Installation Matters: Implications for In Situ Water Quality Monitoring

Elizabeth G. Erwin[1,2], Daniel L. McLaughlin[2], Ryan D. Stewart[3*]

[1] City of Hendersonville, Department of Water and Sewer, NC, USA

[2] Virginia Tech, Department of Forest Resources and Environmental Conservation, Blacksburg, VA, USA

[3] Virginia Tech, School of Plant and Environmental Sciences, Blacksburg, VA, USA

*corresponding author: Ryan Stewart (ryan.stewart@vt.edu)

Key points:

- Study was conducted to evaluate effects of common sensor housings on specific conductance measurements
- Housings with smaller openings appeared to reduce rate of water exchange, causing measurement artifacts and errors
- We recommend water quality sensors be installed in housings with large holes or openings for sufficient water exchange

Abstract

Novel *in situ* sensor technologies can measure water chemistry at high temporal frequencies, yet few studies have evaluated how installation affects measurements. In this study, we assessed the effects of commonly used protective housings on *in situ* sensor readings. Working in two mountain streams, we co-located specific conductance sensors in four different housing types that varied in openings for water exchange (mesh, screen, holes, and open). We compared measured conductance values through time, and performed repeated salt tracer additions to evaluate the influence of housing type on calculated discharge. Sensors readings in mesh and, to a lesser extent, screen housings frequently diverged from housings with larger openings (i.e., holes and open), indicating reduced water exchange between stream water and housed sensors. Further, mesh and screen housings recorded more damped and delayed response to salt tracer additions compared to the other two housings, resulting in markedly different discharge values. From these findings, we recommend that water chemistry sensors should be deployed in a protective housing with large openings for sufficient water exchange.

Plain Language Summary

Many sensors are now available to measure water quality parameters in streams and rivers. Sensors are commonly installed in a housing to secure them in stream locations and for protection from floating debris. Yet, it is not well understood if different housing options influence measurements. In this study, we placed sensors that measured the electrical conductivity of water in four different housing types. Housings with smaller openings, including metal meshes and PVC pipes with narrow slots, caused sensor readings to differ from sensors placed in housings with larger openings. From these findings, we recommend that water quality

sensors should be deployed in a protective housing with large openings for sufficient water exchange.

Introduction

The suite of parameters that can be measured with *in situ* sensors has grown rapidly, including nitrate, dissolved organic matter, turbidity, and phosphate (Etheridge et al., 2014; Rode et al., 2016). Yet, there is limited guidance for sensor installation in streams (Clark et al., 2016). While studies have shown that sensors provide more consistent and representative values when installed in a well-mixed section of the main stream channel (Bergamaschi et al., 2012; Pellerin et al., 2012), little attention has been paid to the choice of protective housing types. As a consequence, sensor installations have varied widely between studies and applications. In streams characterized by fine suspended sediments, filter fabric has often been used to protect against sediment clogging. In streams with turbulent flows, metal housings – often with fine mesh screening – have been used to protect sensors from water velocities and contact with rocks and large woody debris (Stamp et al., 2014). Other users have encased sensors within PVC pipes with either screening or drilled holes of various densities and apertures (Jones et al., 2017). Such housing options vary in their size and density of openings, with potential, but largely unknown, effects on water, and thus solute, exchange between the stream and housed sensor. High-resolution data collected by *in situ* sensors are useful only as much as they accurately represent concentration variation, making it important to evaluate whether different housing materials affect sensor readings.

We assessed potential housing effects on specific electrical conductance (i.e., electrical conductivity at 25°C, hereafter referred to as SC) sensor readings, noting that such measurements are widely used to evaluate salinity impairment (Eaton, 2016) and identify water sources (Cox et al., 2007). Further, SC sensors are commonly used when estimating stream discharge via salt tracer injections, particularly in mountain streams where irregular channels and turbulence make meter-based velocity measurements unreliable (Moore, 2005). Working in two mountain streams, we compared SC time series and SC-derived discharge values from salt injections using four common housing types. While we chose SC sensors for this assessment, we submit that our findings will be applicable to the installation of most *in situ* water quality sensors.

Methods

SC *Sensors and Housing Types*

We used self-logging SC sensors (HOBO U20L-04, accuracy = 5 µS/cm, resolution = 1 µS/cm, Onset Corporation, Bourne, Massachusetts, United States) to determine if housing type influences sensor measurements. We compared four different housing types (Table 1, Figure 1): 1) mesh housing (MH), a steel well-point (1.0 m length by 0.05 m diameter) with 5 mm diameter holes covered by an outer 80-mesh stainless steel screen; 2) screened housing (SH), a PVC housing with 1.3 mm wide slots along the length of the housing; 3) holes housing (HH), a PVC housing with 6.3 mm holes and no additional screen or filter fabric; and 4) open housing (OH), a 0.18 m long section of PVC installed without caps such that the openings were perpendicular to the direction of flow and allowed unobstructed flow along the sensor. We did not include a sensor without housing in our field comparison; however, we assumed that the OH provides immediate exchange with stream water and thus considered it to be our experimental control.

Laboratory Test

We performed a laboratory test to evaluate whether potential leaching of the stainless steel material of the MH could affect SC readings. We measured SC every five minutes over a one-week period in two tapwater-filled (30-L) plastic tubs where three SC sensors were deployed in different positions: i) inside the MH submerged in one of the plastic tubs, ii) in the same tub approximately 10 cm from MH, and iii) in the other tub to serve as the control. Sensors were also rotated among positions on Day 4 to test for possible calibration differences.

