A comparison of water quality sensor deployment designs in wadeable streams

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Abstract

The design of infrastructure used for deploying water quality sensors can potentially impact data quality. Despite this, sensor infrastructure design has not been well discussed in the peer-reviewed literature. Here, we present side-by-side measurements from two contrasting designs; a “monopod” consisting of a strut driven into the streambed and a downrigger suspended from an “overhead cable.” We collected measurements over an approximately 6-month period from two wadeable stream monitoring sites within the National Ecological Observatory Network. In general, we observed minimal differences between measurements, suggesting both designs to be viable options from a data quality perspective under normal operating conditions. However, the monopod design was more susceptible to coming out of the water during low stage and burial by sedimentation. While more expensive and logistically complex to install, the overhead cable design exhibited greater survivability, adjustability, and serviceability. We discuss additional design considerations and potential modifications that we hope will prove useful to other researchers in instrumenting their own sites.

The past decade has seen widespread deployment of in situ sensors for high-frequency measurement of stream and river water quality (Kirchner et al. 2004; Rode et al. 2016). The location and manner sensors are deployed can potentially impact measurements (Siders et al. 2017; Jacobs et al. 2020). Within the literature, sensor make/model, principles of operation, and calibration procedures are often described in great detail, while descriptions of how they were actually deployed are often limited to “in a well-mixed point” (Mulholland et al. 2005), “in the center of the channel” (Pellerin et al. 2009), or “in the advective zone” (Cohen et al. 2013) with no mention of the additional supporting infrastructure required. While enabling sampling of a well-mixed, representative location to ensure data quality is paramount, minimizing potential damage to sensors and infrastructure should also be considered as this reduces repair or replacement costs and results in decreased sensor downtime (White 1999; Wagner et al. 2006; Lewis and Eads 2009). Whether sensors can be easily accessed or retrieved for maintenance activities, such as calibration and cleaning, throughout the annual flow regime (including during high flow events) is another important consideration. While multiple studies have compared side-by-side performance across sensor types (Johnston and Williams 2006; Downing et al. 2012a; Pellerin et al. 2013; Rymszewicz et al. 2017), similar side-by-side comparisons of sensor deployment infrastructure performance are critically lacking.

The National Ecological Observatory Network (NEON; https://neonscience.org) is a National Science Foundation-funded project designed to collect long-term, open-access data to better understand ecological change at continental scales (Keller et al. 2008; McDowell 2015). NEON includes 34 freshwater aquatic field sites spread across 19 different ecoclimatic regions, from Puerto Rico to Alaska (Goodman et al. 2015). While the NEON aquatic field sites include 7 lake sites and 3 large rivers sites which present their own instrumentation challenges, here we focus on deployment of water quality sensors in the 24 wadeable stream sites. Despite comprising the majority of total drainage network length (Downing et al. 2012b) and exerting considerable influence on downstream water chemistry (Peterson et al. 2001; Alexander et al. 2007), small headwater streams are instrumented with automated sensors far less frequently than larger rivers. Of the almost 900 sites with in situ dissolved oxygen (DO) sensors listed in the U.S. Geological Survey database (https://waterdata.usgs.gov/nwis), fewer than 100 have a contributing area less than 12 km², the median size of NEON stream sites. For nitrate (NO₃−N) sensors, this number drops to only nine sites. At high frequencies, water quality of small streams is more variable than large rivers (Hensley et al. 2018) arguably making sensor-based measurements of even greater utility. However, instrumenting small streams involves several
logistical challenges compared to larger rivers. Small streams typically exhibit a greater range of flow conditions under which sensors must continue to operate. Small streams are also less likely to have existing infrastructure (such as bridge pilings) on which to mount sensors.

