Video Article

Continuous Instream Monitoring of Nutrients and Sediment in Agricultural Watersheds

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Abstract

Pollutant concentrations and loads in watersheds vary considerably with time and space. Accurate and timely information on the magnitude of pollutants in water resources is a prerequisite for understanding the drivers of the pollutant loads and for making informed water resource management decisions. The commonly used "grab sampling" method provides the concentrations of pollutants at the time of sampling (*i.e.,* a snapshot concentration) and may under- or overpredict the pollutant concentrations and loads. Continuous monitoring of nutrients and sediment has recently received more attention due to advances in computing, sensing technology, and storage devices. This protocol demonstrates the use of sensors, sondes, and instrumentation to continuously monitor *in situ* nitrate, ammonium, turbidity, pH, conductivity, temperature, and dissolved oxygen (DO) and to calculate the loads from two streams (ditches) in two agricultural watersheds. With the proper calibration, maintenance, and operation of sensors and sondes, good water quality data can be obtained by overcoming challenging conditions such as fouling and debris buildup. The method can also be used in watersheds of various sizes and characterized by agricultural, forested, and/or urban land.

Video Link

The video component of this article can be found at https://www.jove.com/video/56036/

Introduction

Water quality monitoring provides information on the concentrations of pollutants at different spatial scales, depending upon the size of the contributing area, which can range from a plot or a field to a watershed. This monitoring takes place over a period of time, such as a single event, a day, a season, or a year. The information garnered from monitoring water quality, mainly relating to nutrients (*e.g.,* nitrogen and phosphorus) and sediment, can be used to: 1) understand hydrological processes and the transport and transformation of pollutants in streams, such as agricultural drainage ditches; 2) evaluate the efficiency of management practices applied to the watershed to reduce the nutrient and sediment load and to increase the water quality; 3) assess the delivery of the sediment and nutrients to the water downstream; and 4) improve the modeling of nutrients and sediment to understand the hydrological and water quality processes that determine pollutant transport and dynamics over the range of temporal and spatial scales.

This information is crucial to aquatic ecosystem restoration, sustainable planning, and the management of water resources[1].

The most commonly used method for nutrient and sediment monitoring in a watershed is grab sampling. Grab sampling accurately represents a snapshot concentration at the time of sampling[2]. It can also depict a variation of pollutant concentrations with time if frequent sampling is done. However, frequent sampling is time intensive and expensive, often making it impractical[2]. Additionally, grab sampling may under- or overestimate the actual pollutant concentrations outside of the sampling time[2,3,4]. Consequently, loads calculated using such concentrations may not be accurate.

Alternatively, continuous monitoring provides accurate and timely information on water quality in a predetermined time interval, such as a minute, an hour, or a day. Users can select the appropriate time intervals based on their needs. Continuous monitoring enables the researchers, planners, and managers to optimize sample collection; develop and monitor time-integrated metrics, such as total maximum daily loads (TMDLs); evaluate the recreational use of the water body; assess baseline stream conditions; and spatially and temporally evaluate the variation of pollutants to determine cause-effect relationships and develop a management plan[5,6]. Continuous monitoring of nutrients and sediment has recently received increased attention due to advances in computing and sensor technology, the improved capacity of storage devices, and the increasing data requirements needed to study more complex processes[1,5,7]. In a global survey of over 700 water professionals, the use of multi-parameter sondes increased from 26% to 61% from 2002 to 2012 and is expected to reach 66% by 2022[5]. In the same survey, 72% of respondents indicated the need for the expansion of their monitoring network to meet their data needs[5]. The number of stations in a monitoring network and the number of variables monitored per station in 2012 are expected to increase by 53% and 64%, respectively, by 2022[5].

However, continuous water quality and quantity monitoring in agricultural watersheds is challenging. Large rainfall events wash away sediment and macrophytes, contributing to high sediment load and debris buildup in the sensors and sondes. The runoff of excess nitrogen and phosphorus applied to agricultural fields creates ideal conditions for the growth of microscopic and macroscopic organisms and for the fouling of instream sensors and sondes, especially during the summer. Fouling and sediment buildup can cause sensors to fail, drift, and produce unreliable data. Despite these challenges, finer temporal resolution (as low as per minute) data are required to study the runoff processes and non-point source contamination, as they are affected by watershed characteristics (*e.g.,* size, soil, slope, *etc.*) and the timing and intensity of rainfall[7]. Careful field observation, frequent calibration, and proper cleaning and maintenance can ensure good-quality data from the sensors and sondes, even at the finer time resolution.

Here, we discuss a method for the *in situ* continuous monitoring of two agricultural watersheds using multi-parameter water quality sondes, area-velocity and pressure transducer sensors, and autosamplers; their calibration and field maintenance; and data processing. The protocol demonstrates a way in which continuous water quality monitoring can be performed. The protocol is generally applicable to continuous water quality and quantity monitoring at any type or size of watershed.

The protocol was carried out in Northeast Arkansas in Little River Ditches Basin (HUC 080202040803, 53.4 km^2 area) and Lower St. Francis Basin (HUC 080202030801, 23.4 km^2 area). These two watersheds drain into tributaries of the Mississippi River. A need for monitoring tributaries of the Mississippi River was identified by the Lower Mississippi River Conservation Committee and the Gulf of Mexico Hypoxia Task Force to develop a watershed management plan and to record the progress of management activities[8,9]. Moreover, these watersheds are characterized as focus watersheds by the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS), based on the potential for reducing nutrient and sediment pollution and for improving water quality[10]. Edge-of-field monitoring is being carried out in these watersheds as part of the statewide Mississippi River Basin Healthy Watershed Initiative (MRBI) network[11]. More details of the watersheds (*i.e.,* site locations, watershed characteristics, *etc.*) are provided in Aryal and Reba (2017)[6]. In short, the Little River Ditches Basin has predominantly silt loam soils, and cotton and soybean are the major crops, whereas the Lower St. Francis Basin has predominantly Sharkey clay soil, and rice and soybean are the major crops. At each watershed, *in situ* continuous water quantity and quality monitoring (*i.e.,* discharge temperature, pH, DO, turbidity, conductivity, nitrate, and ammonium) was carried out at three stations in the mainstream using this protocol to understand the spatial and temporal variability in the pollutant loads and the hydrological processes. Additionally, weekly water samples were collected and analyzed for suspended sediment concentration.

Protocol

1. Site Selection

1. **Watershed selection**
    1. Select watershed(s) based on the magnitude of the pollution problem, priority of the watershed, proximity to the research facility, access to the site, and data objectives.
2. **Stream sampling locations**
    1. Select stream sampling location(s) based on the study purpose.
    NOTE: Optimal sampling locations are well-mixed within a cross-section, safely and easily accessible, geophysically stable (*i.e.,* constant cross-section and a bank supportive of instrument station housing), and representative[12,13,14]. Stations not immediately downstream from the confluence of two streams and in a straight channel section, without a converging or diverging channel cross-section, are more homogenous and representative[14].
    2. Co-locate hydrological and water quality measurements at a cross-section to calculate the loads.
    NOTE: If identifying the spatial variation of nutrients and sediment in a watershed, select multiple stations to target potential sources throughout the watershed.

