LABORATORY EVALUATION OF CONDUCTIVTY SENSOR ACCURACY AND TEMPORAL CONSISTENCY[1]

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Abstract. The focus on specific conductivity ($EC_{25°C}$) in the Appalachian Coal Belt Region of the U.S. has highlighted the need to obtain accurate $EC_{25°C}$ measurements, particularly in light of the U.S. Environmental Protection Agency (USEPA) guidance that water discharged from mine sites in this region should have $EC_{25°C}$ levels less than 300-500 µS cm^{-1}. Being able to accurately determine the $EC_{25°C}$ levels of mine discharged waters has significant implications for the USEPA as well as mine operators particularly when $EC_{25°C}$ levels approach this designated threshold. Presently, a number of sensors are available on the market for recording $EC_{25°C}$ measurements; however, a detailed study comparing sensor performance under controlled conditions (e.g. temperature and $EC_{25°C}$ levels) has not been performed. The objectives of this paper were to 1) evaluate sensor measurement stability over time (i.e. consistency) and 2) evaluate sensor accuracy of four commonly used sensors YSI 6600 V2-4 data sonde, HOBO U-24-001, Solinst Model 3001 LTC Levelogger Junior, and In-situ Aqua TROLL 100 at seven temperatures, ranging from 0 to 35°C, for six NIST traceable $EC_{25°C}$ standards, ranging from about 5 to 10,000 µS cm^{-1}. Results indicated that three of the four sensors recorded consistent $EC_{25°C}$ values over time for the majority of the given temperatures while the Onset HOBO U24-001 displayed temporal fluctuations for most of the temperatures. Pair-wise comparisons demonstrated that these temporal fluctuations were present most often at the highest $EC_{25°C}$ tested, 10,000 µS cm^{-1}. With regards to accuracy, the Onset HOBO U24-001 consistently overestimated $EC_{25°C}$ values while the other sensors tended to underestimate $EC_{25°C}$ values. Examination of the individual sensors within each sensor types revealed that in many instances at least one sensor performed quite differently than the others of the same type. As such, careful attention should be paid to individual sensor performance, particularly when the sensor is used for regulatory enforcement.

Additional Key Words: Coal mining, Appalachia, water quality.

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Introduction

Electrical conductivity (EC) is the measure of the ability of water to pass an electric current (Hayashi, 2004) and is a function of the both types and quantities of dissolved substances or ions (e.g. Ca, Mg, Na, K, SO_4^{2-}, HCO_3^-, Cl^-) in solution (Chapman et al., 2000; Wagner et al., 2006). Increases in EC are linked to increases in the concentration of ions. For this reason combined with the fact that EC measurements can be taken rapidly and inexpensively, EC serves a common surrogate for total dissolved solids (TDS) concentrations (Tchobanoglous et al., 2003). Equation 1 can be used to estimate TDS concentrations for a wide spectrum of water samples given EC values.

$$\text{TDS}\ (\text{mg L}^{-1}) \cong \text{EC}(\mu S\ \text{cm}^{-1}) \times (0.55 - 0.70) \quad (1)$$

In addition to ion concentrations, EC is largely dependent on temperature, and thus needs to be corrected to a common temperature (25°C) to allow for comparison of values across sites and times (Hayashi, 2004). Such temperature corrected EC is termed specific conductance ($EC_{25°C}$).

The composition of ions comprising TDS is affected by a number of factors such as geology, land use, and precipitation (Kimmel and Argent, 2010; Barton, 2011). Presently, no national water-quality criterion exists for TDS (USEPA, 2012). While elevated TDS and hence conductivity levels can negatively impact aquatic life (Black, 1977; Pond et al., 2008), what are more important are the combinations and concentrations of ions within the water (Chapman et al., 2000). As noted by Barton (2011), two streams can have good water quality and high biodiversity but very different conductivity levels (50 µS cm^{-1} versus 500 µS cm^{-1}).

Research by Pond et al. (2008) found a negative correlation between biologic condition and $EC_{25°C}$. Significantly fewer taxa and a lower percentage of insects belonging to the Ephemeroptera family were found in West Virginia streams when $EC_{25°C}$ levels were greater than 500 µS cm^{-1}. In large response to this study, the USEPA issued guidance in April 2010 (final in July 2011) indicating that water discharged from mines in Appalachia should have $EC_{25°C}$ levels below 300-500 µS cm^{-1} (USEPA, 2011; Barton, 2011). Being able to accurately determine $EC_{25°C}$ levels of mine discharge waters has significant implications for the USEPA as well as mine operators particularly as $EC_{25°C}$ levels approach the designated thresholds. Presently, a number of conductivity sensors are available on the market; however, a detailed study comparing sensor performance under controlled conditions has not been performed.

This study was conducted to compare the performance of four commercially available continuously recording conductivity sensors. Objectives of the study were to: (1) evaluate sensor measurement stability over time (i.e. consistency), and (2) evaluate sensor.

