115v 60 Hz | DC 24V, 75W | No Power | DC 12V, 111W |

| Developer | Rotor Flush | Xiamen Kelungde Env. Engineering Co., Ltd | Sea-Bird Coastal for HydroCycle | Our team |
|---|---|---|---|---|
| **Cleaning Process** | Back-flushing with water jet | Back-flushing with compressed air | Replacement of filters | Back-flushing with water pressure |
| **Filtration Rate** | 150L/h | 60L/h | 100mL/h | 100mL-1000mL/h |
| **Component costs in US Dollars (Year 2019)** | 3049 | 2345 | 650 | 900 |
| **Maintenance costs in US Dollars (Year 2019)** | 27 | 55 | 75 | 15 |
| **Required Infrastructure** | Pump+ Access to AC power + datalogger | Air compressor + access to AC power + datalogger | Datalogger + battery | Datalogger + battery |

Of the four systems presented in Table 3, both the RF100AN and the CZGL-15 require significant up-front costs (>$1,000 USD) to operate each filtration system. They also require access to AC power, which frequently is not an option at monitoring sites. The RF100AN requires separate purchase of a pump, which adds additional cost to complete the system. The CZGL-15 runs on DC power, which could be converted from the AC source, but also requires the purchase of an air compressor for backwashing of the filters. While upfront costs are an important consideration, so are maintenance costs. For example, the upfront costs to purchase the SeaBird filter for the HydroCycle $PO_4$ are considerably lower ($650) than the SC-FLAWLeSS. However, this system requires regular filter replacement, e.g., every 4 days for 1-hour monitoring intervals in medium-turbidity waters, i.e., ~ 100 NTU. The maintenance costs (i.e., purchase of materials, excluding costs associated with regular field visits) for the SeaBird filtration system equal $643 USD per month, in comparison to 15 USD/month for the SC-FLAWLeSS. Thus, while upfront costs for the SeaBird filter are lower, the expected total cost for one year of 1-h monitoring reaches

$8,304 USD, while the equivalent maintenance replacement costs for the SC-FLAWLESS filtration system would be only $180 USD considering the cost of a LifeStraw® replacement as $15/month.

In addition to optimizing costs, the SC-FLAWLeSS has been designed for remote deployment in high-turbidity systems dominated by fine particulates. The SC-FLAWLeSS has been engineered to effectively remove particle diameters ≥ 0.2um, which are at least one order of magnitude smaller than those that the other three filtration systems presented in Table 3 can remove. The SC-FLAWLeSS also uses smaller volumes of water, which further improves filter life, and features a simple, low-power cleaning system that is portable. These characteristics make our system ideal for deployment in remote locations or at sites with limited access. For comparison, the power requirements of the RF100AN and CZGL-15, along with the air compressor required for the CZGL-15, make both systems impractical for remote deployments. Likewise, the regular need to replace SeaBird filters makes long-term deployment difficult, as site visits must be conducted multiple times each week during high-turbidity conditions.

The SC-FLAWLeSS is specifically designed to be easily integrated into existing monitoring station infrastructure. The flexible design of the SC-FLAWLeSS system enables the coupling to water quality monitoring systems such as flow-through, in-situ or those featuring internal logging. This is achieved by using a shared datalogger/programmer unit and selecting a set of available control ports to control the timing of the electronic hardware in SC-FLAWLeSS. Finally, the design and materials used to construct the SC-FLAWLeSS are all readily available, making it simple and easy for users to replicate our design, and to alter the system to fit site-specific or project-specific requirements.