Installation for Field Comparisons

We installed the SC loggers at two neighboring mountain streams, Dismal Creek and No Business Creek (Giles County, Virginia; Figure S1), with sensors placed within the four different housing types co-located within each stream (see Figure 1). The streams have the same bedrock type, with formations composed primarily of Dolostone, Limestone, Shale, and Sandstone. Dismal Creek lies on a scarp slope of the Blue Ridge Escarpment, and its streambed consists of a thin layer of sediment overlying planar sheets of bedrock (DiPietro, 2013). No Business Creek lies on a scarp face and has a streambed made up of cobbled rocks and boulders. Stream widths at study locations were 10 m at Dismal Creek and 3 m at No Business Creek.

At Dismal Creek, the MH well point was installed approximately 0.10 m into the stream bed, with deeper depths not possible due to the planar bedrock at this site. We secured the MH well point by anchoring it to a boulder near the middle of the stream. While this location had noticeable flow and mixing, it was not in the main thalweg and thus likely experienced lower water velocities. The OH was attached to the MH well point using zipties, oriented such that the PVC pipe was perpendicular to stream flow and flow was unobstructed along the sensor (Figure 1). The SH and HH were anchored by cinder blocks placed approximately 0.5 m away from the location of MH and OH, with an attempt to match flow conditions as closely as possible. At No Business Creek, the MH well point was installed approximately 0.45 m into the stream bed in the thalweg, with the OH secured to the MH and oriented perpendicular to stream flow. The SH and

HH were also installed near the thalweg, approximately 0.5 m away from each other and 1 m downstream from the MH and OH. For all housing types, SC sensors were installed to be near the middle of the water column; however, during very low flow conditions some sensors were above the water surface (e.g., the SH sensor at Dismal Creek from 24 October to 26 October and again from 27 October to 2 November 2018). The housed sensors collected SC and temperature measurements every 15 minutes between October 2018 and February 2019.

We also measured stage in each creek to explore how flow conditions (as indicated by stream stage) may affect differences among housings. We installed total pressure transducers (HOBO U20L-04, Onset Corporation, Bourne, Massachusetts, United States) inside the mesh housings at both Dismal and No Business Creeks. The pressure transducers recorded measurements every 15 minutes, and were corrected for barometric pressure variation using another pressure transducer installed in a dry belowground well at No Business Creek. The dry well was designed to reduce temperature variations and their induced error in barometric pressure measurements (McLaughlin & Cohen, 2011).

Temporal Patterns in SC Observations

Differences in measured SC time series were assessed to evaluate influences of housing type and how potential differences among housed sensors varied with flow conditions. We summarized the SC values based on their mean (μ), standard deviation (σ), and coefficient of variation (C.V.), with C.V. (%) = $100\sigma/\mu$. We also compared temperature time series among sensors to distinguish between housing effects on uncorrected electrical conducitivity (i.e., ion concentrations) and those that influence temperature and thus temperature-corrected SC values.

Tracer Tests and Discharge Measurements

To further compare differences between installation methods, flow measurements were collected at variable stage conditions using salt tracer methods (Moore, 2005). For each test, 1,500 g (low flows) to 3,000 g (high flows) of NaCl was mixed with 18 L of water. The solution was then introduced as a single point injection from the left stream bank, 50 m upstream of the sensors at Dismal Creek and 25 m upstream of the sensors at No Business Creek. Following Moore (2005), we used SC readings collected at 1 s intervals to calculate discharge for the four housing types. We performed eight salt tracer tests at each site and captured a variety of conditions, including high, medium, and low flows. We then developed rating curves to relate calculated discharge and observed stage.

Results

Laboratory Test

Although there were small (ca. 10 $\mu S\ cm^{-1}$) differences in calibration offsets among sensors, temporal SC patterns were similar among the three tested positions, thus indicating no influence from the MH on SC readings (Figure S2). Sensors readings were also similar following sensor rotation between the two tests, demonstrating consistent performance among sensors. Based on this information, we determined that the stainless steel material of the MH did not influence SC readings via dissolution of the metal. This test also showed that, after an initial equilibration period, the relative offsets of the SC sensors were stable through time, meaning that any fluctuations in SC values observed during the field tests likely reflected actual SC variations in the water near the sensors.

Temporal Patterns in SC Observations

At both stream sites, sensors installed in the four housings collected similar temperature measurements (Figure S3), but SC readings differed between housings, with the MH in particular diverging from the others (Figure 2). In Dismal Creek, the MH sensor recorded SC values as high as 130 μS cm^{-1}, versus ≤30 μS cm^{-1} for sensors in the other housings (Figure 2a). Mean SC values for the period shown in Figure 2a were μ = 21 μS cm^{-1} for OH, 22 μS cm^{-1} for the HH, and 38 μS cm^{-1} for the MH (Table 2). The MH also had much higher variation (σ = 26 μS cm^{-1}; C.V. = 70%) compared to OH and HH, which both had σ and less than 2 μS $cm^{-1}$and C.V. values less than 10%. Statistics for SH were not calculated due to data gaps during low flows when the sensor was above water surface.