2. Instrument and Sensor Selection

1. Choose instruments and sensors to measure discharge and water quality and to collect water samples at the intended interval. Choose the instrument and sensors based on data need, watershed, and available resources.
NOTE: Ideal sensors are reliable, accurate, sensitive, precise, low-cost, and suitable for the stream environment and require limited maintenance and minimal training of the field technician[13]. In an agricultural watershed, fouling and debris buildup are the greatest causes of concerns. Consequently, sondes equipped with self-cleaning and anti-fouling features are preferred.
    1. Use an autosampler, sondes, an area-velocity sensor, a pressure transducer, and a portable flowmeter.
    NOTE: The sonde should have a wiper to clean the turbidity sensor and a brush to clean the pH, ammonium, nitrate, and DO sensors.
    NOTE: The instrument in this protocol refers to a water sampling unit consisting of an autosampler, hose, strainer or flow module, and area-velocity sensor.
2. Select water quality parameters based on the data objective, sensor cost, and availability. Measure the temperature, pH, DO, conductivity, turbidity, ammonium, and nitrate every 15 min.
NOTE: Temperature, pH, DO and conductivity are the most common parameters chosen and are measured at USGS stations, whereas nitrate, ammonium, and turbidity are less common but are gaining popularity[1,14].
NOTE: The data objectives depend on the watershed characteristics. For example, nitrogen and phosphorus monitoring may be more important in agricultural watersheds compared to phosphorus monitoring in urban watersheds.

3. Sonde Calibration and Programming

1. Calibrate the sensors on the sonde as per manufacturer recommendations. Modify the calibration protocol as needed based on the local environmental conditions.
   NOTE: The frequency of calibration depends on the environment in which the sensors are exposed. Generally, it falls within 2 - 4 weeks. Here, the sondes are calibrated every 2 weeks during growing season and every 3 weeks in non-growing season (November to April).
2. At the laboratory, clean the sonde thoroughly before calibration. Clean the sensor surfaces using soft brushes (*e.g.,* toothbrushes) and soap or all-purpose cleaner. Remove the circulator wiper and brush using a hexagonal Allen key; clean the wiper and brush.
3. Pour the electrolyte in the pH reference electrode, refill it with fresh electrolyte solution, and add a potassium chloride salt pellet to maintain the conductivity of the electrolyte solution. Close the cap so that it is airtight; some electrolyte will spill out while the cap is being screwed on. Rinse the sonde with deionized water.
4. Suspend the sonde on a sturdy support so that the bottom of the sonde rests approximately 20 - 30 cm above the table top, allowing for easy workability. Connect the sonde to the computer using a communication cable. Start the manufacturer's software. Press "operate sonde" to enter into the sonde program.
5. Set the number of calibration standards at the "parameter setup" tab.Calibrate the sensors in the following order: conductivity, pH, DO, turbidity, nitrate, and ammonium.
   NOTE: The order of the calibration is important, as nitrate and ammonium sensors use conductivity and pH values.
   NOTE: The number of calibration standards are 2 for conductivity, 2 or 3 for pH, 1 for DO, 2 or 4 for turbidity, 2 for nitrate, and 2 for ammonium.
6. Rinse the sensor(s) with DI water multiple times and dry the sensor(s) surface(s) with wipes before introducing a standard to the sensor to prevent cross-contamination.
   NOTE: Before calibrating each sensor, note the values the sensor reads for the following standards: DO, pH 7, turbidity for DI and 50 NTU, nitrate for 50 mg/L, and ammonium for 50 mg/L. These values can be used to evaluate whether the sensors were accurate in the field. They may also be prudently used to correct field values.
7. After the calibration of each sensor (steps 3.8 - 3.13) for a standard, "calibration successful" will appear; if the calibration fails, reset the sensor and try again. If the sensor still fails, the consumables may need replacement or the sensor may need factory repair.
   NOTE: Resetting the nitrate or ammonium sensor will reset both sensors.
8. Calibrate the conductivity sensor using 2-point calibration; 0 µs/cm for a dry sensor and 1,412 µs/cm for the standard solution. Choose "SpCond [µs/cm]" in the "calibration" tab.Dry the oval portion of the sensor completely with wipes. Enter "0.0" in µs/cm and enter "calibrate."
   1. Insert the standard in a pouch to entirely cover the oval portion of the sensor. Wait until the sensor reading stabilizes (~2 - 5 min), enter "1412" in µs/cm, and enter "calibrate." "Calibration successful" will appear; if the calibration fails, reset the sensor and try again.
9. Calibrate the pH sensor using pH 7 and pH 10 standards and check the linearity of the calibration with pH 4. Select the "pH[units]" tab in the calibration tab. Insert the pH 7 standard into a pouch covering both the pH junction and the reference electrode. Wait approximately 5 min for it to stabilize. Enter "7.0" as the pH value and enter "calibrate."
   1. Rinse the electrodes and dry them using wipes. Insert pH 10 and follow the same procedure as for pH 7. Insert pH 4 to check if the linearity of the calibration curve is met; the calibrated sensor should read 4 ± 0.2 for the pH 4.0 standard.
10. Calibrate the DO sensor using temperature-stabilized, air-saturated, deionized water (18 MΩ-cm) as single point standard.
    1. Select the "LDO%[Sat]" tab. Fill the calibration cup with DI water to the almost-full level and place the cup on the sonde. Invert the sonde to make sure that the temperature sensor and DO membranes are completely covered by the water.
    2. Wait approximately 5 min to stabilize the percent saturation reading. Once stabilized, enter "100" for the percent saturation. Enter the barometric pressure in mmHg by checking a local weather station and enter "calibrate."
       NOTE: DI water is temperature-stabilized and air-saturated by leaving it open to the atmosphere at least overnight in the laboratory for gas exchange, saturation, and temperature stabilization. Barometric pressure needs to be provided, since the DO saturation depends on atmospheric pressure in addition to the temperature (measured by the sonde itself).
    3. Check the scale factor, which should be 0.5 - 1.5, for acceptable calibration. Exit the calibration program, enter terminal mode, use the arrows to highlight "Log In," and press "enter." Highlight "level 3" and press "enter." Highlight "setup" and press "enter." Highlight "sensors" and press "enter." Highlight "DO" and press "enter." Highlight "DO% Sat" and press "enter." Note the scale factor.
    4. Press "Esc" to exit and enter "operate sonde" again. Select the "calibration tab" to continue the calibration.
    5. Invert the sonde back and suspend it so that the sensors face the ground.
11. Calibrate the turbidity sensor using 4 standards: DI, 50 NTU, 100 NTU, and 200 NTU.Select the "Turbidity[NTUs]" tab.In a calibration cup, put enough DI water to cover at least the bottom of the turbidity sensor. Let the turbidity reading stabilize. Enter point "1" for the DI standard, a "0.6" NTU turbidity value, and "calibrate."
    1. Similarly, calibrate the turbidity sensor for other standards. Prevent bubble formation by homogenizing the standards, turning the bottle up and down (do not shake) and pouring the standards along the cup.
    2. After calibrating all standards, check the sensor readings for DI and 50 NTU to see if the calibration was acceptable (*i.e.,* within ±1%).
12. Calibrate the nitrate sensor using two standards: high (50 mg/L NO_3^--N) and low (5 mg/L NO_3^--N). Select the "NO_3^-[mg/L-N]" tab.
    1. Pour the 50 mg/L standard to fill the calibration cup up to three-quarters full and place the cup on the sonde, making a watertight connection. Invert the sonde so that the nitrate and temperature sensors are completely covered. Wait for 15 min (or until the reading is stable). Once stabilized, enter the standard level "1" and a value of "46.2." Record the temperature and mV readings in a notebook. Enter "calibrate."
       NOTE: The nitrate sensor uses the temperature sensor in addition to the conductivity and pH sensors.
    2. Rinse the sensors with DI water several times and dry them with wipes. Repeat the same procedure for the low standard. The difference between the two voltage readings should be 50 - 65 mV, and the difference between the temperature readings should not exceed 5 °F for the calibration to be acceptable.
13. Calibrate the ammonium sensor similarly to the nitrate sensor.