Methods

Experimental Procedure

A laboratory experiment was conducted in 2010 at the University of Kentucky Biosystems and Agricultural Engineering Water Quality Laboratory in Lexington, Kentucky. Four commercially available conductivity sensors, capable of continuous monitoring, were evaluated: YSI 6600 V2-4 data sonde, HOBO U-24-001, Solinst Model 3001 LTC Levelogger Junior, and In-situ Aqua TROLL 100. Henceforth, the sensors will be referred to as YSI, HOBO, Solinst, and Aqua TROLL, respectively. A total of six YSI, six HOBO, three Solinst, and three Aqua TROLL sensors were tested. The difference in the number of each type of sensor tested was due to budgetary constraints. Each sensor was tested at seven temperature levels (5, 10, 15, 20, 25, 30 and 35°C) for six National Institute of Standards and Technology (NIST) traceable specific conductivity standards (5.66, 10.08, 98.9, 999, 1,411 and 9,986 μS cm^{-1}) resulting in 42 temperature and conductivity combinations. Conductivity and temperature data were recorded at 15 second intervals for a 15 minute period for the YSI, HOBO, and Solinst sensors yielding 60 observations per temperature and conductivity combination. For the Aqua Troll sensors, the minimum sampling interval was one-minute, so 15 observations were obtained for each temperature and conductivity combination.

All testing occurred in a Lauda Ecoline Staredition RE 220 water bath (Lauda-Königshofen, Germany) to allow for precise temperature control. Conductivity sensors were placed in the respective standards, and the temperature in the water bath was allowed to equilibrate at each tested temperature for 45 minutes prior to the collection of data. Hollow polypropylene balls were placed on the water surface of the water bath, in unoccupied locations, to prevent evaporation and to help maintain a constant temperature in the water bath by providing a thermal insulation barrier between the water and the surrounding air. For the YSI and Aqua TROLLs, the sensors were placed in their respective calibration cups. Calibration cups were not provided for the Solinst and HOBO conductivity sensors. As such, conductivity standards were placed in 200 mL beakers, and the tops of the beakers were covered with parafilm to prevent evaporation.

In all instances, a sufficient volume of conductivity standard was added to ensure both the temperature and conductivity components of the sensors were fully submerged.

Sensor Description

A brief description of each sensor evaluated in the study follows. The descriptions include information on operating parameters, calibration technique, and the manufacturer of the sensors.

YSI The YSI data sonde is equipped with a 6560 conductivity and temperature probe to discretely or continuously record data. The 6560 sensor measures conductivity using four pure nickel electrodes: two electrodes are current driven while the other two measure voltage drop, which is converted into a conductance value. The full conductivity range of the sensor is 0 to 100,000 µS cm^{-1} with a reported accuracy of ±0.5 percent of the reading plus 1 µS cm^{-1}. Resolution of the conductivity sensor is range dependent and varies from 1 to 100 µS cm^{-1}. The conductivity sensor is very linear over the full conductivity range. Specific conductance is determined using equation 2.

$$EC_{25^{\circ}C} = \frac{EC}{1 + TC \times (T - 25)} \qquad (2)$$

The variable $EC_{25^{\circ}C}$ is specific conductance (conductivity corrected to 25ºC), µS cm^{-1}; EC is the raw conductivity value (non-temperature corrected conductivity), µS cm^{-1}; TC is temperature coefficient (0.0191 per degree Celsius); and T is the raw temperature value. Temperature is measured using a thermistor with a range of -5 to 50ºC and an accuracy of ±0.15ºC. Resolution of the temperature sensor is 0.01ºC.

Calibration of the conductivity sensor was performed per manufacturer's specifications. The manufacturer supplied calibration cups were filled with manufacturer recommended NIST traceable calibration solution (10,000 µS cm^{-1}) ensuring the sensor was fully submerged. Next, the YSI data sonde with the 6560 conductivity and temperature probe was shaken vigorously to expel any bubble from the conductivity sensor. No calibration of the temperature sensor was required. The YSI data sondes and 6560 conductivity and temperature probes were manufactured by YSI Incorporated, Yellow Springs, OH, USA. (www.ysi.com).

HOBO The HOBO U24-001 is a continuous conductivity and temperature data logger designed for freshwater environments. The HOBO is a non-contact sensor meaning a magnetic field is used to determine conductivity (Rizzoni, 1993). The full calibrated conductivity range for the sensor is 0 to 10,000 µS cm^{-1} with a full range accuracy of 3 percent of the reading or 20 µS cm^{-1}, whichever is greater. Resolution of the conductivity sensor is 1 µS cm^{-1}. Temperature is measured using a thermistor with a range of 5 to 35ºC and an accuracy of ±0.1ºC. Resolution of the temperature sensor is 0.01ºC.

Calibration of the conductivity sensors was performed per manufacturer's specifications. The manufacturer states that temperature and conductivity readings, from a secondary source, are required at the beginning and end of deployment to assist in post-processing of data and to help account for sensor drift that may occur during deployment. Temperature readings were obtained from the water bath while the NIST specified conductivity levels were used. The HOBO conductivity sensors were manufactured by Onset Computer Corporation, Cape Cod, MA, USA. (www.onsetcomp.com).