In No Business Creek, where there was less variability in both flow and SC, MH measured SC values as high as 64 μS cm^{-1}, versus <12 μS cm^{-1} for the other housings (Figure 2b). Mean SC values for the period shown in Figure 2b were μ = 11 μS cm^{-1} for both OH and HH, 8.8 μS cm^{-1} for SH, and 20 μS cm^{-1} for the MH (Table 2). The OH and HH had σ < 0.2 μS cm^{-1}, compared to a higher value for SH (σ = 0.43 μS cm^{-1}) and even higher for MH (σ = 26 μS cm^{-1}). Similarly, OH and HH had similar and low C.V. values (1.8% and 1.6%, respectively) versus a higher value in the SH (C.V. = 4.9%). The MH had more than an order of magnitude greater variance, with C.V. = 80%.

At both streams, MH SC values progressively increased and diverged from other housing types during stream recession periods, and quickly converged to the others during high flow events (e.g., the event in No Business Creek on 2-3 November 2018; Figure 2b). Rapid decline of MH readings and convergence with other housings also occurred following sensor retrieval and redeployment during data downloads (red arrows in Figure 2). By contrast, the other three housing types (OH, HH, SH) captured similar SC patterns, but with some unexplained drift in SH readings at Dismal Creek (inset in Figure 2a).

Tracer Tests and Discharge Measurements

For most salt tracer tests, the different housings produced distinct SC responses. During a representative tracer test conducted at low flow in Dismal Creek, HH showed the earliest response to the tracer, with SC starting to increase 850 seconds after tracer injection and reaching a peak SC value of 64 μS cm^{-1} (Figure 3a). The OH showed an increase starting approximately 100 seconds later and reaching a peak SC of 41 μS cm^{-1}. Both SH and MH recorded much more delayed responses, with SC values starting to rise after 1,300 seconds, and had peak SC values of 28-30 μS cm^{-1}, thus showing a more damped signal than the OH or HH. Using these tracer-induced SC responses, we calculated discharge and found similar values for OH, HH, and SH housings (356-405 L s^{-1}) and substantially greater discharge for MH (1,270 L s^{-1}). In a representative high flow event at Dismal Creek, OH and HH had similar time to response and peak SC values, which translated to similar discharges: 15,300 L s^{-1} for OH and 12,200 L s^{-1} for HH (Figure 3b). The SH responded more slowly and provided a lower calculated discharge (4,920 L s^{-1}). The MH did not record any change in SC, and therefore the data were not useful for estimating discharge. We note that, during this high flow event (Figure 3b), the measured changes in SC in all housings were relatively small compared to typical salt dilution tests, and therefore the calculated discharges likely had some uncertainty.

Similar trends were seen at No Business Creek. In the representative low flow event, OH and HH showed similar responses to the tracer addition, rising quickly to peak SC values of 232 μS cm^{-1} (OH) and 290 μS cm^{-1} (HH), whereas SH and MH reponses were delayed (starting to rise 60-70 seconds after the other housings) and damped, rising only to peak SC concentrations of 40 µS cm^{-1} (SH) and 53 µS cm^{-1} (MH; Figure 3c). Calculated discharge for this event was similar for the OH and HH (244-248 L s^{-1}) and greater for the MH (309 L s^{-1}) and SH (380 L s^{-1}). In the representative high flow event, the OH, HH, and SH responded to the salt tracer at similar times but with different peak SC values (Figure 3d). Specifically, the HH peaked at 265 µS cm^{-1}, while the OH and SH peaked between 151 and 158 µS cm^{-1}. The HH and OH peaked within 1 second of another, while the SH peaked 8 seconds later. Among these three housings, OH provided the lowest calculated discharge (859 L s^{-1}) compared to 1,021 L s^{-1} for HH and 988 L s^{-1} for SH. The MH only recorded a very minor response to this tracer addition (maximum SC increase of 6 µS cm^{-1}), and yielded the highest discharge value of all: 1,129 L s^{-1}, which was 31% higher than the value from the OH.

To further assess differences between housing options, we compared calculated discharge rates from all tracer tests for MH, SH, and HH to those from OH, which served as the experimental control. At Dismal Creek, there was poor correspondence between MH and OH (R^2 = 0.11), and also between SH and OH (R^2 = 0.022), with the OH generally yielding lower discharge values in low flow conditions and higher discharge values as flow increased (Figure 4a). At No Business Creek, discharge values estimated from the other housings generally exceeded discharge from OH (Figure 4b). The only exception was the test performed at the lowest flow conditions, when the MH did not record a change in SC, while the SH gave an estimated discharge of less than half that of the OH and HH. Here, the calculated discharges were better correlated, with R^2 = 0.91 (MH versus OH) and R^2 = 0.93 (SH versus OH). At both sites, OH and HH provided discharge estimates that were similar in magnitude and strongly correlated (R^2 = 0.95 in Dismal Creek and R^2 = 0.99 in No Business Creek), with differences increasing under high flow conditions.

We also assessed the influence of installation on calculated flows by examining rating curves between calculated stream discharge and observed stage. The estimated parameters and goodness of fits varied substantially between installation types. For example, at Dismal Creek, OH had the highest R^2 value (0.95), HH had the next highest R^2 value (0.53), and SH and MH both had R^2 values < 0.35 (Figure S4). In No Business Creek, OH also had the best fit (R^2 = 0.84), while HH and SH also had R^2 values ≥ 0.80 (Figure S5). The MH had an R^2 of 0.70.