As NEON data are intended to enable both spatial comparisons across sites and track long-term change within sites, data collection and processing procedures are designed to be as standardized as possible (Goodman et al. 2015). However, during the construction of the Observatory and the initial operations period, site-specific approaches to aquatic sensor deployment infrastructure designs were needed to accommodate a wide array of streams with different channel morphologies, substrates, and hydrologic regimes. Common problems include damage during high flow events, fouling, burial due to sedimentation, sensors coming out of the water during low flow, and ice formation (Fig. 1). None of these challenges are unique to the NEON program and are commonly encountered when deploying sensors in any smaller stream environment.

Here, we present two contrasting water quality sensor deployment designs and discuss their relative advantages and disadvantages. As high-quality data collection is our primary objective, we performed side-by-side comparisons at two different NEON sites to verify that the deployment design does not significantly impact measurements. Additional factors such as installation costs and logistics, susceptibility to fouling and damage, and serviceability are also discussed. Finally, we suggest additional modification and designs which could be used to improve performance in specific situations or environments. The intent here is not to provide an exhaustive list of potential designs or to suggest these designs are optimal for every situation. Rather, we seek to present several potential designs and associated modifications for other researchers to consider when instrumenting their own sites.

**Materials and procedure**

Regardless of how they are deployed, NEON instruments all wadeable stream sites with the same set of in situ water quality sensors at an upstream (S1) and downstream (S2) location. EXO2 multiparameter sondes (Yellow Springs Instruments [YSI], Yellow Springs, OH) measure water quality, including specific conductance (SpC), DO, and fluorescent dissolved organic matter (fDOM). Measurements are collected every minute using the sonde’s accelerated averaging mode. Platinum resistance thermistors (PRTs; Thermometrics, Northridge CA) measure water temperature (Temp) every 1 s. These are used to generate 5-min Temp averages. Submersible ultraviolet nitrate analyzers (SUNA; Sea-Bird Scientific, Bellevue, WA) measure nitrate–nitrogen (NO₃⁻N). A burst of 20 measurements is collected every 15 min; the first 10 measurements are discarded to allow the sensor lamp to warm up, and the next 10 measurements are averaged. The NEON Calibration and Validation Lab (CVAL) tests each sensor prior to deployment to verify accuracy and quantify individual sensor-specific uncertainty values.

Each sensor is deployed in its own protective housing constructed of schedule 120 polyvinyl chloride (PVC). Machined slots through the PVC housings allow free exchange of water, and locking pins and collars hold the sensors securely within the housings. At sites with a large amount of transported sediment, fine wire mesh may be installed around the PVC housing to prevent it from becoming clogged with sediment. Field cables with wet mate connections power each sensor and transmit data. Both the sonde and the SUNA are equipped with automated wipers to prevent biofouling. Additional preventative maintenance includes inspection, manual cleaning, and field calibration. As part of this process, all sensors deployed at the site (S1 and S2 locations, and in the case of this experiment co-located sensors) are run side by side in a bucket of stream water to verify that offsets between sensor measurements are within an acceptable range. Data undergo

![Fig. 1. The monopod design (a) is simple, but susceptible to fouling by debris (b), low water levels (c), and freezing in ice (d).](image)
automated plausibility testing and data quality flagging (QF) for gaps, range, steps, and spikes, and a manual science review (Smith et al. 2014).

The majority of NEON wadeable stream sites use a vertically oriented 1–5/8″ (4.13 cm) slotted stainless-steel strut (Fig. 1a). The strut is either driven to refusal in sandy substrate or bolted to underlying bedrock. PVC sensor housings are then bolted to support arms extending horizontally off the main strut (a “monopod”). Additional bracing struts may be used for support where necessary (creating a “bipod” or “tripod”). In accordance with the EXO2 user manual (YSI 2019), the sonde is deployed either vertically or horizontally depending on site-specific considerations. In accordance with the manual recommendations (Seabird 2018), the SUNA is always mounted horizontally, parallel to flow with the optical window facing down.