*Conclusions and future directions:*

We present the SC-FLAWLeSS, a DIY, cost-effective and adaptive solution to filtration problems faced at aquatic monitoring sites across the globe. Low energy usage (estimated at 43.12 kWh/year for 1-h frequency data, equivalent to using a 100 watt bulb for 1.5 h/day, for a year) and usage of common site equipment (data loggers, 12V batteries) mean that the systems will easily integrate into the existing infrastructure of a typical site without significant additional power or equipment requirements. A combination of flow-driven and gravity filtration steps increases the lifetime of consumables and reduces servicing requirements and costs (the filter, costing $10-20 as of 2019, lasts 1 month in turbid conditions (> 100 NTU) based on our tests). These results suggest that the SC-FLAWLeSS system can operate reliably in turbid systems, providing remarkably improved data quality for optical and wet-chemistry sensors, without considerably increasing financial or personnel requirements. Importantly, the flexible design of the SC-Flawless system enables users to customize the design and adjust functional parameters to fit into the deployment to most current water quality monitoring systems, including flow-through and in-situ systems. Furthermore, the SC-FLAWLeSS is designed for use with Campbell Scientific dataloggers, but can easily be controlled by any programmable datalogger (including cost-effective DIY solutions like Arduino and Raspberry Pi), making the system easy to adapt into an existing water quality monitoring system. Through a multi-month field deployment at an existing in-situ water quality station in Rio Grande, Albuquerque, the SC-FLAWLeSS successfully provided low turbidity water for analysis during periods of very high turbidity while eliminating potential interference from bio-fouling, air bubbles, or creating erroneous data associated with mechanical failures common in high turbidity systems (wiper failure, debris covering or damaging sensors, clogging with fine sediments, etc.). Furthermore, the reduction in turbidity produced much cleaner data compared to simultaneously deployed optical instruments not connected to the system, virtually eliminating spikes, negative values, and high noise levels. The SC-FLAWLeSS makes it easier to monitor parameters of interest using existing instrumentation in systems where turbidity would normally inhibit monitoring, providing data for load assessment, source identification, event evaluation, determination of aquatic processes and real-time decision support in currently unmonitored aquatic ecosystems. We see additional potential for future versions of this system to reduce size and cost by altering the quantity of water filtered and selecting a more economical pump (60% of current system cost). Other adaptations of this technology, such as incorporating a clean water line to run blanks in between each measurement to assess drift and fouling, or adding heating and cooling elements to maintain operation in harsh environments hold great potential to address existing limitations for autonomous aquatic monitoring. Consequently, the SC-FLAWLeSS system already offers vast possibilities for monitoring solutes in turbid aquatic systems, and as a DIY product, we anticipate will grow in value as it is adapted and improved.

*Appendices*

## List of Appendices

*Settling of suspended solids in the settling tank* ........................................................ 25
*Assessing the hollow fiber membrane* ........................................................ 26
*Determination of pumping flow rate* ........................................................ 27
*Controlling the SC-FLAWLeSS* ........................................................ 28

***Settling of suspended solids in the settling tank (C2 in Table 1 and Figure 1):***

Gravity separation is a widely used treatment process for separating suspended particles, and is one of the simplest methods for reducing turbidity. Since gravity separation does not require a filtration device, any solids removed during settling will not be passed through a filter, improving the longevity of the filtration system. For this reason, we decided to incorporate gravity separation as a settling tank into the design of the SC-FLAWLeSS. We conducted tests on water collected from the Rio Grande river in Albuquerque, NM to evaluate settling velocities and times. Tests were conducted in a 4L clear glass beaker, using water collected 50 cm from the river bank, at a depth of 10 cm. During the tests, turbidity readings were taken in the clarified zone within the top $1/3^{rd}$ of the water column in the beaker. After a series of field experiments, we determined that a detention time of 20 minutes resulted in a ~70% reduction in turbidity values: from 120 NTU to 40 NTU (Figure S1). After 20 minutes, the settling rate decreased, suggesting 20 minutes as the optimal balance between short settling times (allowing for higher frequency data collection) and low turbidity (to increase the lifetime of the filter). For reference, our tests concluded that settling for 15 minutes reduced turbidity values by 66%, while settling for 30 minutes reduced turbidity values by 71%. Thus, doubling the retention time (and reducing data collection frequency by a factor of 2), only reduced turbidity levels by an additional 5%. This reduced "return on investment" supports the selected retention time of 20 minutes as an appropriate balance between lower turbidity and higher data frequency.