Discussion

Temporal Patterns in SC *Observations*

At both stream locations (No Business and Dismal Creeks), SC time series indicated differences among housing options. During declining flow conditions, SC values increased markedly in the MH and drifted from the other housing measurements (Figure 2). While the exact mechanism for these SC increases during low flow remains unknown, this drift could reflect localized groundwater upwelling through the portion of the wellscreen below the streambed (Bischof et al., 2019). Flow increases from precipitation events then caused MH readings to rapidly decrease and converge with SC values from other housing types. The MH also reverted to similar SC values as the other housings following sensor removal and redeployment for data download, likely from water displacement and transient increase in water and solute exchange within the housing. While less extreme than the MH, the SH also recorded greater variability compared to OH and HH at No Business Creek, with 2-3x higher standard deviation and C.V. values (Table 2). Data gaps for SH at Dismal Creek precluded such a comparison, but we did observe periods of unexplained drift in SH readings (e.g., Figure 2a inset). At both sites, however, SC values recorded by OH and HH were similar in magnitude and variation. Taken altogether, these data suggest that housings with smaller openings for water exchange (i.e., MH, and to a lesser extent, SH) can affect sensor readings. In the case of SC data, such errors may falsely indicate salinity impairment, an increasing global concern for freshwater systems (Kaushal et al., 2018).

Tracer Tests and Discharge Measurements

In mountain streams and other turbulent waters, tracers and *in situ* sensors often represent the only viable method for estimating discharge (Moore, 2005; Gravelle, 2015), emphasizing the importance of appropriate housing installation. Our salt tracer experiments indicated clear differences in SC patterns between housing types (examples shown in Figure 3). Sensors located in the MH either responded more slowly to the tracer addition compared to the other housings, or in a few cases did not respond at all (e.g., Figure 3b). The OH and HH tended to have the fastest response to the salt additions, while SH often had a damped and delayed response. These variable responses caused differences among housing types in estimated discharge values (Figure 4) and rating curves (e.g., lower R^2 values for MH and SH; Figures S4 and S5).

We note that our mixing lengths were less than the suggested range for mountain streams, potentially resulting in incomplete tracer mixing across our stream reach. While this factor may have introduced some error in calculated discharge rates, it did not confound our findings regarding relative differences among housing types. At No Business Creek, all sensors were co-located in the main thalweg and thus experienced the same pulse of elevated stream SC. At Dismal Creek, site conditions required us to anchor the MH, along with the attached OH, behind a boulder and outside the main thalweg, whereas the HH and SH were nearer to the main thalweg, albiet only 0.5 m away. We speculate that these different positions of OH versus HH may partially explain their differences in response to tracer additions, particularly at low flow

(Figure 3a), supporting the common recommendation to avoid such flow obstructions. Nevertheless, OH and MH, which were co-located, had markedly different responses to tracer additions, as did the co-located HH and SH. These pairwise comparisons thus further indicate that housing type affects sensor measurements.

Housing Effects on Water Exchange

We suggest that the variation in sensor data between housings may reflect differences in flow resistance and associated water exchange through the different housing types. While we are unaware of similar studies investigating housing effects on *in situ* sensor readings, Yu et al. (2011) and Klammler et al. (2007) demonstrated that reduced aperture size (and thus increased flow resistance) can result in flow divergence around a porous cylinder, particularly at lower velocities. As such, flow resistance and associated divergence were likely greatest in the MH followed by SH, and were likely minimized in HH and OH. Our results suggest that these differences in flow resistance affected solute exchange across housings and became even more important as discharge (and thus stream velocity) decreased. In contrast to SC, temperature measurements were similar among housings (Fig. S3), further indicating that divergent readings were caused by varying dissolved ion concentrations within housings rather than temperature-induced differences in SC correction factors.

Limited water exchange may also increase biofouling of housed sensors, which would also result in erronous sensor readings. However, we did not observe sensor biofouling in our study, and the sudden convergence of MH and other housing SC values following sensor downloading further implicates solute exchange as the cause of housing differences. That is, we did not clean sensors during downloading, meaning that any biofouling would likely have remained and continued to cause erroneous readings following sensor redeployment (in contrast to our results). Although biofouling did not seem to be a factor in our study, it represents another potential consequence of housing effects on water exchange.

Transferability to other Sensors

Altogether, sufficient water exchange across protective housings is necessary for any *in situ* water chemistry monitoring. Although screens, meshes, and filters can reduce the amount of sediment on the sensor and may offer greater protection against large debris, the results from our study suggest they may result in inaccurate readings. While we focused on only SC sensors, our findings are transferable to a large suite of sensors because flow resistance will impede advection of any solute or suspended particulate. Further, many water quality parameters exhibit similar or even greater temporal variation as SC values, including nutrients and dissolved organic matter (Rode et al., 2016), emphasizing the importance of sensor response to changing concentrations. We note, however, that the transferability of our results to dissolved gas sensors (e.g., dissolved oxygen, CO_2, and CH_4) is less certain due to potential compensation from gas diffusion.

Conclusions

New *in situ* sensor technologies have increased the ability to collect high-frequency surface water quality measurements, making it imperative that researchers use proper installation techniques to ensure data accuracy. Commonly used mesh-covered or screen housings can provide better physical protection for sensors; however, our findings suggest that they can also introduce measurement artifacts due to insufficient mixing between the water outside and inside the housing. Thus, while such protective installations can be useful for measuring water stage (via hydraulic head equilibration), co-located water chemistry sensors should be placed in a separate housing with openings for sufficient water exchange.

Acknowledgments and Data Availability

Funding for this work was provided in part by the Virginia Agricultural Experiment Station and the Hatch Program of the National Institute of Food and Agriculture, U.S. Department of Agriculture.

We ackowledge the following individuals who helped with sensor and housing preparation and installation: Brandon Lester, Tommy Cianciolo, and Zach Perkins.