An alternative NEON design is the “overhead cable,” which utilizes a vertical downrigger hanging from a steel cable suspended horizontally above the stream (Fig. 2a). Support towers (Fig. 2b) on each bank consist of two 3/8″ (6.03 cm) galvanized steel fence posts set in concrete and stayed with guy wires for additional support. A 3/8″ (0.95 cm) steel cable is strung between the towers and tensioned with a pulley and winch. A wheeled trolley (Fig. 2c) is free to roll across the main cable, with a secondary pulley system used to adjust the trolley position. A horizontal sensor carriage (Fig. 2d) mounts to the vertical downrigger arm extending from the bottom of the trolley. Carabiners or zip ties can be used to suspend sensor cabling across the overhead cable. Similar designs have been utilized elsewhere, notably by the National Forest Service in the Pacific Northwest (Lewis and Eads 2009).

Side-by-side comparisons of the monopod and overhead cable designs took place in Lower Hop Brook (HOPB) from 07 May 2019 to 12 November 2019 and in LeConte Creek (LECO) from 28 August 2019 to 18 March 2020. HOPB drains 12.8 km² of mixed evergreen and deciduous forest in central Massachusetts. It has an average width of 5 m and has an average discharge (Q) of 216 L s⁻¹, ranging from 10–1500 L s⁻¹ during the study period (though capable of exceeding 4000 L s⁻¹). LECO drains 9.4 km² of deciduous forest in Eastern Tennessee. It has an average width of 7 m and has an average Q of 226 L s⁻¹, ranging from 20 to 5000 L s⁻¹ during the study period. To help distinguish between measurement differences arising from deployment method vs. sensor offsets, the locations of the EXO2 sondes were swapped from the monopod to the overhead cable and vice-versa partway through the study. Locations of the PRTs could not easily be swapped because the data cables are an integral part of the sensors, and the monopod PRT cables were too short to be deployed with the overhead system. Because utilizing spare SUNAs for prolonged comparisons could not be performed without sacrificing instrumentation at other NEON sites, side-by-side NO₃–N data were only collected for the first week of the study at LECO.

We downloaded the expanded packages of publicly available data (NEON 2021a, 2021b and 2021c) from the NEON data portal for water quality (DP1.20288.001), temperature (PRT) in surface water (DP1.20053.001), and nitrate in surface water (DP1.20033.001) using the neonUtilities R package (https://cran.r-project.org/web/packages/neonUtilities/). Measured fDOM is affected by light attenuation from dissolved substances and suspended particles (Downing et al. 2012a). NEON publishes the raw (calibrated) fDOM measurements recorded by the EXO2, and corrected values using absorbance data from the SUNA. Because a SUNA was not collocated with both sensors for the duration of the study, we used the raw EXO2 measurements to ensure a fair comparison. We excluded
any QF measurements from all analyses, with two exceptions. First, we included data with a validCalQF indicating a field calibration had not occurred in the previous 30 d because this does not automatically mean that the data are bad. Second, the automated wiper on one of the EXO2 sondes at LECO began to malfunction during the final weeks of the comparison, periodically parking in front of the fDOM optical sensor, reducing the measured fluorescence. In order to be able to use these data, we fit a spline curve (using the zoo R package) to the highest fDOM measurement each hour, which we presumed to be accurate. We performed linear regressions of monopod vs. overhead cable measurements, with the expectation that paired measurements would be strongly correlated, with regression slopes close to one and intercepts close to zero. We used a $p$ value of 0.05 to assess significance. Using the CVAL-derived uncertainties of the individual sensor probes, we calculated a combined uncertainty using the root of sum of squares and determined what fraction of measurement differences fell within this range.