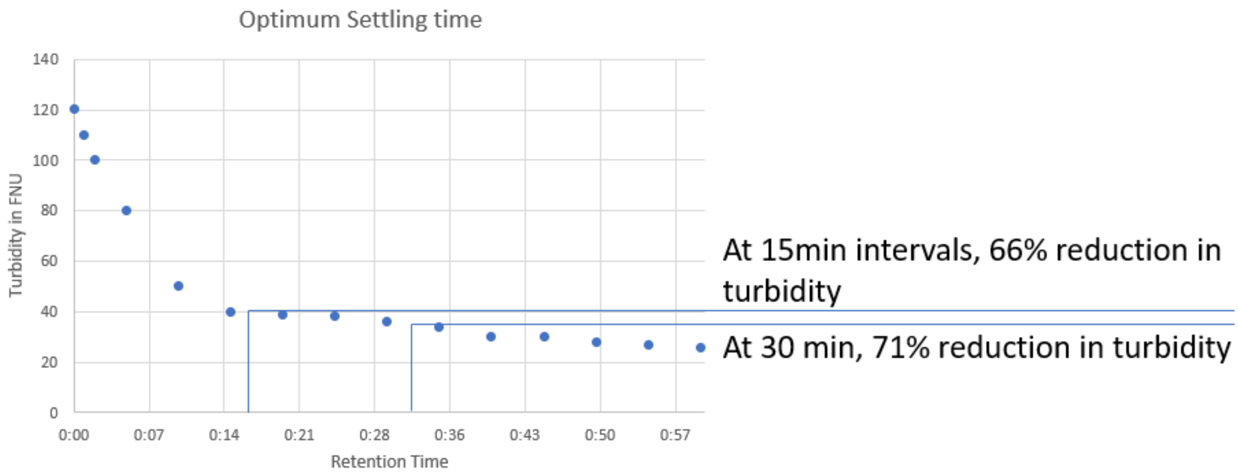


**Figure S1.** Turbidity readings in the clarified zone of surface waters collected from the Rio Grande as a function of retention time (the number of minutes water was allowed to settle prior to measuring turbidity). Turbidity data were collected as individual measurements using a YSI EXO2 equipped with a turbidity sensor (accuracy: ±2% of reading).

While the removal of the suspended particles by gravity separation is a low-cost and low-energy solution, it involves complications as sediments accumulate in the tank. Therefore, we selected a UV stabilized medium density polyethylene 3-gallon cone bottom tank with a slope of 0.4 and 25 cm depth as a flushable settling tank. The tank is equipped with a 3/4" FNPT spin weld fitting at the outlet of the tank, which controls flushing through a solenoid valve after water has been sampled from the clarified zone in the settling tank.

***Assessing the hollow fiber membrane (C4 in Table 1 and Figure 1)***

Low pressure hollow fiber membranes were selected for final filtration of water from the clarified zone of the settling tank. The benefits of using hollow fiber membranes for filtration devices include wide commercial availability, relatively low costs, a smaller physical footprint, backflushing capability, and removal of a broad range of particle sizes. We decided to use a 'sterilizing' grade filter to provide the lowest threshold for particle sizes capable of passing the filter (< 0.2 μm) and reduce potential bio-fouling of SC-FLAWLeSS plumbing from micro-organisms. To meet these performance requirements, the LifeStraw® handheld filtration device was selected. Following an evaluation report from the University of Arizona (Naranjo & Gerba, 2010), the LifeStraw® is capable of meeting U.S Environmental Protection Agency turbidity requirements by reducing input water turbidity from 104 NTU to 0.4 NTU after pumping 1525 L of effluent water. The replacement time for hollow fiber membrane filters was calculated based on the evaluation report, and assuming that the settling process will reduce turbidity to levels below 100 NTU in the clarified zone. We also assumed backflushing of 300 mL for every 2 L of water filtered. Based on these assumptions, the LifeStraw® should be able to perform for 32 days running every hour and using the worst-case turbidity scenario. All these assumptions were proven correct during our long-term validation test in the Rio Grande river, as shown in the main part of the manuscript.