Solinst The Solinst Model 3001 Levelogger Junior continuously measures water level in addition to conductivity and temperature. The sensor measures conductivity using four Pt electrodes: two drive electrode and two sensing electrode. The full conductivity range of the sensor is 0 to 80,000 µS cm^{-1} with a reported accuracy of 2 percent of the reading or 20 µS cm^{-1}. Resolution of the conductivity sensor is 1 µS cm^{-1}. Temperature is measured using a platinum resistance temperature detector (RTD) with a range of 0 to 40°C and an accuracy of ±0.1ºC. Resolution of the temperature sensor is 0.1ºC.

The Solinst sensors used in this study were factory calibrated and deployed for the first time during this study. Since the manufacturer states that the sensor requires minimal calibration (e.g. twice per year), the sensors were not recalibrated prior to the study. No calibration of the temperature sensor was required. The Solinst data loggers were manufactured by Solinst Canada Ltd., Georgetown, Ontario, Canada. (www.solinst.com).

Aqua Troll The Aqua Troll 100 conductivity logger is a continuous conductivity and temperature data logger. Conductivity is measured using a balanced four-electrode conductivity cell: two electrodes are driven and two electrodes are sensing. The full conductivity range of the sensor is 5 to 100,000 µS cm^{-1} with a reported accuracy of ±0.5 percent of reading plus 1 µS cm^{-1} when less than 80,000 µS cm^{-1}; ±1.0 percent of reading when above 80,000 µS cm^{-1}. Temperature is measured using a thermistor with a range of -20 to 65°C and an accuracy of ±0.1ºC. Resolution of the temperature sensor is 0.01ºC.

The Aqua Troll data loggers used in this study were factory calibrated and deployed for the first time during this study. As recommended by the manufacture, the specific conductivity reading was checked with the manufacturer supplied solution prior to use. As the reading was accurate, the manufacturer stated that no further calibration was required. No calibration of the temperature sensor was required. The Aqua Troll data loggers were manufactured by In-Situ Incorporated, Fort Collins, CO, USA (www.in-situ.com).

Statistical Analysis

The statistical analysis component of the project consisted of evaluating the temporal stability of the specific conductivity readings produced by the sensors over time as well as the accuracy of these readings (i.e. how well did the measured conductivity readings match the NIST conductivity standard values). A significant level of $p=0.05$ was used for all statistical analyses. All statistical analyses were performed using SAS version 9.2 (SAS Institute, Inc., 2008).

The first step in the data analysis was to examine the performance of each sensor type (YSI, HOBO, Solinst and Aqua Troll) over time. For each sensor, linear mixed models (PROC MIXED) were used to examine the temporal stability (i.e. consistency) of the specific conductivity measurements at each temperature level (5, 10, 15, 20, 25, 30 and 35°C) over all specific conductivity standards combined. Wang and Goonewardene (2004) noted that the mixed model approach is preferred when dealing with repeated measures data because this model offers the user better capabilities with covariance structure modeling and missing observation management than traditional approaches such as ANOVA and MANOVA. Sensor readings were the response variable, $EC_{25°C}$ standard levels were the categorized variable, time was the continuous variable, and the interaction of the $EC_{25°C}$ standards levels and time were the fixed effects. The covariance structure used was AR(1) to account for autocorrelation resulting from repeated $EC_{25°C}$ measurements. The AR(1) covariance structure assumes observations closer together are more highly correlated (Kleinbaum et al., 2008). The presence of a significant $EC_{25°C}$ standard level and time interaction indicated that, at the tested temperature, the $EC_{25°C}$ readings for all $EC_{25°C}$ standard levels combined fluctuated over time. The null hypothesis that the sensors did not exhibit temporal fluctuations in $EC_{25°C}$ measurements was evaluated using the *F* test.

If the sensors displayed temporal instability meaning a significant $EC_{25°C}$ standard level and time interaction was found, then pair-wise comparisons between all $EC_{25°C}$ standard levels, for each sensor at each temperature level, were conducted. The pair-wise comparisons offered insight into which $EC_{25°C}$ standard level and temperature level combinations resulted in the presence of significant fixed effects (e.g. $EC_{25°C}$ standard level and time interactions, time). For each $EC_{25°C}$ standard value at each temperature level, a slope of zero indicated that no significant temporal changes in $EC_{25°C}$ readings were present. The null hypothesis that the slopes did not differ (i.e. the slopes were zero) was evaluated using the *F* test.

To test the ability of the sensors to accurately measure $EC_{25°C}$ at each temperature level, a second set of linear mixed models (PROC MIXED) were developed for each sensor. Sensor $EC_{25°C}$ readings were the response variable and $EC_{25°C}$ standard values were the continuous predictor variable. To achieve convergence, a compound symmetry covariance structure was used. The 95 percent confidence intervals of the linear slopes were calculated for each sensor and each temperature level. The accuracy of each sensor at each temperature level was determined by comparing the estimated slope and intercept with one and zero, respectively.