**Assessment**

In general, monopod measurements correlated strongly with side-by-side overhead cable measurements at HOPB and LECO (all $p < 0.01$). Regression slopes were always close to one and intercepts relatively close to zero (Fig. 3). Intercepts often flipped in sign (i.e., from positive to negative) when sensor locations were swapped. For most combinations of site parameter, the majority of differences between the monopod and overhead cable measurements fell within the combined uncertainty range of the sensors (Table 1). Taken together, this suggests measurement differences generally resulted from offsets between sensors, not local differences in water quality or deployment method. The exceptions were HOPB–SpC, HOPB–Temp, and LECO–fDOM.

SpC at HOPB exhibited the most marked divergence in side-by-side measurements (Fig. 4a) and was clearly associated with falling water levels (Fig. 4b). The lengths of an EXO2 conductivity probe is slightly shorter than the other sensor probes, and so when vertically oriented, becomes exposed to air first as stage drops. Because SpC from these periods were automatically QF, they were excluded from the analysis shown in Fig. 3c and Table 1. This situation could not easily be rectified by lowering the monopod sonde because of sediment buildup (Figs. 4e,f). Likewise, the entire assembly could not easily be moved to a deeper part of the stream channel. In contrast, the overhead cable sensors could easily be repositioned in a deeper portion of the channel by sliding the downrigger trolley across the cable and remained submerged.

**Table 1.** Fraction of differences between monopod and overhead cable measurements within combined uncertainty range of sensors.

| Parameter | HOPB (%) | LECO (%) |
|-----------|----------|----------|
| Temp      | 1        | 89       |
| DO        | 98       | 98       |
| NO$_3$–N  | 53       | 2        |

*Measurements when monopod probe remained submerged. If all measurements are included this value falls to 55%.
Despite a strong correlation between side-by-side measurements (Fig. 3a), differences in Temp at HOPB were greater than the expected combined uncertainty of the sensors (Table 1). This was potentially also related to the shallower water at the monopod location. The monopod PRT was generally warmer and showed greater diurnal cycling (Fig. 4c). This was most pronounced when water levels were lowest (Fig. 4d). In this case, the sensor was not coming out of the water, but the location was still not ideal because the shallow water along the bank was responding to changes in air temperature to a greater extent than the deeper water near the center of the channel.

Side-by-side measurements of fDOM at LECO were also strongly correlated (Fig. 3h), but consistently greater than the expected uncertainty range of the sensors (Table 1). In this case, however, the offset remained relatively constant across the entirety of the comparison (Fig. 5), and the intercepts of the regressions flipped almost perfectly when the locations of the sondes were swapped (i.e., from +6.7 to −7.0). The same phenomenon occurred for fDOM in HOPB, though the magnitude was smaller (+3.57 to −3.73). Why the offsets were slightly larger than expected based on the sensor uncertainties derived by CVAL is unknown. YSI does not publish a standard uncertainty value for their fDOM probes, only that individual sensor response to changing fDOM is highly linear, which was clearly observed. We do not believe it was related to the malfunctioning wiper at LECO, as the offset was apparent even before this issue emerged, as well as occurring at HOPB where the wiper functioned throughout the study. It could have resulted from poor calibrations; however, we believe that the most likely explanation is that there may be additional fluorescing species present in the stream water that result in a higher measurement uncertainty than that derived in lab conditions.

**Discussion**

In addition to the accuracy and representativeness of measurements, additional factors should also be considered when choosing a design (Table 2). One obvious consideration is the cost and logistics of installation. While varying based on specific characteristics of the site, a typical NOEN monopod costs a few hundred dollars in materials (not including sensors, power supply, etc.) and can usually be assembled and installed in a single day. A typical overhead cable costs two to three times as much, and often takes multiple days to install. However, a single replacement of a site that has been destroyed or needs to be redesigned because of poor data quality can easily negate this cost and labor difference. The monopod may be installed in a greater variety of sites. The overhead cable design requires stable banks on each side of the stream for support towers. The banks must be of approximately equal height so that the cable can be strung horizontally, and sufficiently close that the cable does not sag. For the downrigger
Table 2. Factors to consider when selecting a design.