***Determination of pumping flow rate (C5 in Table 1 and Figure 1)***

We conducted laboratory tests using a high flow peristaltic pump to select the appropriate pumping rate for filtration. The experiment started at a low flow rate of 200 L/min @ 150 rpm and pumping speed was gradually increased, with the flow rate measured for every 50 rpm increase, up to 600 rpm. Below 300 rpm (flow rate of 540 L/min), we observed significant flow oscillations. Between 300 and 450 rpm, flow rates increased from 540 L/min to 1200 L/min, and tranquil flows were observed throughout this range, which is ideal for preventing the formation of air bubbles that may can cause errors in wet-chemistry instruments. At pump speeds from 450 to 600 rpm, we observed a smaller increase in flow rates (1200 L/min to 1550 L/min), and flows became more turbulent, which may cause fiber breakage within the filter, resulting in poor filtration and shortened filter life.

Our final pump setup involved a Masterflex L/S Compact 12-VDC drive operating at 540 rpm using Masterflex L/S peroxide-cured silicone tubing (https://www.coleparmer.com/i/masterflex-l-s-peroxide-cured-silicone-tubing-l-s-24-25-ft/9640024) to provide tranquil flows to the instrument at 600 mL/min. Since this pump is capable of reverse flow, we use this feature for backflushing of filters through inverse polarity.

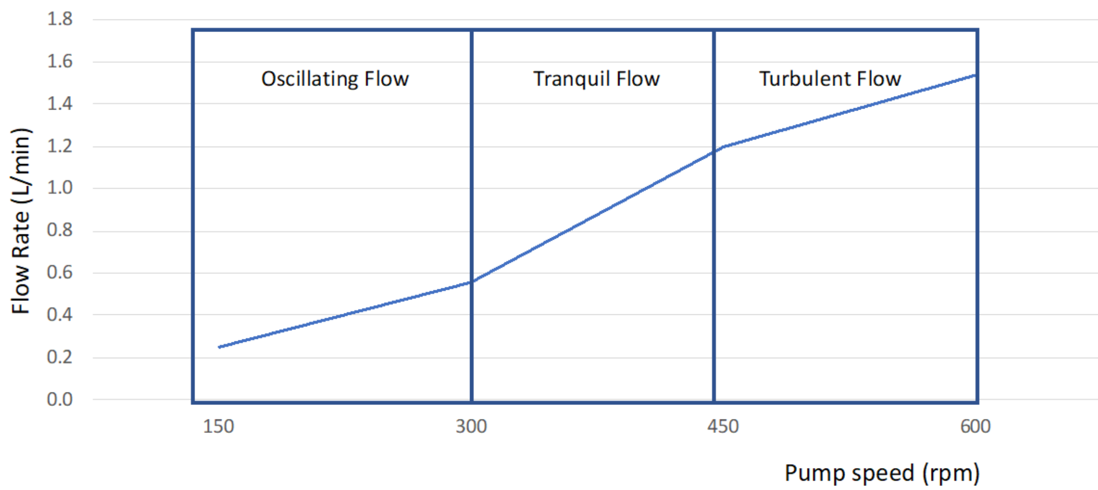


**Figure S2.** Flow rate delivered by the peristaltic pump (C5) as a function of pump speed (rpm). Qualitative flow classifications (i.e., oscillating, tranquil and turbulent) are based on the observation of flow conditions.