14. Reinstall and calibrate the wiper and brush. Choose the "SelfClean[Rev]" tab. Choose "1" rotation and enter "calibrate."
    NOTE: The wiper and brush will rotate one time.
15. Once all sensors are calibrated, program the sonde.Enter "set clock to pc time" in the "system" tab for synchronization.Delete the oldest log file if there are 4 existing log files and create a new log file.Once the log file is created, select the monitoring parameters and the parameters to log. Select the monitoring duration (*i.e.,* until the next calibration, usually 2 - 3 weeks in agricultural watersheds) and interval (15 min) by choosing the start and end time of the log file and the logging interval. Save the log file.
    NOTE: At any time, a sonde can store up to 4 log files.
16. Check the internal battery voltage and replace the internal batteries if necessary.
    1. Select the "online monitoring" tab and start online monitoring.
    2. Check the internal battery voltage reading. If it is below 10.5 V, replace it with eight new C batteries.
       NOTE: The sonde stops recording data if the internal battery voltage drops below ~9.0 V.
    3. Use silicon sealant to seal the cap of the battery compartment to make a watertight connection.

17. Attach the sensor guard and put it in a bucket half-full of water.
    NOTE: The sondes in the bucket are ready for transport and (re)installation at the sites.The sondes must be submerged for the pH electrode to function properly.

4. Instrument and Sensor Installation

1. **Area-velocity sensor and flow module**
    1. Mount the area-velocity sensor securely on a steel plate at a selected cross-section. Mount the steel plate on the "L" bracket (**Figure 1**) that is mounted in the Telspar post driven at the thalweg of the stream (*i.e.,* the deepest part of the channel) (**Figure 1**); the extension of the "L" bracket upstream of the Telspar post should be long enough so that the flow is not affected by the presence of the Telspar post in the stream. Place the sensor on the "L" bracket on the stream bed such that the tip of the sensor faces upstream along the flow lines.
       NOTE: The effect of Telspar post can be evaluated visually if the introduction of the post creates flow disturbance at the sensor position upstream or quantitatively using sensor readings with and without the Telspar post. In this protocol, cross-sectional variability was considered negligible. If it is to be evaluated, multiple sondes or sensors can be placed at a cross-section. The area-velocity sensor measures average velocity using the ultrasonic Doppler method. It does not require a conversion factor based on flow depth or velocity profiling and on-site calibration. The flow module measures velocity from -1.5 to 6.1 m/s and depth from 0.01 m to 9.15 m. As such, it is applicable to different watersheds.
    2. To calculate the discharge, measure the area of the cross-section.
       NOTE: The software can directly calculate the area if the shape of the channel or an equation is provided.
       NOTE: The data from the sensor are directly recorded in the flow module and can be downloaded to a computer using the manufacturer's software and a communication cable.

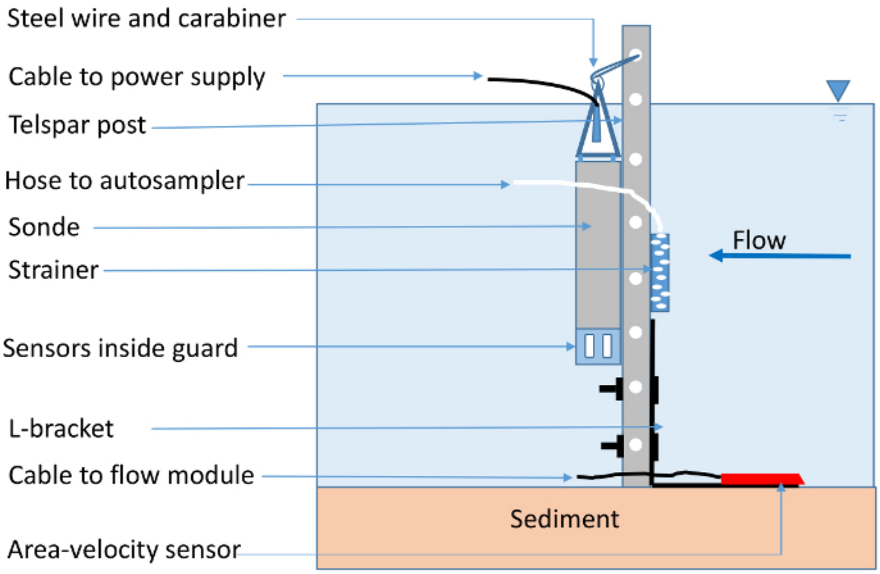

Figure 1. Layout of a Typical Instream Monitoring Station (Not to a Scale). The station contains a Telspar post on which the sonde is suspended using a steel cable, a carabiner, and ferrules. The ferrules are not shown. The L-bracket on which the area-velocity sensor is mounted is placed at the stream bed and is secured tightly to the post using nuts and bolts. The autosampler (not shown in the figure) pulls the water sample from a hose that contains a strainer at the tip. The cable from the area-velocity sensor is connected to the flow module (not shown). Please click here to view a larger version of this figure.

2. **Pressure transducer (PT sensor)**
    1. Whenever the area-velocity sensor is unavailable, measure the depth using a pressure transducer.

   2. Install the PT sensor inside the Telspar post and secure it with a steel wire and ferrules; the tip of the sensor should just touch the stream bed. Program the PT sensor to measure the water depth at 15-min intervals.

3. **Manual discharge measurement**
   1. For stations with a PT sensor as a discharge measuring device, make a stage-discharge curve by manually measuring the discharge over a range of flows, covering at least low, medium, and high flows. Divide the cross-sectional area into several segments (30 - 60 cm wide), depending on the width of flow. Measure the mean velocity in the center line of the segment using a portable flowmeter. If the depth is <10 cm, measure the maximum velocity and multiply by 0.9 to get the mean velocity. If depth is 10 - 75 cm, measure velocity at 0.6 of the depth to determine the mean velocity[15]. For depths greater than 75 cm, measure velocities at three depths (0.2, 0.6, and 0.8 of the depth from the water surface) and average them[15].
   2. Calculate the discharge of a segment using the average velocity, width, and depth of the segment and sum the discharges from all segments to obtain a total discharge.
   3. Follow the procedure for ranges of flows covering low, medium, and high flows.
   4. Determine the relationship between the stage (*i.e.,* depth of flow measured by the pressure transducer at the time of the manual discharge measurement) and the measured discharges.
   NOTE: If the discharge is too high to measure the velocity manually, a temporary area-velocity sensor can be used make a relationship between the discharge measured by the area-velocity sensor and the depth measured by the PT sensor.