| Factor     | Monopod                                      | Overhead cable                                                 | Bank-mounted sliding rail                                         |
|------------|----------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------------|
| Installation| • Can be installed in most sites              | • Requires stable, level banks appropriate distance apart       | • Requires stable banks                                           |
|            | • Lower material and installation costs      | • Higher material and installation costs                       | • Medium material and installation costs                         |
| Adjustability| • Lateral position cannot be adjusted        | • Lateral position easy to adjust using pulley system           | • Lateral position cannot be adjusted                            |
|            | • Vertical position difficult to adjust      | • Vertical position also adjustable                            | • Vertical position easily adjusted                              |
| Serviceability| • Must enter stream to service unless “vertical rail” modification is used | • Can be reeled to shore for servicing                         | • Can be reeled up for servicing                                  |
| Survivability| • Rigid design more susceptible to damage   | • Can be pushed out of the way by debris                      | • Rigid design but position closer to shore offers some protection |

In addition to the monopod and overhead cable designs compared side by side, we also consider the bank-mounted sliding rail design.

design and cable diameter used here, we determined this distance to be approximately 30 m. In wider streams and rivers, for example, the NEON Blue River (BLUE) site in Oklahoma, a downrigger can be mounted directly to a bridge. While water quality is often measured from bridges or other structures (Wagner et al. 2006), this approach requires an existing bridge in the desired location (not commonly found in and around small streams), and often a lengthy permitting process. Downriggers can also be mounted from cantilever booms instead of a cable (Lewis and Eads 2009). The length of the downrigger arm is another consideration. Acting as a lever, a longer arm requires less force to rotate and has a greater potential for the sensor carriage to be pushed to the water surface during high flow.

Survivability is another primary concern (White 1999; Wagner et al. 2006) when considering deployment designs. A rigid object positioned in a stream channel is very susceptible to being struck by debris during a storm. While neither design at HOPB or LECO was substantially damaged by high flows (Fig. 2e) during our comparison period, it is worth noting that similar sized events had severely damaged previous incarnations of the monopod at both sites (a primary reason for development of the overhead cable design). A large (~0.25 m diameter) log struck and became wedged against the LECO monopod during a storm event on 06 February 2020; the main strut was bent slightly but no serious damage resulted. In contrast, the overhead cable downrigger pivots about the attachment point, allowing it to be pushed out of the way by larger debris. Also, if a large flood is expected, the overhead cable can temporarily be reeled closer to the stream bank. This does not mean the overhead cable design is immune from damage, as the possibility exists that rather than pushing the downrigger out of the way, a large enough piece of debris could snag and produce enough tension to snap the overhead cable. A tree falling on the cable or a support tower could also cause a catastrophic failure. Depending on the degree of resulting damage, this could require a longer and more expensive repair than what would be needed to replace a monopod design.

While positioning sensor infrastructure closer to the bank may reduce the risk of damage by debris during storm events, it also increases the potential for coming out of the water during low stage, burial by sedimentation, or becoming disconnected from the well-mixed section of streamflow (Wagner et al. 2006), as demonstrated by the monopod at HOPB (Fig. 4). The ability to easily adjust sensor position based on changing hydrologic conditions is a desirable approach. Once a monopod has been installed, its lateral position within the stream channel cannot be easily adjusted without reinstalling the entire infrastructure in a new location. Adjusting the vertical position of monopod sensors, while possible, is not an easy task as the sensor housings are bolted to immovable support arms. Because of the dimensions of the EXO2 sonde and the additional diameter added by the PVC housing, altering the orientation from vertical to horizontal (Fig. 6a) does not substantially alter the water depth required to keep all the sensors submerged (for other make/models of sensors this may not be the case). It does, however, create a lower profile which appears to reduce the potential for fouling by snagged debris and sedimentation buildup. Covering the sensor housings in fine mesh (Fig. 6a) may prevent sediment from entering the housing and interfering with measurements; however, it will not prevent changes to water chemistry if they become buried. In contrast, the overhead cable design can easily be reeled to a new location using the pulley system. Some degree of vertical adjustment can be achieved by lengthening or shortening the attachment point of the downrigger arm to the trolley, or potentially by using the winch to adjust the tension on the main cable. A related consideration is serviceability (White 1999). The ability to reel the overhead cable to shore means that
sensors can still be serviced when conditions are unsafe for field personnel to enter the stream (Fig. 2e).