Results

Temporal Performance

The results of the linear mixed models evaluating temporal stability of the $EC_{25°C}$ measurements at each temperature level are provided in Table 1 with the average slope of all sensors of a particular type as shown in Fig. 1a. If the sensors exhibited temporal stability, then slopes of $EC_{25°C}$ values over time should equal zero. Neither the YSI nor the Aqua Troll exhibited temporal fluctuations in $EC_{25°C}$ measurements for any of the temperature measurements. Figures 1b and 1c show the stability of the $EC_{25°C}$ readings over the 15-minute period for the YSI and Aqua Troll sensors, respectively, at an $EC_{25°C}$ of 1,411 µS cm^{-1} and a temperature of 15°C. Temporal fluctuations were noted for the Solinst sensors only for the 35°C temperature level. Otherwise, as seen in Fig. ld, no significant temporal fluctuations were noted. For the HOBO sensors, however, significant temporal fluctuations were noted for all of the temperature levels except 30 and 35°C (Fig. 1e).

Table 1. Performance of conductivity sensors with regards to temporal measurement stability (H_o = sensor does not exhibit temporal fluctuations in specific conductivity measurements).

Temp. (ºC)	YSI			HOBO			Solinst			Aqua Troll		
	p-value[1]	F_{calc}	Reject H_o?	*p*-value	F_{calc}	Reject H_o?	*p*-value	F_{calc}	Reject H_o?	*p*-value	F_{calc}	*Reject H_o?*
5	1.0000	20.55	No	<0.0001	0.00	Yes	1.000	0.01	No	1.000	0.01	No
10	0.9999	14.25	No	<0.0001	0.01	Yes	1.000	0.00	No	1.000	0.00	No
15	1.0000	18.03	No	<0.0001	0.00	Yes	1.000	0.00	No	1.000	0.00	No
20	0.9736	30.89	No	<0.0001	0.17	Yes	1.000	0.00	No	1.000	0.00	No
25	1.0000	97.95	No	<0.0001	0.00	Yes	0.9192	0.29	No	1.000	0.00	No
30	1.0000	1.24	No	0.2878	0.00	No	0.1755	1.54	No	1.000	0.00	No
35	1.0000	0.77	No	0.5688	0.00	No	<0.0001	7.95	Yes	1.000	0.00	No

[1]Statistically significant at the p=0.05 level.

As seen in Fig. 1e for a specific conductance of 1,411 µS cm^{-1} and a temperature of 15°C, the readings from the HOBO sensors tended to drift over the 15-minute monitoring period, in this case, upward. Important to note is that the presence of significant temporal fluctuations does not indicate the sensors performed in this manner for all temperature and conductivity combinations. Instead, the presence of significant temporal fluctuations means that for at least one conductivity level, at the specified temperature level, the resulting slope of conductivity versus time was significantly different than zero.

For Fig. 1a-1e, an $EC_{25ºC}$ value of 25 µS cm^{-1} and a temperature of 15ºC were chosen for display as those values was the closest, of the standard levels and temperature intervals, to the mean $EC_{25ºC}$ values and water temperatures recorded by Fritz et al. (2010) at valley fill sites in eastern Kentucky. Fritz et al. (2010) recorded average $EC_{25ºC}$ of about 2,500 µS cm^{-1} and water temperatures of about 13ºC. Results from the $EC_{25°C}$ pair-wise comparisons provided insight into which $EC_{25ºC}$ levels resulted in temporal fluctuations (i.e. slope $\neq$ 0) for the Solinst and HOBO sensors. At an $EC_{25°C}$ level of 9,986 µS cm^{-1}, the HOBO sensors consistently displayed temporal fluctuations (5, 10, 15, 20, and 25°C). Like the HOBO sensors, the Solinst sensors exhibited temporal fluctuations at 9,986 µS cm^{-1} (35°C). For both sensors, no significant differences were noted for any other $EC_{25°C}$ levels. These results were somewhat surprising for the Solinst sensors as they are rated for use up to 80,000 µS cm^{-1} and a temperature of up to 40°C. The $EC_{25°C}$ and temperature combination of 9,986 µS cm^{-1} and 35°C was within this