4. **Water quality multi-parameter sonde**
   1. Mount the sonde on the Telspar post with a steel wire, ferrules, and a carabiner for sonde safety and easy installation and removal (**Figure 1**). Place the sonde on the downstream side of the Telspar post to prevent damage from debris or wood logs that can come floating with the stream water, especially during flooding. Place the bottom of the sonde at least 1 - 10 cm above the stream bed to reduce the probability of sediment buildup on the sonde.
   NOTE: The sonde should always be submerged in the water. Therefore, in a stream with varying flows, the sonde should be high enough to reduce the buildup of the sediment on the sonde and low enough to prevent the sonde from getting exposed to air. However, for a channel with less variable flow, the sonde can be placed such that the sensors are approximately 10 cm below the water surface.
   NOTE: If the sonde has a depth sensor, the height of the depth sensor from the channel bed should be measured to account for the depth of installation of the depth sensor above the channel bed.
   2. Power the sonde with internal batteries and/or external batteries. Use a portable battery box to house the external battery and a communication cable to connect to the sonde. Program the sonde to collect data every 15 min and download the data directly to the computer using the communication cable.

5. **Autosampler**
   1. Install an autosampler in weather-protective housing at the top of stream bank on stable ground. Power the autosampler with a lead acid battery. Install a 20-W solar panel to charge the battery onsite.
   2. Secure a strainer pipe under water with the Telspar post or L-bracket and connect it to the autosampler with a hose.
   NOTE: The autosampler pulls water from the stream via the strainer and hose.
   NOTE: The positioning of the strainer pipe is important to obtain representative data. In this protocol, it was positioned assuming no cross-sectional variability.
   3. Program the autosampler to sample water weekly or based on need. Refer to the autosampler manual provided by the manufacturer.
   NOTE: The autosampler can be programmed to sample water based on rainfall, flow, time, or a combination. The sampler can be programmed to sample one sample into many bottles, many samples into one bottle (composite), or a combination.
   NOTE: The autosampler collects a volume of water (2,000 mL) necessary for the analysis of additional parameters in the laboratory. In addition to continuous water quality monitoring using the sonde, samples are analyzed on a weekly basis for suspended sediment concentration.

5. Sensor and Sonde Maintenance

1. Clean area-velocity sensor on every visit to reduce the debris on or near the sensor surfaces.
2. Frequently calibrate the sensors on the sonde.
NOTE: Frequency is dependent upon season, hydrology, watershed, sensor type, and rate of fouling. In the watersheds chosen here, calibration was required every 2 weeks to collect good-quality data.
3. Replace the consumable parts as recommended by the manufacturer.
NOTE: This includes a pH reference electrode/cap, a cap (membrane) for the DO sensor, ion-tip sensors (nitrate and ammonium sensors), and a circulating wiper and brushes.
4. Send the sonde for factory repair if necessary (*i.e.,* if the sensor does not read acceptable values for the standards, even after resetting and recalibrating, or if the sensors fail calibration).

6. Field Sampling and Laboratory Analysis

1. Prepare in advance for the field trip to maintain the sensors and to collect the automatically collected water samples or manually sample and collect water samples if an autosampler is not available at the site. Make sure to include the items listed in the checklist (**Table 1**).
2. Collect the water samples in a clean (*i.e.,* acid washed and rinsed) and dry jar (10 L), label them, and transport them on ice to the laboratory as soon as possible for analysis.
NOTE: The collected water sample is a representative sample under actual conditions at the time of sampling and at the particular location; the integrity of the collected sample should be preserved against contamination and physical, chemical, and biological changes[12].
NOTE: The container material required may be different for some analytes of interest, whereas acidification and/or filtration may be required at the site.

3. Analyze the collected water samples in the laboratory using standard methods before the approved holding times[16].
   NOTE: Water samples can be analyzed using EPA 353.2; 4500-NO3 for nitrate, EPA 353.2; 4500-NO2 for nitrite, EPA 365.1; 4500-PI for phosphate, EPA 350.1; 4500-PJ for total nitrogen, EPA 365.4; 4500-PJ for total phosphorus, 2540-D for total suspended solids, 2540-C for total dissolved solids, and D 3977-97 for the suspended sediment concentration[16,17].
4. Follow the appropriate quality control and checks, such as blanks, standards, replicates, *etc.*, during analysis. Follow the Quality Assurance Project Plan (QAPP).
5. Fill the chain of custody sheets for both the sample collector and the laboratory personnel and keep a copy of each. Note any unusual or notable events observed in the field on the chain of custody sheets.

7. Data Collection and Analysis

1. Collect water quality and quantity data from the sondes, flow module, and laboratory.
2. Save a copy of all raw data before working with the data correction and analysis.
3. Carefully inspect the collected data on turbidity and remove any zero (*e.g.,* 0.0 NTU), NAN, or unreasonable values (*e.g.,* 3,000 NTU; upper limit of detection of the sensor) before further analysis.
   NOTE: Caution should be exercised when removing any data. They are removed only when site-specific conditions in the field notes identify and determine that the data are not reasonable.
4. Use the stage-discharge relationship to calculate the discharge from the PT sensor.
   NOTE: The depth measured by the PT sensor must be pressure compensated.
    1. Use the manufacturer (*In situ* Inc.) software, "Baromerge," to post-correct the PT sensor data.
       NOTE: The data can be corrected by a fixed barometric pressure value by entering many barometric pressure values manually and automatically with a baroTroll log file. This protocol uses a baroTroll log file deployed at a nearby location to automatically correct the PT sensor data.

5. For area-velocity sensor data, remove any negative flow that could be sensor artifact.
   Caution: Sometimes there could actually be negative flow, depending on the site. In that case, do not ignore the negative velocity.
6. Calculate missing discharge data using a linear regression between upstream or downstream discharge and the discharge at the station.
   NOTE: The relationship should be statistically significant, which is usually the case between discharges for any upstream and downstream stations. In the watersheds tested here, the relationship was significant ($p<0.01$) and the correlation coefficient was greater than 93%. However, the missing discharge data can only be filled using this method if the distance between sites is short and the watershed characteristics remain similar.
7. Do not fill missing water quality data.
   NOTE: Water quality data are affected by many variables (*i.e.,* timing and application of fertilizer, whether the discharge is increasing or decreasing, site specific conditions, *etc.*).
8. Perform a regression analysis between the suspended sediment concentration (SSC) from the laboratory results and the turbidity (NTU) measured at the stream.
   NOTE: Such a regression is sensitive to sediment size distribution, such that if sand constitutes a significant but variable fraction of the SSC, the regression will be poor. However, it can be improved if sands and fines are separated during sample analysis and if the fines are correlated to the SSC. Use the regression to calculate continuous SSC values.
9. Since pollutant concentrations vary with discharge, calculate flow-weighted concentrations using Equation 1[6]. Calculate the flow-weighted mean concentrations (FWMC) on a daily basis using hourly data. Alternatively, calculate it on an hourly basis using 15-min data; the FWMCs are time-integrated as well.

   $$FWMC = \frac{\sum(c_i t_i q_i)}{\sum(t_i q_i)}$$

   where
   FWMC = flow-weighted mean concentration on a daily basis
   c_i = concentration of i^{th} sample
   t_i = time, 1 h
   q_i = discharge for i^{th} sample
   $i = 1$ to 24
10. Apply appropriate statistical techniques to meet the data objectives. When the data are non-normal, transform the data to make them normal or use the median ± interquartile range. Perform non-parametric tests for non-normal data.