Data from this paper is permanently archived at https://data.lib.vt.edu/files/df65v800k.

References

Bergamaschi, B. A., Fleck, J. A., Downing, B. D., Boss, E., Pellerin, B. A., Ganju, N. K., . . . Stephenson, M. (2012). Mercury dynamics in a San Francisco estuary tidal wetland: Assessing dynamics using in situ measurements. *Estuaries and coasts*, *35*(4), 1036-1048.

Bischof, S. M., Herwig, B. R., Sebestyen, S. D., Hanson, M. A., Zimmer, K. D., Cotner, J. B., & Kroeger, T. J. (2019). Further Development of a Specific Conductivity Approach to Measure Groundwater Discharge Area within Lakes. *JAWRA Journal of the American Water Resources Association, 55*(2), 485-496.

Clark, E. V., Greer, B. M., Zipper, C. E., & Hester, E. T. (2016). Specific conductance–stage relationships in Appalachian valley fill streams. *Environmental Earth Sciences, 75*(17). doi:10.1007/s12665-016-6026-2

Cox, M. H., Su, G. W., & Constantz, J. (2007). Heat, chloride, and specific conductance as ground water tracers near streams. *Ground Water, 45*(2), 187-195. doi:10.1111/j.1745-6584.2006.00276.x

DiPietro, J. A. (2013). Chapter 13 - Crystalline Deformation Belts. In J. A. DiPietro (Ed.), *Landscape Evolution in the United States* (pp. 197-217). Boston: Elsevier.

Eaton, T. T. (2016). Tidal reversal and flow velocities using temperature and specific conductance in a small wetland creek. *Journal of Hydrology, 542*, 552-563.

Etheridge, J. R., Birgand, F., Osborne, J. A., Osburn, C. L., Burchell, M. R., & Irving, J. (2014). Using in situ ultraviolet-visual spectroscopy to measure nitrogen, carbon, phosphorus, and suspended solids concentrations at a high frequency in a brackish tidal marsh. *Limnology and Oceanography: Methods, 12*(1), 10-22. doi:10.4319/lom.2014.12.10

Gravelle, R. 2015. Discharge estimation: techniques and equipment, in Geomorphological Techniques, Chapter 3.3.5, British Society for Geomorphology, eds. Clark, J., Nield,

Jones, A. S., Aanderud, Z. T., Horsburgh, J. S., Eiriksson, D. P., Dastrup, D., Cox, C., . . . Carling, G. T. (2017). Designing and implementing a network for sensing water quality and hydrology across mountain to urban transitions. *JAWRA Journal of the American Water Resources Association, 53*(5), 1095-1120.

Kaushal, S. S., Likens, G. E., Pace, M. L., Utz, R. M., Haq, S., Gorman, J., & Grese, M. (2018). Freshwater salinization syndrome on a continental scale. *Proc Natl Acad Sci U S A, 115*(4), E574-E583. doi:10.1073/pnas.1711234115

Klammler, H., Newman, M. A., Szilágyi, E., Padowski, J. C., Hatfield, K., Jawitz, J. W., & Annable, M. D. (2007). Initial test results for a passive surface water fluxmeter to measure cumulative water and solute mass fluxes. *Environmental Science & Technology, 41*(7), 2485-2490.

McLaughlin, D. L., & Cohen, M. J. (2011). Thermal artifacts in measurements of fine□scale water level variation. *Water Resources Research, 47*(9).

Moore, R. (2005). Slug injection using salt in solution. *Streamline Watershed Management Bulletin, 8*(2), 1-6.

Pellerin, B. A., Saraceno, J. F., Shanley, J. B., Sebestyen, S. D., Aiken, G. R., Wollheim, W. M., & Bergamaschi, B. A. (2012). Taking the pulse of snowmelt: in situ sensors reveal seasonal, event and diurnal patterns of nitrate and dissolved organic matter variability in an upland forest stream. *Biogeochemistry, 108*(1-3), 183-198.

Rode, M., Wade, A. J., Cohen, M. J., Hensley, R. T., Bowes, M. J., Kirchner, J. W., . . . Jomaa, S. (2016). Sensors in the Stream: The High-Frequency Wave of the Present. *Environ Sci Technol, 50*(19), 10297-10307. doi:10.1021/acs.est.6b02155

Stamp, J., Hamilton, A., Craddock, M., Parker, L., Roy, A. H., Isaak, D. J., . . . Bierwagen, B. G. (2014). *Best practices for continuous monitoring of temperature and flow in wadeable streams*. Washington, DC.

Yu, P., Zeng, Y., Lee, T. S., Chen, X. B., & Low, H. T. (2011). Steady flow around and through a permeable circular cylinder. *Computers & Fluids, 42*(1), 1-12.

Tables

Table 1. Physical dimensions and details of housing types used in the study. Opening size and density reflect dimensions perpendicular to streamflow.

Housing Type	Opening Size (mm)	Opening Density (#/mm)	Housing Length (mm)	Housing Diameter (mm)
Open (OH)	38.1 (ends)	N/A	178	38.1
Holes (HH)	6.3 (holes)	0.08	610	50.8
Screen (SH)	1.3 (slots)	0.2	610	50.8
Mesh (MH)	0.18 (mesh)	3.2	914	50.8

Table 2. Summary statistics for the specific conductance time series, including mean (μ), standard deviation (σ), and coefficient of variation (C.V. (%) = $100\sigma/\mu$). Statistics were calculated using data recorded every 15 minutes between 24 October 2018 and 14 November 2018, which is the period shown in the Figure 2. Statistics for SH at Dismal Creek are not shown due to data gaps.