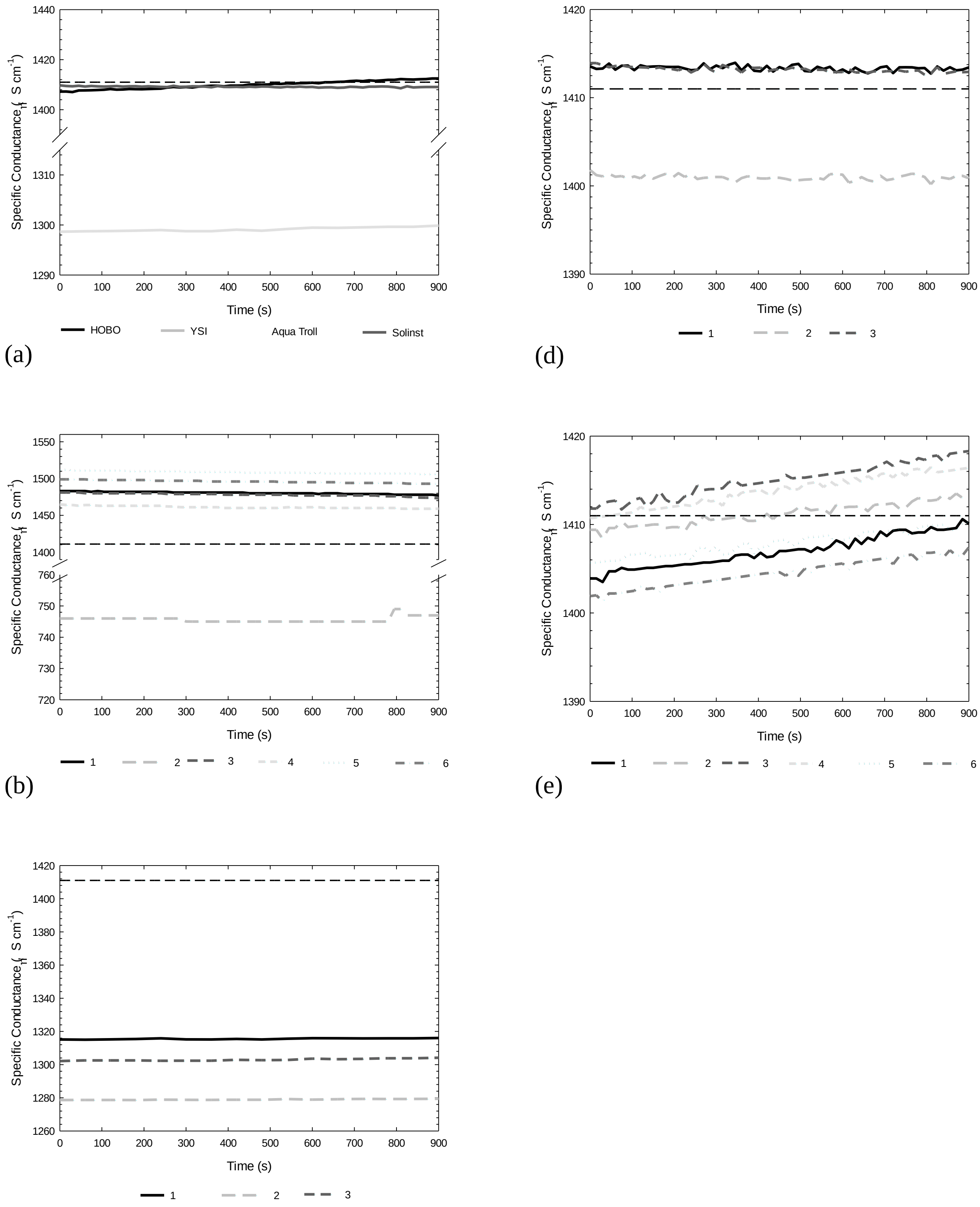

Figure 1. Temporal fluctuations associated with 1,411 µS cm^{-1} EC$_{25°C}$ and 15ºC temperature level for (a) sensor type, (b) YSI sensors, (c) Aqua Troll sensors, (d) Solinst sensors, and (e) HOBO sensors. *Black dashed line represents NIST standard. Numbers 1, 2, 3, 4, 5, and 6 represent the individual sensors tested within a sensor type.*

range. However, for the HOBO sensors, the temporal fluctuations were less surprising as the $EC_{25°C}$ level for the test (9,986 μS cm^{-1}) was just under the stated full calibrated range of 10,000 μS cm^{-1} for these sensors. For the HOBO sensors, these results are highlighted in Fig. 2a-e at the 15°C temperature level. For the Solinst sensors, these results are highlighted in Fig. 2f.

<u>Accuracy</u>

The results of the linear mixed models testing the ability of the sensors to accurately measure specific conductance at each temperature level are presented in Table 2. For all sensors at all temperature levels, the slopes of the lines generated from regressing measured specific conductance values on NIST standard conductance values (1:1 lines) differed statistically from one; however many of these values were quite close to one. For the YSI and Aqua Troll sensors, the slopes were consistently less than one, for all temperature levels, indicating that these sensors tended to under-predict or under-measure the true specific conductance values (Fig. 3a-3b). Except for the 5°C temperature level, the Solinst sensors also under-predicted the true specific conductance values (Fig. 3c). As for the HOBO sensors, both under- and over-prediction of true specific conductance values was seen (Fig. 3d). In all cases, the intercepts did not significantly differ from zero.

Table 2. Results of regressing measured specific conductivity versus specific conductivity standard values (H_o = slope equals one and intercept equals zero).[1, 2]

Temperature (°C)	YSI		HOBO		Solinst		AquaTroll	
	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept
5	0.947^r	267.240	1.002^r	0.166	1.008^r	13.968	0.867^r	36.436
10	0.926^r	273.750	0.998^r	0.841	0.974^r	17.513	0.864^r	39.788
15	0.891^r	268.350	0.996^r	0.345	0.953^r	20.467	0.861^r	42.713
20	0.867^r	259.870	0.997^r	-0.478	0.939^r	24.012	0.861^r	45.699
25	0.831^r	280.020	1.002^r	-1.971	0.932^r	22.371	0.862^r	53.588
30	0.848^r	77.792	1.003^r	0.250	0.937^r	21.348	0.930^r	4.705
35	0.850^r	82.992	0.999^r	-1.619	0.919^r	29.944	0.931^r	31.817

[1]Coefficient of determination (R^2) values for all regressed measured versus standard specific conductivity comparisons were greater than 0.999.
[2]The superscript r indicates that the null hypothesis was rejected at the p=0.05 level.