Representative Results

In the Aryal and Reba (2017) publication, this protocol was used to study the transport and transformation of nutrients and sediment in two small agricultural watersheds[6]. Additional outcomes from this protocol are described below.

Rainfall-runoff Water Quality Relationships:

The strength of continuous monitoring is that users can choose a fine time resolution to study cause-effect relationships, such as the relationship between rainfall, runoff, and turbidity, using 15-min data (**Figure 2A**). Rainfall data were downloaded from weather stations (www.weather.astate.edu), one inside the Little River Ditches Basin and the other 6.3 miles away from the Lower St. Francis Basin. From 00:00 to 09:00 on 7/22, a total of 25.4 mm of rainfall occurred. The rainfall increased the discharge from 0.71 m^3/s at 00:00 to 4.89 m^3/s at 17:45 on 7/22. There were multiple local discharge peaks during the event, likely tied to the spatial variability of rainfall and the drainage patterns of the rice and soybean fields that contributed to the majority of the flow. The Lower St. Francis Basin had approximately 94% of the area in row crops, primarily soybean and rice. As the discharge gradually subsided, another 14-mm rain event occurred on 7/23 at 07:00 and lasted for 5 h. Consequently, another increase in discharge was measured.

As expected, turbidity increased with discharge following the rain event and subsided gradually (**Figure 2A**). Turbidity increased from 13 NTU at 23:34 on 7/21 to 409 NTU at 02:04 on 7/23. The highest turbidity was obtained during the increasing discharge portion of the hydrograph. It was likely due to the first flush that washed soil particles from the agricultural fields. As with discharge, the turbidity also showed two clear peaks.

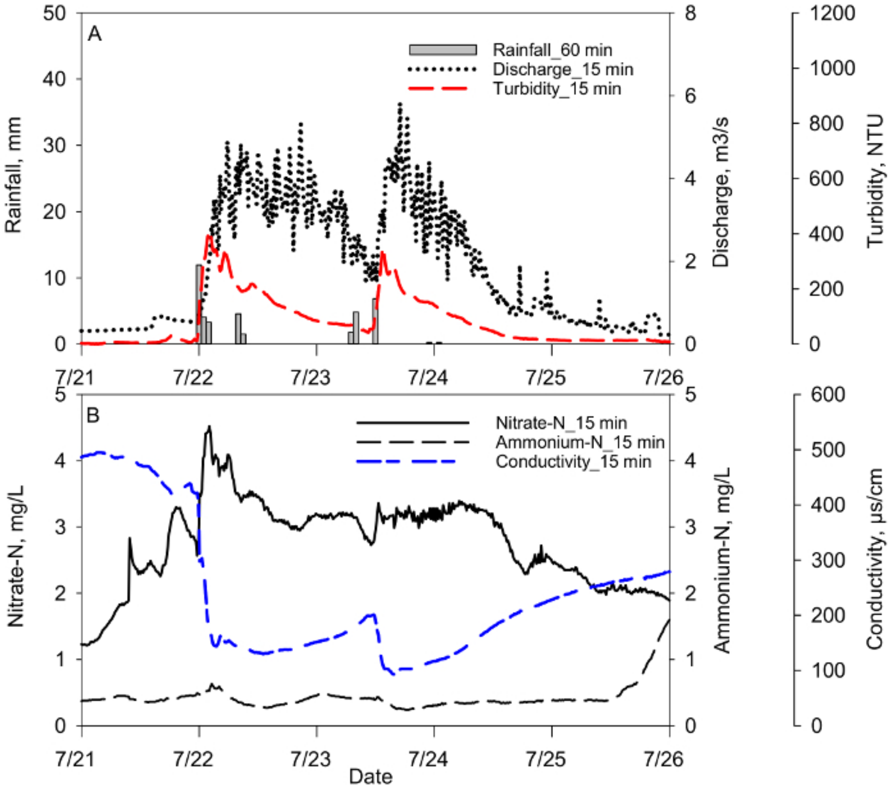

Figure 2. Variation of Rainfall, Discharge, and Water Quality on an Event Basis in the Lower St. Francis Basin, an Agricultural Watershed.
(A) Rainfall, discharge and turbidity. **(B)** Nitrate, ammonium, and conductivity from 7/21 to 7/26. The majority of the watershed crops were soybean and rice. The rainfall, discharge, and turbidity plots are based on 60-, 15-, and 15-min data, respectively. Please click here to view a larger version of this figure.

Similarly, nitrate, ammonium, and conductivity showed variations with runoff and time (**Figure 2B**). During a runoff event, nitrate concentration can either decrease due to a dilution effect or increase due to a mixing of concentrated runoff from fields. In the considered time frame, nitrate increased up to 4.52 mg/L at 02:04 on 7/22 and gradually decreased. The highest concentration of nitrate coincided with the first flush runoff, as recently applied but unused soluble nitrogen was washed away. The second peak of the nitrate concentration corresponded with the second peak in the discharge, but it had a lower concentration than the first peak. This is likely due to the washout of easily soluble nitrogen by the first flush. The shape of the nitrate peaks was similar during both events, despite differences in magnitude.

The mean ammonium concentration was 0.80 mg/L, likely due to the contribution from rice fields. The ammonium concentration varied slightly with two discharge peaks (*i.e.,* increased with an increase in discharge). However, the increase in the ammonium concentration with the second discharge peak was less than that with first discharge peak, for the same reasons as nitrate (**Figure 2B**). As with nitrate, the ammonium concentration peaked before the discharge peaked.

The conductivity ranged from 93 - 495 µS/cm during the period. The conductivity showed an inverse relationship to discharge (**Figure 2A and 2B**) (*i.e.,* conductivity was high during base flow and decreased with an increase in flow during both peak discharges). Nitrate and ammonium were likely minor contributors to the water conductivity, since the conductivity of water decreased during peak discharge, even though the nitrate and ammonium were higher than during base conditions. The dilution of rain water, which has lower conductivity, may have contributed to the lower conductivity of water in the stream.

Diurnal variations of pH, temperature, and DO are clearly illustrated by the sonde results (**Figure 3**). The temperature varied from 36.1 to 24.6 °C from 7/9 - 7/10. The water temperature in the stream was the lowest at 06:00-07:00 and the highest at 17:00-18:00.