Apart from sites in Alaska, NEON stream sites remain instrumented year-round. While shallow locations closer to shore are more likely to freeze solid in winter, deeper locations in the center of the channel are more susceptible to damage during the ensuing spring melt pulse. Moving sensors between locations is a potential solution (White 1999) but carries the cost of designing and installing additional infrastructure and the logistical challenge of making the swap. At HOPB, the monopod location was shallow enough that it often froze solid (Fig. 1d). In contrast, the overhead cable, positioned in the deepest part of the channel, continued to measure liquid water under the ice (Fig. 2f). Becoming encased in a thick sheet of ice which begins to flow is a potential danger to either design, which can be reduced by periodically breaking up ice surrounding the infrastructure.

**Comments and recommendations**

The two designs compared in the side-by-side comparison are not the only possibilities. Bank-mounted designs are another common way of deploying water quality sensors. A handful of NEON sites are instrumented using a modification of a bank mounted design (Fig. 6b). Unlike many bank mounted designs where the vertical position of the sensors is fixed (similar to the monopod design), the NEON design includes a wheeled trolley (Fig. 6c) that can slide up and down the forward flange of a steal T-beam using a winch mounted at the top. Horizontal bracing struts, which connect the T-beam to the bank, are mounted to the rear so as not to impede the motion of the trolley. A similar design has been used by other researchers elsewhere, notably the Luquillo Critical Zone Observatory in Puerto Rico (W. McDowell pers. corres.).

An advantage of this design is that being closer to the bank provides some degree of protection from flood debris. It is cheaper and easier to install than the overhead cable design, and potentially safer in environments with overhanging tree branches that might fall during a storm and damage the cable. The vertical position of the sensors can be easily adjusted based on hydrologic conditions and can also still be retrieved for servicing or repair during high flows. A constraint of the design, and of bank mounted designs in general, is that the installation location is limited by the need for a nearby stable bank (bedrock or bridge abutment) to anchor to, while still being in a location where flow is well mixed. Like the monopod, lateral position cannot be adjusted without a complete reinstallation.

Choosing an appropriate design requires accounting for site-specific characteristics such as channel morphology and hydrologic regime, and understanding how these factors will affect data quality, site survivability, adjustability, and serviceability. This paper focuses primarily on infrastructure; for a detailed review of factors to consider in site selection, see White (1999) and Wagner et al. (2006). In general, detailed site surveys can provide valuable information prior to instrumenting a site. Similarly, an examination of the hydrologic record, or other indicators such as high water marks, can provide a range of expected water levels and flows. When repairing sites, conduct a thorough analysis of the factors leading to failure and consider how likely these are to recur. Keep in mind that relocation or redesign of a site, while more costly in the short term, may be more economical in the long term. Do not assume a more complicated or more expensive design
is always necessary, especially for shorter-term projects as opposed to long-term monitoring. Both the short-term and long-term environmental footprint, and the ability to decommission infrastructure at the end of a project may also be considerations.

Instrumenting small streams is clearly challenging, yet has rarely been addressed in the literature. Our intent here is not to provide an exhaustive list of potential designs or to suggest those presented here are optimal for every situation. Indeed, NEON infrastructure will continue to evolve to meet emerging challenges over the 30 year life of the Observatory. Our goal is to expand the literature available to the research community, and hope the discussion provided here will prove useful to other researchers when instrumenting their own sites.

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