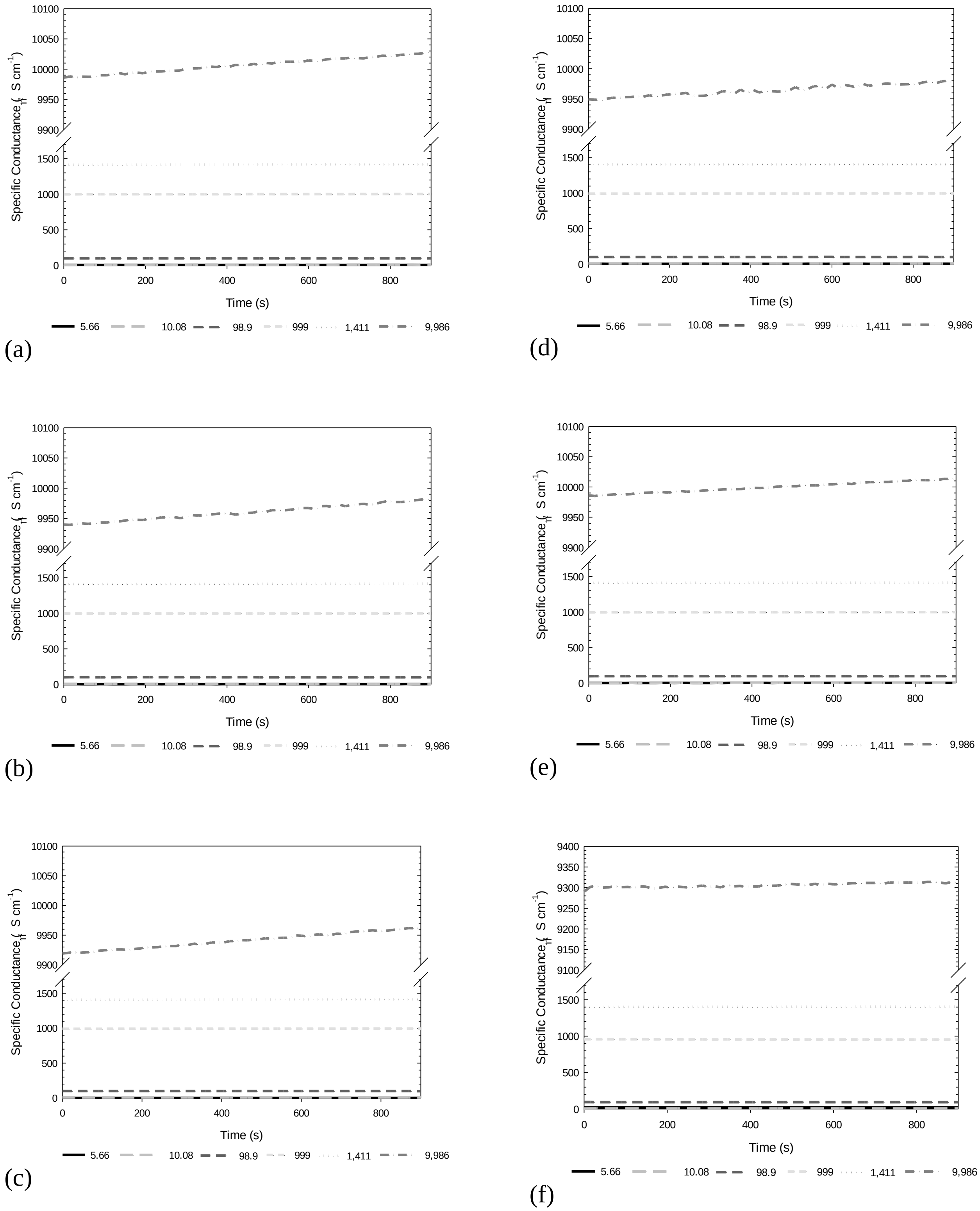

Figure 2. Pair-wise comparisons for all $EC_{25ºC}$ levels for HOBO at (a) 5ºC, (b) 10ºC, (c) 15ºC, (d) 20ºC, and (e) 25ºC and (f) Solinst at 35ºC. *Black dashed line represents NIST standard. Numbers 5.66, 10.08, 98.9, 999, 1411, and 9986 are $EC_{25ºC}$ standards values.*