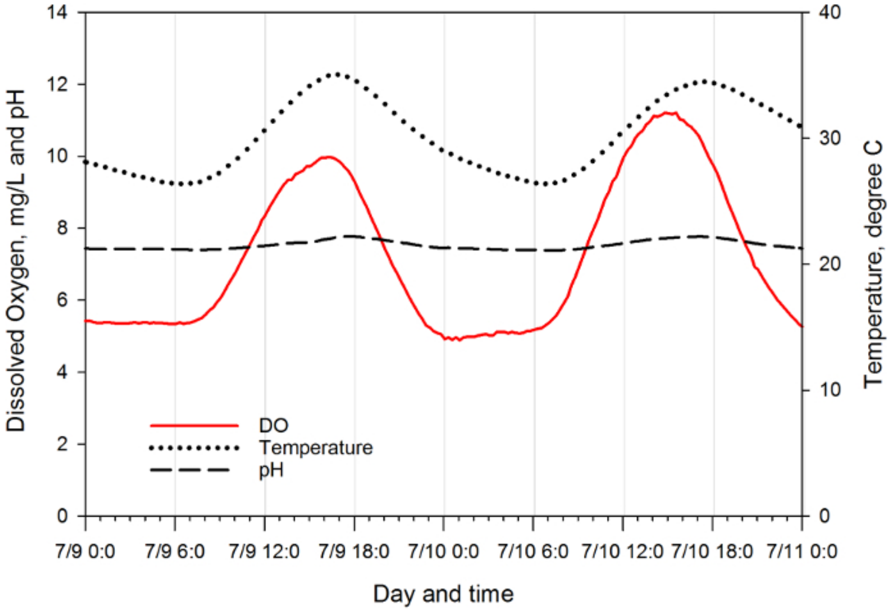

Figure 3. Diurnal Variation of pH, Temperature, and DO at a Stream Section in the Lower St. Francis Basin, an Agricultural Watershed. Please click here to view a larger version of this figure.

The dissolved oxygen was lowest from midnight to 06:00. As the photosynthesis activity of plants starts after sunrise, the DO increased steadily until it peaked at 16:19 on 7/9 (9.98 mg/L, 144.9% saturation) and at 15:34 on 7/10 (11.21 mg/L, 159.9% saturation). The DO steadily decreased until midnight and remained constant. Bacterial and algal respiration, photosynthesis, carbonaceous and nitrogenous oxidation, and temperature likely affected the diurnal variation of DO[18].

The pH varied between 7.4 and 7.8 from 7/9-7/10. The pH was highest at 17:34 on 7/9 (7.78) and at 17:04 on 7/10 (7.77). Diurnal variation in pH was also affected by the rate of respiration, photosynthesis, and buffering capacity, since carbon dioxide, which decreases pH, is removed during photosynthesis and is added during respiration in the aquatic systems.

The concentrations shown in **Figure 2** and **Figure 3**, if measured over a longer period (*i.e.,* a month, season, year) can provide information on how the water quality changes with time under natural or managed conditions.

Temporal (Monthly) Variation of Pollutant Loads:

Temporal variation at a section of the stream can be studied over different time scales. Monthly variation at the Little River Ditches Basin, a small agricultural watershed in northeast Arkansas, revealed a pattern of nitrogen and sediment loss from the watershed throughout the year (**Figure 4**). Pollutant loads were high in the early summer and late fall. The months of September and October were characterized by low pollutant loading, mainly due to low flow. The SSC was highest in November and December due to high rainfall on recently harvested and disturbed fields. The data also showed that variations were very high, since daily loads were driven by rainfall events that varied significantly. The high loads during late fall (November and December) demonstrated that nutrient reduction programs may be more effective if they focus on reducing November/December loads. Consequently, techniques that reduce the loss of pollutants in the winter, such as the use of cover crops[19], must be considered in watershed management programs.

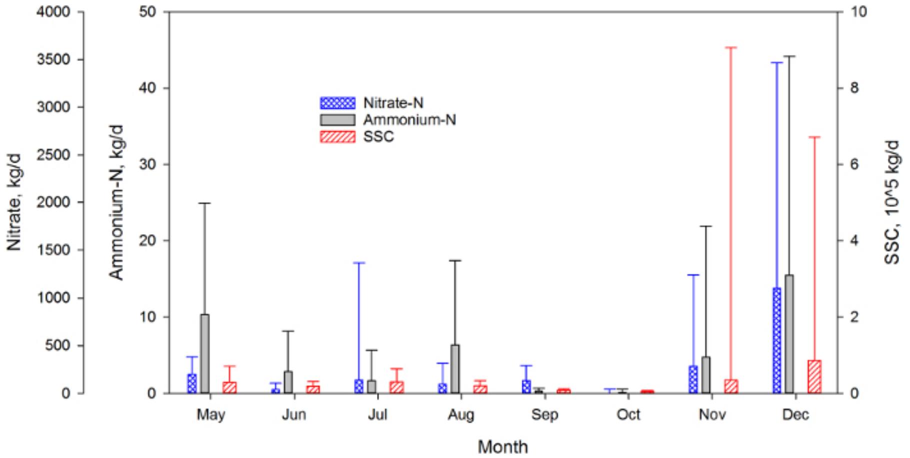

Figure 4. Monthly Variation of Nitrate, Ammonium, and SSC Load (kg/d) at the Outlet of the Little River Ditches Basin.
The values are median ± interquartile range. Please click here to view a larger version of this figure.

Spatial Variation of Pollutant Loads:

The protocol can also provide the data for spatial variations in addition to temporal variations if multiple stations within a watershed are chosen. Pollutant loads in an agricultural watershed (**Figure 5**) show distinctly increasing nitrate and ammonium loads as the water travels downstream. The loss in 9.6 kg/ha nitrate per year was within the 8 - 14 kg/ha per year range reported in Missouri in small agricultural watersheds with similar soil typs[20]. This type of information can be used to evaluate the effectiveness of instream water management practices and pollutant transport, among others.

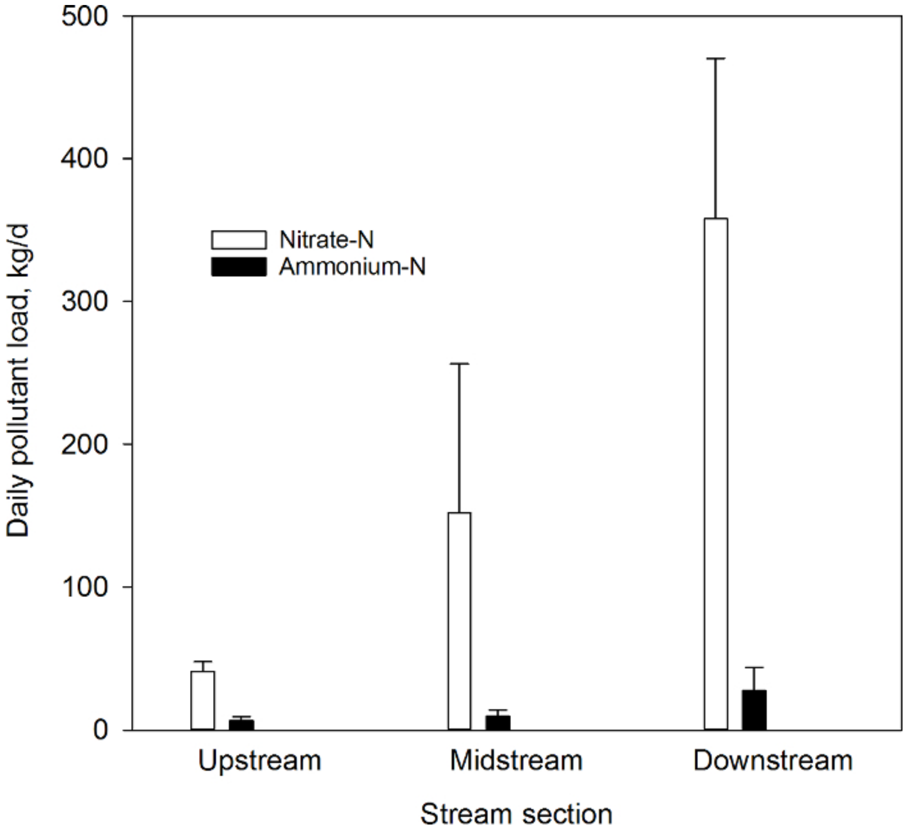

Figure 5. Nitrate and Ammonium Transport in the Little River Ditches Basin.
Upstream, midstream, and downstream sites were located approximately 2 km apart. The values are the mean ± standard error of mean on a daily basis for August 2015. Please click here to view a larger version of this figure.