***Controlling the SC-FLAWLeSS (C8 in Table 1 and Figure 1)***

We used a Campbell Scientific CR1000 datalogger to control the electronic components described in Table 1, according to the timing shown in Table 2. Below, we provide an example of the code that we used:

```
'CR1000 Series Datalogger
'To create a different opening program template, type in new
'instructions and select Template | Save as Default Template
```

```
'date: 5/15/18

'program author: Aashish Khandelwal


'Declare Public Variables

'Define Data Tables

DataTable (Test,1,1000)

	DataInterval (0,15,Sec,10)

	Minimum (1,batt_volt,FP2,0,False)

	Sample (1,PTemp,FP2)

EndTable


'Define Subroutines

'Sub

	'EnterSub instructions here

'EndSub


'Main Program

BeginProg

	Scan (1,Sec,0,0)

		PanelTemp (PTemp,250)

		Battery (Batt_volt)

		'Enter other measurement instructions

		'Call Output Tables

		'Example:


'River pump.

   If IfTime(00,60,Min) Then  'Turn on relay for River Pump (C1) Start.

        PortSet(1,1)

    ElseIf IfTime(01,60,Min) Then 'River pump stop and, flushes and fill up the settling tank
(C2).

        PortSet(1,0)
```

```
    EndIf


    'Reversible pump normal Flow.

    If IfTime(23,60,Min) Then  'Turn on relay for Reversible pump (C5) pulls water through
the membrane filter (C4).

        PortSet(2,1)

    ElseIf IfTime(27,60,Min) Then 'Reversible pump stops filling the filtered chamber (C6).

        PortSet(2,0)

    EndIf


   'Reversible pump reverse Flow.

    If IfTime(50,60,Min) Then  'Turn on Reversible pump circuit.

        PortSet(2,1)

    ElseIf IfTime(52,60,Min) Then

        PortSet(2,0)

           If IfTime(50,60,Min) Then  'Turn on relay for reversible pump start back-flushing
membrane filter (C4).

        PortSet(3,1)

    ElseIf IfTime(52,60,Min) Then 'Reversible pump stops.

        PortSet(3,0)

    EndIf


   'Soleniod Valve.

        If IfTime(52,60,Min) Then  'Turn on relay for Activation of solenoid valve (C3)
flushes the settling tank.

        PortSet(4,1)

    ElseIf IfTime(53,60,Min) Then

        PortSet(4,0)


    If IfTime(35,60,Min) Then 'Collect data from cycle

Call Cycle(CycleP_data,Cycle_Comport)'call subroutine and collect

data
```

```
    EndIf

    If IfTime(28, 60, Min) Then
    ' SerialOutBlock (ComRS232,"$RUN" + CHR(13),5)'Issue Cycle run command
      SerialOutBlock(Com5,"$STP" + CHR(13),5)'Flush Cycle
      SerialFlush(Com5)
    EndIf
      NextScan
EndProg
```

***Refrences:***

Aguilera, R., Marcé, R., & Sabater, S. (2013). Modeling nutrient retention at the watershed scale: Does small stream research apply to the whole river network? *Journal of Geophysical Research: Biogeosciences*, *118*(2), 728–740. https://doi.org/10.1002/jgrg.20062

Chen, J., & Lu, J. (2014). Effects of Land Use, Topography and Socio-Economic Factors on River Water Quality in a Mountainous Watershed with Intensive Agricultural Production in East China. *PLOS ONE*, *9*(8), e102714. https://doi.org/10.1371/journal.pone.0102714

Chinchilla, M., L., Heasley, E., Loiselle, S., & Thornhill, I. (2019). Local and landscape influences on turbidity in urban streams: a global approach using citizen scientists. *Freshwater Science*, *38*(2), 303–320. https://doi.org/10.1086/703460

Duff, John H., and Frank J. Triska. 2000. "8 - Nitrogen Biogeochemistry and Surface–Subsurface Exchange in Streams." In Streams and Ground Waters, edited by Jeremy B. Jones and Patrick J. Mulholland, 197–220. Aquatic Ecology. San Diego: Academic Press. https://doi.org/10.1016/B978-012389845-6/50009-0.