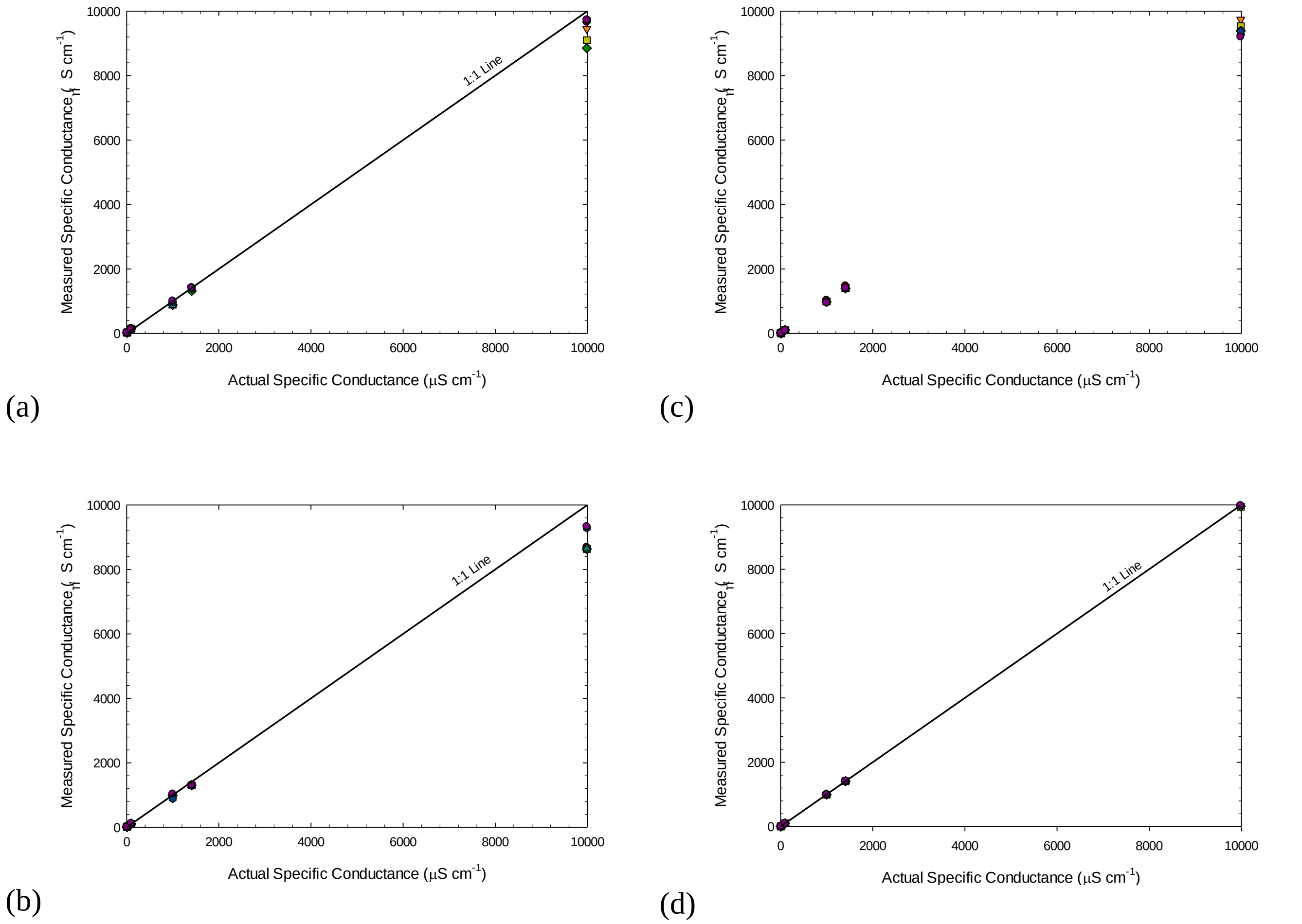

Figure 3. Actual $EC_{25°C}$ plotted against measured $EC_{25°C}$ of the (a) YSI, (b) Aqua Troll, (c) Solinst, and (d) HOBO sensors.

As seen in Fig. 3, the higher conductance level of 9,986 µS cm^{-1} was influential in evaluating sensor performance, particularly for the YSI, Aqua Troll, and Solinst sensors. For all three of these sensor types, the under-prediction of specific conductance resulted in reduced linear slope estimates and likely increased intercept estimates. Though the slope of the 1:1 line for the HOBO sensors was statistically different than one, it appeared to have the best fit.

These results are somewhat surprising as the YSI, Aqua Troll, and Solinst sensors are rated for much higher specific conductance levels while the HOBO was operating near its limits.

<u>Individual Sensor Variation</u>

Also of interest is the variation in individual sensor performance. Figures 1a-1e display individual sensor specific conductance measurements at the 1,411 µS cm^{-1} specific conductance level and the 15°C temperature level. As seen in these figures, though temporal trends are the same for all sensors of a particular type, individual sensors can perform quite differently from one another. For the YSI sensors, five sensors over-predicted specific conductance by about 50 to 150 µS cm^{-1} while one sensor under-predicted by about 650 µS cm^{-1}. For the Aqua Troll sensors, all three sensors under-predicted by about 100 to 140 µS cm^{-1}. The Solinst sensors were all quite close to the standard value of 1,413 µS cm^{-1}. The HOBO sensors, though displaying temporal fluctuations, were closely grouped with all sensors measuring within less than 10 µS cm^{-1} of each other.