Dismal Creek	μ (μS cm^{-1})	σ (μS cm^{-1})	C.V. (%)
Open (OH)	21	1.9	9.2
Holes (HH)	22	1.7	7.4
Screen (SH)	–	–	–
Mesh (MH)	38	26	70
No Business Creek	**μ (μS cm^{-1})**	**σ (μS cm^{-1})**	**C.V. (%)**
Open (OH)	11	0.19	1.8
Holes (HH)	11	0.17	1.6
Screen (SH)	8.8	0.43	4.9
Mesh (MH)	20	16	80

Figures

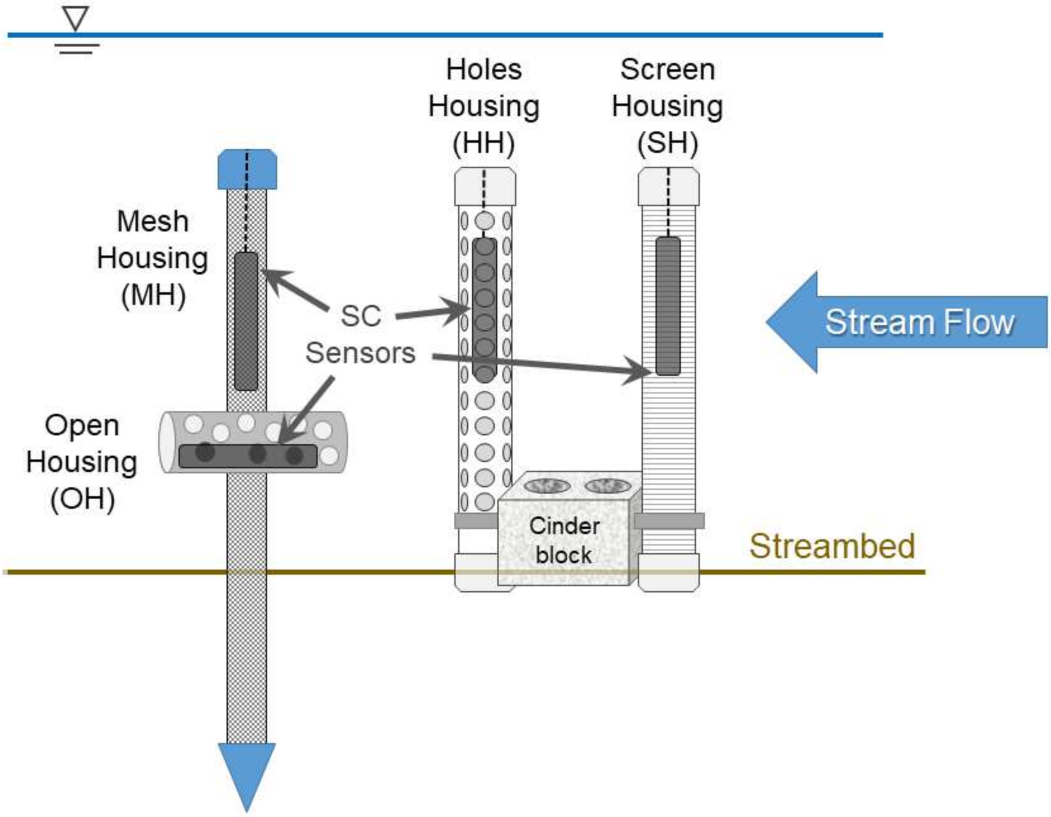

Figure 1. Schematic showing the four housing types and relative position and orientation of the specific conductance (SC) sensors in each. Note that the open housing was attached to the mesh housing in both streams, and the holes and screen housings were both attached to a single cinder block in each stream.