Sensor Fouling and Sediment Buildup:

In agricultural watersheds, the presence of nutrients, such as nitrogen and phosphorus, in the runoff water at high concentrations can accelerate the rate at which bio-fouling occurs at a given temperature. Additionally, runoff water can carry high sediment loads that originate from the tilled fields and eroded waterways. The high sediment load can lead to the deposition of the sediment particles at the sensor and sonde surfaces and to the buildup of sediment. Such fouling and sediment buildup can result in drift and in inaccurate results.

The diurnal variation of DO decreased until 7/15, increased on 7/16 after the sensor was cleaned at the site, and abruptly decreased after 13 or 14 days (**Figure 6**) due to fouling. The growth and resulting accumulation of microorganisms on the surfaces of the sonde are visible in **Figure 7**. The fouling is severe on the surfaces where wipes or brushes do not clean. The effect of sediment buildup on the turbidity reading was observed on 12/26 (**Figure 8**). The rainfall on 12/23 and 12/25 increased the turbidity up to 1595 NTU and 1073 NTU. The turbidity decreased once the discharge decreased in the stream. However, the big rain event on 12/26 caused the turbidity to reach the upper limit of 3000 NTU. The turbidity reading remained stable at 3000 NTU due to the accumulation of debris on the sonde guard and the presence of weeds and plants on the Telspar post. Once the debris accumulated, the turbidity readings were erratic (*i.e.,* changed abruptly from 3000 NTU to less than 50 NTU in 15 min) and incorrect. Hence, the turbidity data from 12/26 to 12/29 are not of good quality.

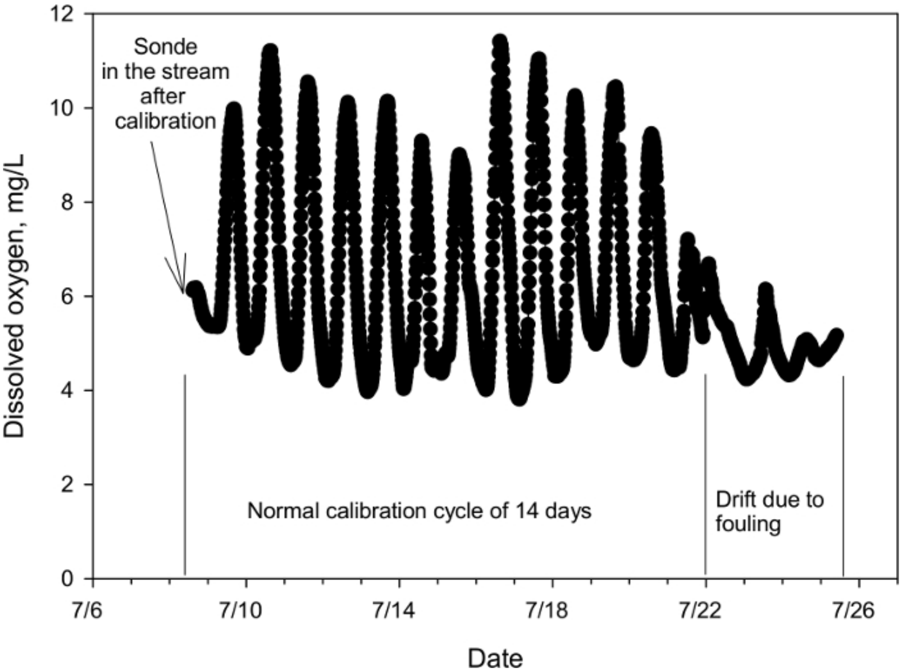

Figure 6. Drift of the DO Sensor Reading after the Sonde Remained in the Stream for Two Weeks.
After calibration, the sonde was installed on 7/8, and the drift started on 7/22. The drift in the sensor reading after 7/21 resulted in a lower DO than normal. Please click here to view a larger version of this figure.

Figure 7. Images Showing the Fouling on the Sensor Surfaces (left) and Clean Sensing Surfaces of the Sensors (right) after Wiping with a Brush and Wiper. Please click here to view a larger version of this figure.

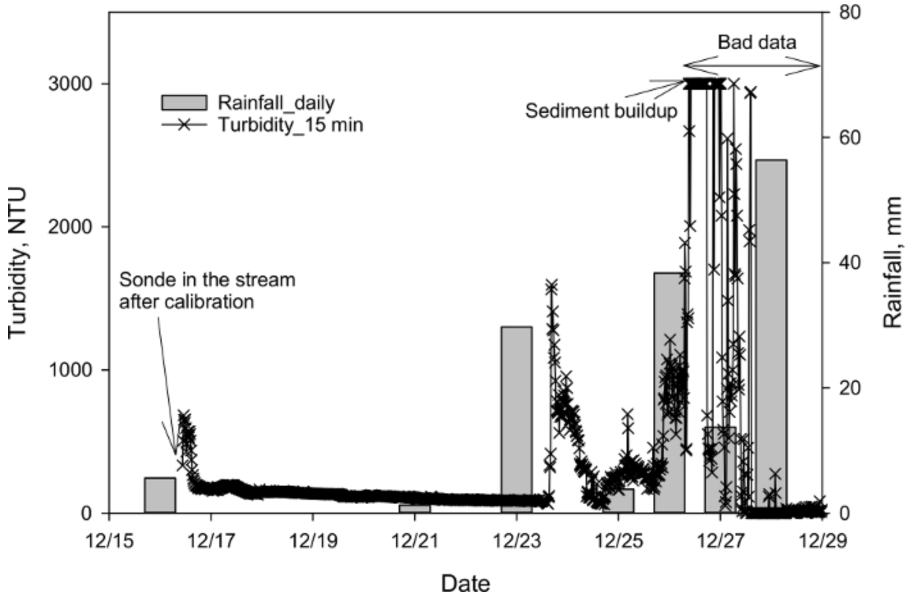

Figure 8. Turbidity (NTU) in the Stream Before and After Sediment Buildup in the Sonde Guard. Rainfall (mm) is shown on the secondary y-axis. The turbidity showed an excellent response to rainfall on 12/16, 12/23, and 12/25. However, the large rainfall event of 12/26 created sediment buildup in the sonde guard, and the turbidity readings after 12/26 were faulty (mostly 3000 NTU) and erratic. Please click here to view a larger version of this figure.