Conclusions

Four $EC_{25°C}$ sensor types (six YSI, six HOBO, three Solinst, and three Aqua Troll) were evaluated at seven temperature levels (5, 10, 15, 20, 25, 30 and 35°C) and six NIST traceable $EC_{25°C}$ standards (5.66, 10.08, 98.9, 999, 1,411 and 9,986 µS cm^{-1}) to assess sensor performance with regards to temporal stability and accuracy. All sensors were factory calibrated or locally calibrated per manufacturer's recommendations. The YSI and Aqua Trolls sensors exhibited temporal stability over the $EC_{25°C}$ and temperature ranges evaluated while the Solinst and HOBO sensors did not. For the Solinst sensors, temporal fluctuations were found only at 35°C; such fluctuations were noted at 5, 10, 15, 20, and 25°C for the HOBO sensors. Results of pair-wise comparisons for the sensors demonstrating temporal fluctuations found that the highest tested $EC_{25°C}$ of 9,986 µS cm^{-1} consistently had a different slope, and hence a different response. With regards to accuracy, regression of measured $EC_{25°C}$ values on NIST standard conductance values revealed that, for all sensor types, slopes differed from one. The driver of this difference appeared to be the higher specific conductance level of 9,986 µS cm^{-1} particularly for the YSI, Aqua Troll, and Solinst sensors all of which are rated for much higher $EC_{25°C}$ values.

Examination of the individual sensors within each sensor type revealed that in many instances at least one sensor performed quite differently than the others of the same type. For the examples presented herein for the $EC_{25°C}$ and temperature combination of 1,411 µS cm^{-1} and 15°C, which are levels common for waters discharging mined lands (Fritz et al., 2010), within sensor type differences could be relatively large (~150 µS cm^{-1} for the YSIs; ~140 µS cm^{-1} for the Aqua Trolls) or small (~10 µS cm^{-1} for the HOBOs; ~5 µS cm^{-1} for the Solinsts). Careful attention should be paid to such differences in individual sensor performance, particularly when the sensor is used for regulatory enforcement. For the sensors tested, it is quite possible that one sensor could indicate a stream was in compliance with the 300-500 µS cm^{-1} threshold established by the USEPA (USEPA, 2011) while another sensor of the same type could indicate non-compliance. It is recommended that $EC_{25°C}$ sensors used in instances where the determination of regulatory compliance be regularly checked against NIST $EC_{25°C}$ standards.

In addition to performance, the choice of which $EC_{25°C}$ sensor to purchase also requires consideration of costs, both unit and fixed, as well as additional parameters that a particular sensor can monitor and calibration needs of the sensor. For the sensor types evaluated, costs varied considerably as seen in Table 3. The YSI data sonde had the largest initial cost at $7,000 U.S. (sensor and fixed software and communications costs); however, the YSI also had the capability of monitoring the largest number of parameters. Additional components can be added to the YSI data sonde to allow the simultaneous monitoring of rhodamine, turbidity, dissolved oxygen, water depth, pH, ORP, and blue-green algae in addition to $EC_{25°C}$ and temperature. Of the other three sensors, the Solinst was the only one that simultaneously measured another parameter in addition to $EC_{25°C}$ and temperature. The Solinst, at a cost of $1,385 U.S. (sensor and fixed software and communications costs) also measures water level. With regards to calibration, the HOBO sensors are the only ones to require a secondary device to measure specific conductivity and temperature at the beginning and ending of deployment to account for sensor drift.

Table 3. Cost comparison of tested specific conductivity sensors.

Sensor	Sensor Unit Cost ($U.S)	Software and Communications Fixed Cost ($U.S)[2]	Parameters Monitored
YSI	6,450[1]	550	$EC_{25°C}$, temperature[4]
HOBO	700	450[3]	$EC_{25°C}$, temperature
Solinst	1,200	185	$EC_{25°C}$, temperature, water level
Aqua Troll	1,800	500	$EC_{25°C}$, temperature

[1] $EC_{25°C}$ and temperature sensors are supplied with sonde. Measurement of additional parameters possible with the purchase of additional add-on sensors. These costs are for each site monitored.
[2]Includes software for managing data and download and communications cables. These costs are fixed regardless of the number of sites monitored.
[3]HOBO sensors require $EC_{25°C}$ and temperature measurements from a secondary device for data post-processing. Secondary measurements must be taken at the beginning and ending of deployment. The costs of a secondary device are not included in the table.
[4]Additional components can be added to sonde to measure rhodamine, turbidity, dissolved oxygen, water level, pH, ORP, and blue-green algae.

As the results of this study provide insight into conductivity sensor performance with regards to temporal stability and accuracy in a controlled environment, care should be taken when extrapolating these results to field conditions. Under field conditions, natural conductivity levels can fluctuate widely and sensor fouling can occur. These factors are expected to affect sensor accuracy to a greater extent than what was recorded in this study where conductivity levels were steady and no fouling was present. Future work is required to evaluate the performance of conductivity sensors operating under a wide-range of field conditions (e.g. temperature and $EC_{25°C}$ variations).

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