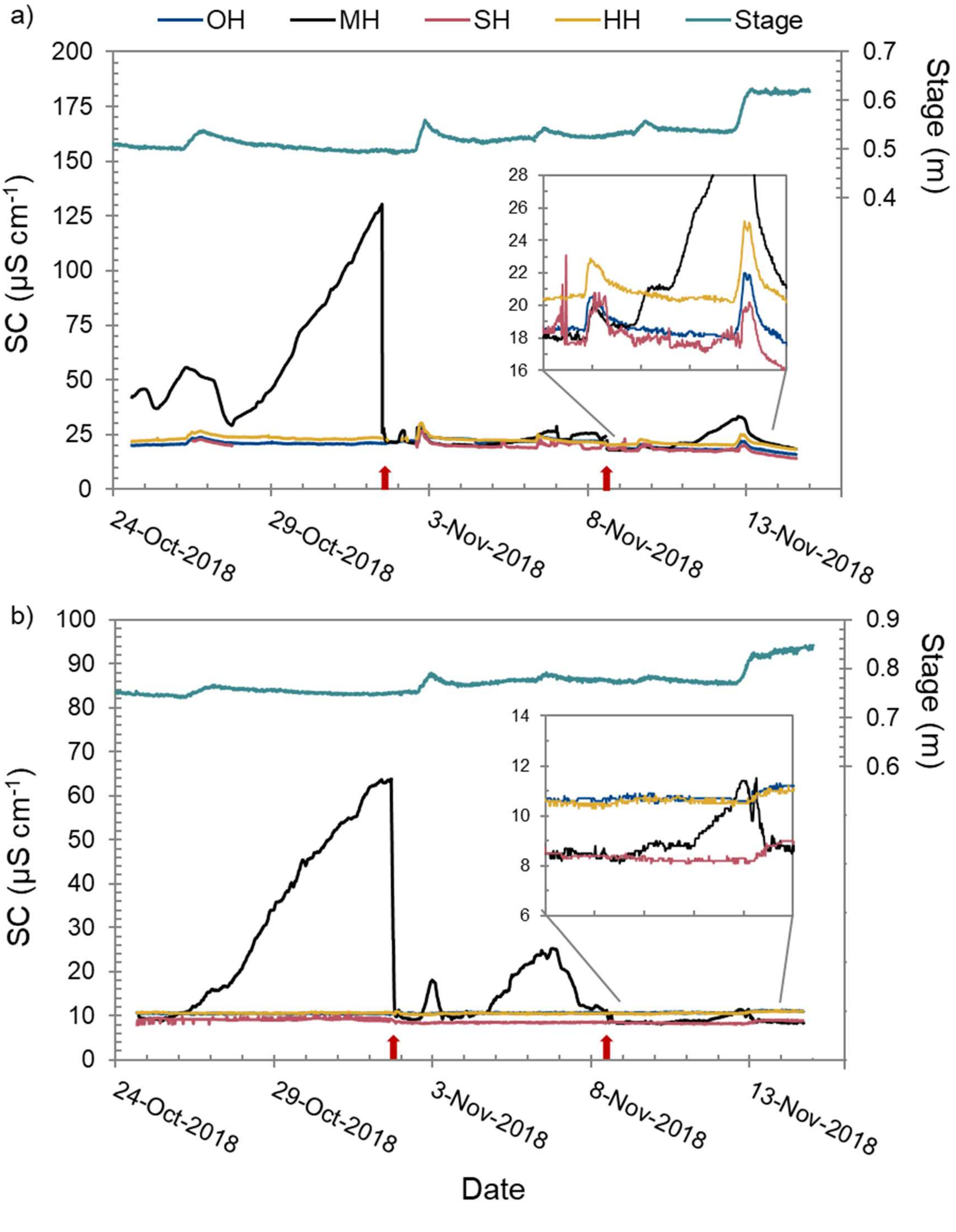

Figure 2. Specific conductance (SC) measured by co-located sensors installed in four different housing types at a) Dismal Creek and b) No Business Creek. Stream stage is shown at top. Red arrows denote sensor data download times. OH = open housing; MH = mesh housing; SH = screen housing; HH = holes housing. Here we present data collected between 24 October 2018 and 14 November 2018, which encompassed a range of flow conditions and revealed characteristic behaviors of the different sensor housings.