Item listing	**Item listing**	**Check**
Documents	QAPP (Quality Assurance Project Plan)	
	Chain of Custody Sheets	
	Field notebook	
	Navigation maps/GPS	
	Pen, Marker, label tape	
Safety	Sunscreen/sunglasses	
	Wasp spray	
	First-aid kit	
	Drinking water	
	Communication (cell phone)	
	Personal Protective Equipment-Wader, rubber boot, gloves, hat	
	Rope and anchor	
	Antiseptic hand wash	
Sample collection, storage, transport	Cooler and ice	
	Sample bottle and lid	
	Labeling tape	
Sensor/Instrumentation	Communication cables	
	Charged external batteries	
	Field laptop	
Sonde	Communication cable	
	'C' batteries	
	Brush and soap	
	Field laptop	
Other	Tool box (screw drivers, volt meter, zip ties, wrench, …)	

Table 1. Checklist of Items Recommended for a Field Visit to Sample Water and Repair and Maintain Sensors.

Discussion

Overall, the continuous monitoring of nutrients and sediment has several advantages over monitoring using the grab sampling method. Hydrological and water quality processes are affected by rainfall over a very short span of time. Users can obtain high temporal-resolution data on nutrients and sediment to study complex problems. Other water quality parameters, such as conductivity, pH, temperature, and DO, can be obtained simultaneously and at the same cost as for monitoring nitrate, ammonium, and turbidity. Moreover, there are other sensors from manufacturers that allow for the measurement of even more water quality parameters, such as chlorophyll, salinity, and oxidation-reduction potential, along with nutrients and sediment.

This protocol can be used to identify the temporal variation of the pollutants over a chosen period of study; the spatial variation of pollutants in a watershed, if monitoring is carried out at multiple stations; and the cross-sectional variation of pollutants, if monitoring is carried out at several points in a cross-section. As shown in this protocol, the diurnal variation in pH, conductivity, DO, nitrate, ammonium, turbidity, and temperature can demonstrate cause-effect relationships and contribute to a better understanding of the drivers of pollutant loads.

Despite the successful continuous measurement of nutrients and sediment, the greatest limitation of the method is the loss of data or the collection of a low-quality data due to sensor failure, loss of power, and sediment/debris buildup. While site selection is important, it is equally important to frequently check the calibration or to calibrate when necessary, replace internal and external batteries (if not solar powered), and download and check data. Data quality can be compromised at several stages, from data acquisition to data processing. At the acquisition stage, the focus of this paper, remedies for possible problems are discussed below.

Data Loss:

Inappropriate programming of sensors, loss of power to the sensor, *etc.*, can cause gaps in the data. If possible, a solar charger can be installed at the stations to recharge the battery. Otherwise, the frequent replacement of internal (for sondes) and/or external batteries is required. Downloading the data frequently will help to identify the problem quickly and to address it, reducing the loss of data due to memory limitations. Rodents can damage cables and incur losses of data. These losses can be avoided by using wire guards to cover the cables.

Low-quality Data Due to Fouling:

The fouling of sensor surfaces and the resulting drift or inaccuracy in the data can be minimized by covering the sensor guard with copper tape, by using copper guard, and by using copper mesh around the sensor guard. We found that covering the sonde surfaces (not sensors) with all-weather adhesive tape greatly facilitated the cleaning of the sensors. Self-cleaning sondes with wipers and brushes, like in the one used in this study, helped to clean the surfaces of the sensors (**Figure 7**). The use of copper materials, such as tape, guard, or mesh, reduced the growth of microorganisms and the resulting fouling.

Low-quality Data Due to Debris Buildup:

Positioning of the sensor and the sonde and burying the cables under sediment can limit debris buildup. For example, placing the sonde a certain depth above the stream bed but below the water surface helps to limit sediment buildup. Similarly, placing the sonde on the downstream side of the Telspar post reduces the debris, as the Telspar post catches the large woods, grasses, *etc.* Cleaning the sonde during every field visit can help to produce better-quality data. Wrapping the sensor guard with copper mesh reduces the sediment and debris buildup, interference from aquatic plants and macroinvertebrates, and fouling.

While the sonde can be placed upstream or downstream of the Telspar post, suspending the sonde on the downstream side is recommended. The requirement for the sensors in the sonde to measure without bias is having the movement of water across the sensor surfaces or having no standing water. The thin width of the post (4.0 cm) and the holes in the post ensure that the water flows through the sensor surfaces. Additionally, when the sonde is on the upstream side of the post, aquatic weeds and plant material/debris may enclose the sonde guard, as observed in this study. Another drawback of placing the sonde on the upstream side is that, while the guard protects the sensors, the sonde body is still in danger of being damaged by debris/wood on the upstream side of the post. The effect of the post on the velocity measurement can be tested by visually observing and comparing the velocity readings with and without the post. In this protocol, the area-velocity sensor was approximately 50 cm upstream of the Telspar post, and the presence of the Telspar post did not affect the velocity.

Identifying the frequency of calibration under site-specific conditions is important. It is a balance of not compromising the data quality by under-calibrating and not wasting resources by over-calibrating. In the agricultural streams in this study (*i.e.,* hot, humid tropical climate), laboratory calibration every 2 weeks in the summer (**Figure 6**) and every 3 weeks in the winter was sufficient. However, sensors were cleaned on the site every week during the summer.

The preparation of a QAPP for all activities, including quality control checks in advance of the project, helps to identify potential problems, keeps the study consistent and uniform, and produces better-quality data. Following the guidelines provided in the QAPP procedure is required.

Documentation of the events or unusual observations in notebooks or photographs is very important. Many times, the results of monitoring are linked to events that are atypical. For example, the dredging (*i.e.,* cleaning) of a stream (ditch), which is infrequent, will increase the turbidity of the water sample, even without increased discharge.

The safety of the personnel involved in the field work, as well as instrument safety, are very important. A safety, health, and welfare plan should be devised before the start of a project. Some of the safety concerns include snakes, temperature hazards, flood, high wind, driving conditions, lightning, *etc.* Logistics and recommended items to take during field visits are provided in **Table 1**.

One of the limitations of the current technology for measuring the nitrate and ammonium (*i.e.,* ion-selective electrode) is that it does not measure them precisely up to very low nutrient values. While the resolution of the sensors is 0.01 mg/L for both nitrate and ammonium sensors, the accuracy is 5% of the reading, or up to ± 2 mg/L. The accuracy of the DO, turbidity, pH, and conductivity sensors are ± 0.1 - 0.2 mg/L, or 0.1%; ± 1 - 3% up to 400 NTU; ± 0.2; and ± 5 µS, respectively. Moreover, the protocol is difficult to follow during flooding due to inaccessibility.

While this protocol was tested in agricultural watersheds, it can also be applied to other watersheds in other regions, such as watersheds impacted by other land use activities, including mining. This method is also useful in assessing interactions between multiple contaminants. Future applications of the method described here include sensor advancement to cope with the fouling of sensors and the accumulation of debris/sediment on the sonde guard; further improvements in the accuracy and precision of the sensors; the development of wireless networks and the remote transfer of data to the servers; and the buildup of larger networks for standard data acquisition systems, data management, and applications.

Disclosures

The authors have nothing to disclose.

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