Downing, B. D., Pellerin, B. A., Bergamaschi, B. A., Saraceno, J. F., & Kraus, T. E. C. (2012). Seeing the light: the effects of particles, dissolved materials, and temperature on in situ measurements of DOM fluorescence in rivers and streams. *Limnology and Oceanography: Methods*, *10*, 9. https://doi.org/10.4319/lom.2012.10.767

Gabrielle, V. (2019, March 28). The Renaissance of Hydrology - Eos. Retrieved September 26, 2019, from https://eos.org/features/the-renaissance-of-hydrology

González-Pinzón, R., Dorley, J., Regier, P., Fluke, J., Bicknell, K., Nichols, J., … Horn, D. J. V. (2019). Introducing "The Integrator": A novel technique to monitor environmental flow systems. *Limnology and Oceanography: Methods*, *17*(7), 415–427. https://doi.org/10.1002/lom3.10322

González-Pinzón, R., Mortensen, J., & Van Horn, D. (2015). Comment on "Solute-specific scaling of inorganic nitrogen and phosphorus uptake in streams" by Hall et al. (2013). *Biogeosciences*, *12*(18), 5365–5369. https://doi.org/10.5194/bg-12-5365-2015

Hall Jr., R. O., Baker, M. A., Rosi-Marshall, E. J., Tank, J. L., & Newbold, J. D. (2013). Solute-specific scaling of inorganic nitrogen and phosphorus uptake in streams. *Biogeosciences*, *10*(11), 7323–7331. https://doi.org/10.5194/bg-10-7323-2013

Huey, G.M. & Meyer, M.L. (2010) Turbidity as an Indicator of Water Quality in Diverse Watersheds of the Upper Pecos River Basin. *Water*, 2, 273-284.

https://doi.org/10.3390/w2020273

Johnson, K. S., & Coletti, L. J. (2002). In situ ultraviolet spectrophotometry for high resolution and long-term monitoring of nitrate, bromide and bisulfide in the ocean. *Deep Sea Research Part I: Oceanographic Research Papers*, *49*(7), 1291–1305. https://doi.org/10.1016/S0967-0637(02)00020-1

Kirchner, J. W., Feng, X., Neal, C., & Robson, A. J. (2004). The fine structure of water-quality dynamics: the (high-frequency) wave of the future. *Hydrological Processes*, *18*(7), 1353–1359. https://doi.org/10.1002/hyp.5537

Krause, S., Lewandowski, J., Dahm, C. N., & Tockner, K. (2015). Frontiers in real-time ecohydrology – a paradigm shift in understanding complex environmental systems. *Ecohydrology*, *8*(4), 529–537. https://doi.org/10.1002/eco.1646

Lee, E.-J., Yoo, G.-Y., Jeong, Y., Kim, K.-U., Park, J.-H., & Oh, N.-H. (2015). Comparison of UV–VIS and FDOM sensors for in situ monitoring of stream DOC concentrations. *Biogeosciences*, *12*(10), 3109–3118. https://doi.org/10.5194/bg-12-3109-2015

Marce, R., & Armengol, J. (2009). Modeling nutrient in-stream processes at the watershed scale using Nutrient Spiralling metrics. *Hydrol. Earth Syst. Sci.*, 15.

https://doi.org/10.1021/acs.est.6b01351

Mortensen, J., González-Pinzón, R. Dahm, C.N., Wang, J., Zeglin, L. & Van Horn, D. (2016). Advancing the Food-Energy–Water Nexus: Closing Nutrient Loops in Arid River Corridors, *Environmental Science & Technology*, 50(16), 8485-8496.

Naranjo, J., & Gerba, C. (2010) Evaluation of Vestergard-Frandsen's hollow fiber LifeStraw® for the removal of Escherichia Coli and Cryptosporidium according to the U.S. Environmental Protection Agency guide standard and protocol for evaluation of microbiological water purifiers. Department of Soil, Water and Environmental Science, University of Arizona. Accessed 10/01/2019 at https://cdn.shopify.com/s/files/1/2631/0778/t/4/assets/Lifestraw-Evidence-Dossier-1544004581248.pdf?3599906565368887774