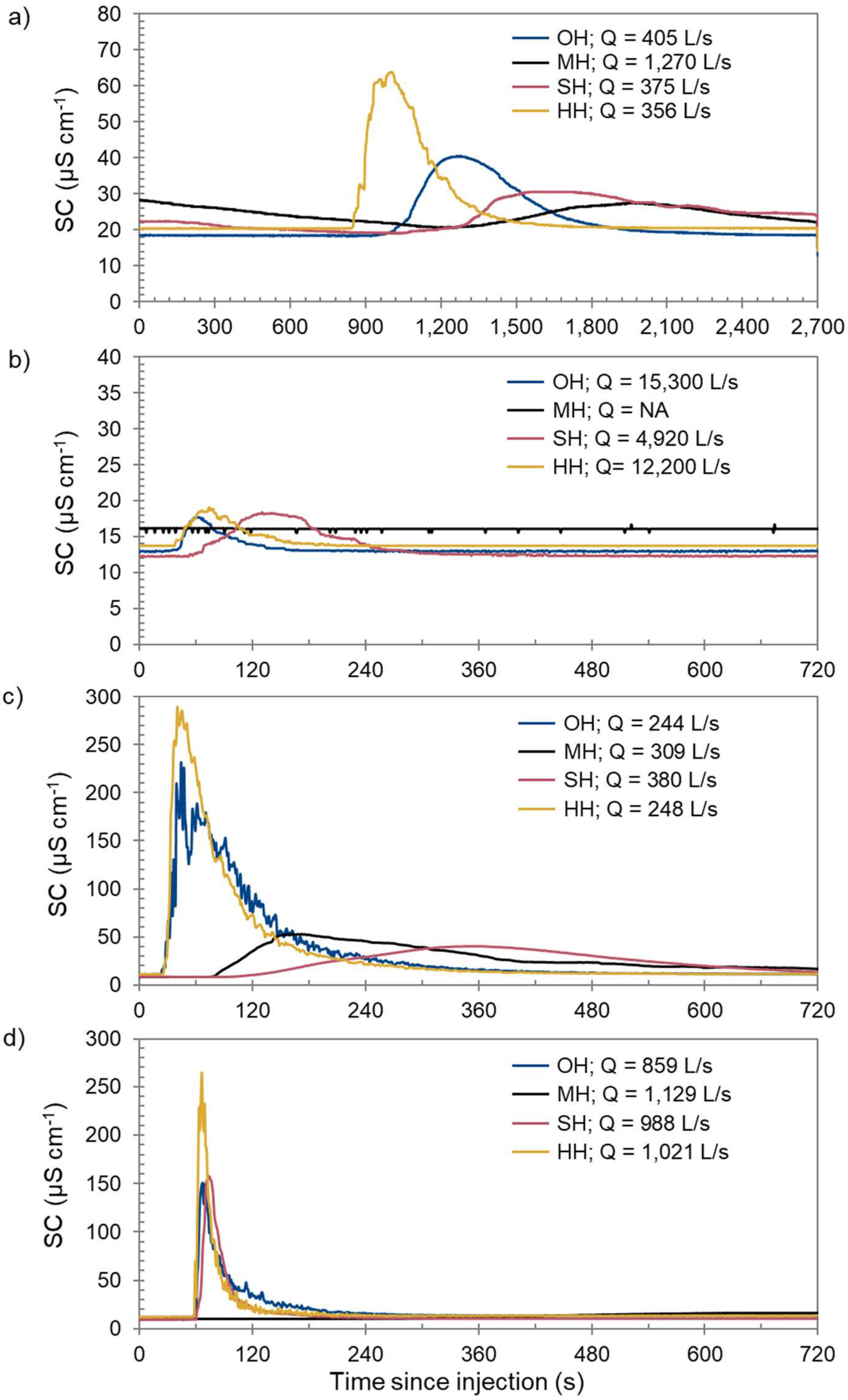

Figure 3. Comparison of specific conductance (SC) measurements in the four different housing types during salt tracer tests at relatively a) low flow (stage = 0.53 m) and b) high flow (stage = 0.74 m) conditions at Dismal Creek, and at relatively c) low flow (stage = 0.78 m) and d) high flow (stage = 0.94 m) conditions at No Business Creek. OH = open housing; MH = mesh housing; SH = screen housing; HH = holes housing. Discharge (Q) values indicated in each legend were calculated based on the measured SC changes within each housing type.

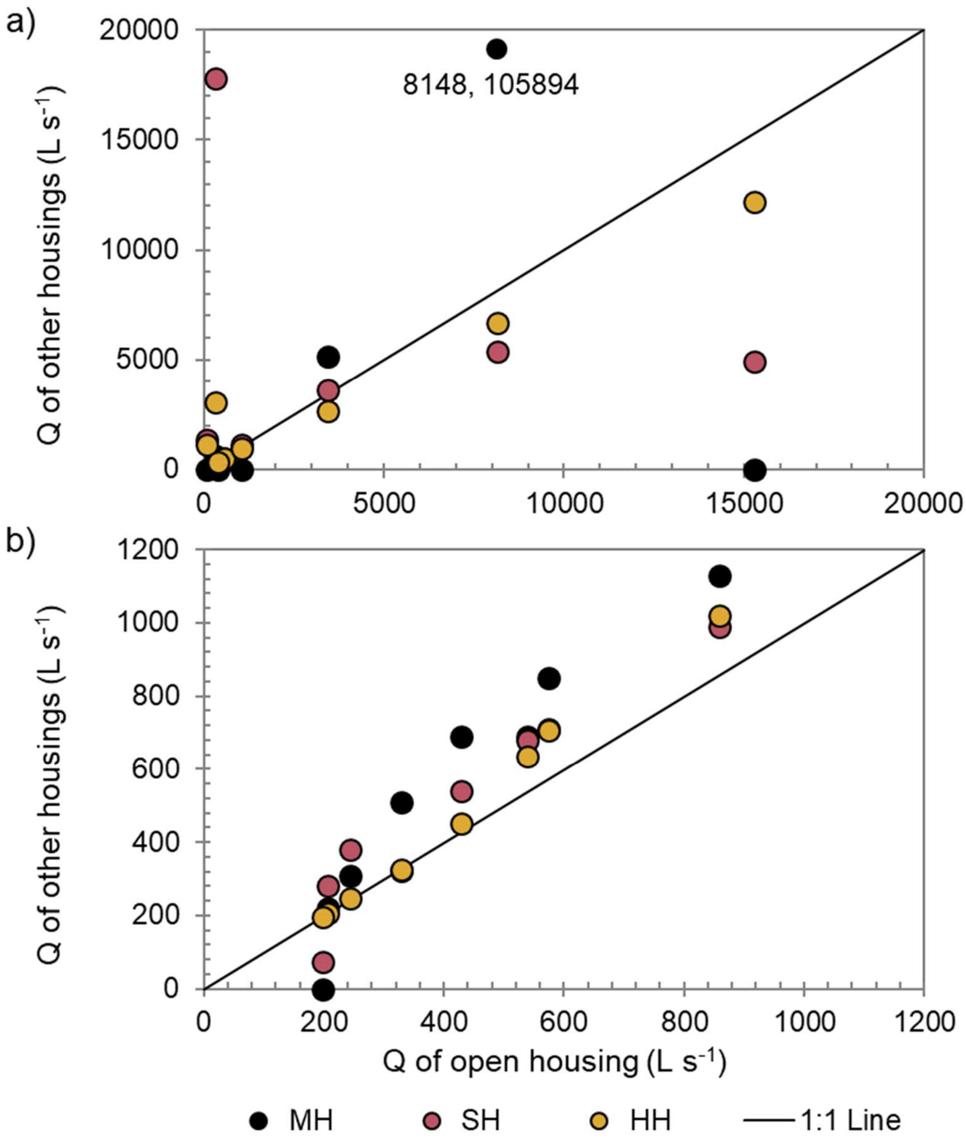

Figure 4. Comparison of calculated discharge, Q (L s^{-1}), based on SC measurements in three housing options (MH = mesh housing, SH = screen housing, and HH = holes housing) versus the open housing (OH) at a) Dismal and b) No Business Creeks. The black lines indicate 1:1 relationships.