Neal, C., Reynolds, B., Rowland, P., Norris, D., Kirchner, J. W., Neal, M., … Armstrong, L. (2012). High-frequency water quality time series in precipitation and streamflow: From fragmentary signals to scientific challenge. *Science of The Total Environment*, *434*, 3–12. https://doi.org/10.1016/j.scitotenv.2011.10.072

Pellerin et al. (2013). USGS Techniques and Methods 1–D5: Optical Techniques for the Determination of Nitrate in Environmental Waters: Guidelines for Instrument Selection, Operation, Deployment, Maintenance, Quality Assurance, and Data Reporting. Retrieved September 26, 2019, from https://pubs.usgs.gov/tm/01/d5/

Pellerin et al. (2016). Emerging Tools for Continuous Nutrient Monitoring Networks: Sensors Advancing Science and Water Resources Protection - Pellerin - 2019 - JAWRA Journal of the American Water Resources Association - Wiley Online Library. Retrieved September 26, 2019, from https://onlinelibrary.wiley.com/doi/abs/10.1111/1752-1688.12386%4010.1111/%28ISSN%291752-1688.open-water-data-initiative

Raymond, P. A., & Saiers, J. E. (2010). Event controlled DOC export from forested watersheds. *Biogeochemistry*, *100*(1), 197–209. https://doi.org/10.1007/s10533-010-9416-7

Reddy, K. R., and DeLaune, R. D. (eds.). (2008). "Phosphorus," in Biogeochemistry of Wetlands: Science and Applications (Boca Raton, FL: CRC Press, Taylor and Francis Group, LLC), 325–404.

Saraceno, J. F., Shanley, J. B., Downing, B. D., & Pellerin, B. A. (2017). Clearing the waters: Evaluating the need for site-specific field fluorescence corrections based on turbidity measurements. *Limnology and Oceanography: Methods*, *15*(4), 408–416. https://doi.org/10.1002/lom3.10175

Snyder, L., Potter, J. D., & McDowell, W. H. (2018). An Evaluation of Nitrate, fDOM, and Turbidity Sensors in New Hampshire Streams. *Water Resources Research*, *54*(3), 2466–2479. https://doi.org/10.1002/2017WR020678

Summers, B.M., Van Horn, D.J., González-Pinzón, R., Bixby, R.J., Grace, M.R., Sherson, L.R, Crossey, L.J., Stone, M.C., Parmenter, R.R., Compton, T. S. & Dahm, C.N (2020). Long-term data reveal highly-variable metabolism and transitions in trophic status in a montane stream. *Freshwater Science*, https://doi.org/10.1086/708659.

Tank, J. L., Rosi-Marshall, E. J., Baker, M. A., & Hall, R. O. (2008). Are rivers just big streams? A pulse method to quantify nitrogen demand in a large river. *Ecology*, *89*(10), 2935–2945. https://doi.org/10.1890/07-1315.1

Vercruysse, K., Grabowski, R. C., Rickson, R.J. (2017). Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation, *Earth-Science Reviews*

(166), 38-52. https://doi.org/10.1016/j.earscirev.2016.12.016

Watras, C. J., Hanson, P. C., Stacy, T. L., Morrison, K. M., Mather, J., Hu, Y.-H., & Milewski, P. (2011). A temperature compensation method for CDOM fluorescence sensors in freshwater. *Limnology and Oceanography: Methods*, *9*(7), 296–301. https://doi.org/10.4319/lom.2011.9.296

Watson SJ, Cade-Menun BJ, Needoba JA and Peterson TD (2018) Phosphorus Forms in Sediments of a River-Dominated Estuary. *Frontiers in Marine Science, 5*(302). doi: 10.3389/fmars.2018.00302

Zielinski, O., Voß, D., Saworski, B., Fiedler, B., & Körtzinger, A. (2011). Computation of nitrate concentrations in turbid coastal waters using an in situ ultraviolet spectrophotometer. *Journal of Sea Research*, *65*(4), 456–460. https://doi.org/10.1016/j.seares.2011.04.002