ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD):

SURFACE WATER ELEVATION

PREPARED BY	ORGANIZATION	DATE
Jesse Vance	AQU	11/30/2016
Charles Bohall	AQU	09/20/2013

APPROVALS	ORGANIZATION	APPROVAL DATE
Laura Leyba-Newton	ENG	06/26/2018
Santiago Bonarrigo	ENG	07/05/2018

RELEASED BY	ORGANIZATION	RELEASE DATE
Judy Salazar	CM	07/05/2018

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Change Record

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A	07/05/2018	ECO-04914	Initial Release

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LIST OF TABLES AND FIGURES

1 DESCRIPTION

Contained in this document are details concerning surface water elevation measurements made at all NEON aquatic sites. Specifically, the processes necessary to convert "raw" sensor measurements into meaningful scientific units and their associated uncertainties are described. Surface water elevation will be continuously monitored by NEON at core and relocatable Aquatic sites using a single sensor (In-Situ, Inc. LevelTroll 500).

1.1 Purpose

This document details the algorithms used for creating NEON Level 1 data products for Surface Water Elevation from Level 0 data, and ancillary data as defined in this document (such as calibration data) obtained via instrumental measurements made by a pressure transducer. It includes a detailed discussion of measurement theory and implementation, appropriate theoretical background, data product provenance, quality assurance and control methods used, approximations and/or assumptions made, and a detailed exposition of uncertainty resulting in a cumulative reported uncertainty for this product.

1.2 Scope

The theoretical background and entire algorithmic process used to derive Level 1 data from Level 0 data for Surface Water Elevation is described in this document. The pressure transducer employed is the LevelTroll500 (hereafter referred to as LT500) manufactured by In-situ, Inc., which is mounted within a submerged sensor enclosure. This document does not provide computational implementation details, except for cases where these stem directly from algorithmic choices explained here.

2 RELATED DOCUMENTS, ACRONYMS AND VARIABLE NOMENCLATURE

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON OBSERVATORY DESIGN
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.002652	NEON Level 1, Level 2 and Level 3 Data Products Catalog
AD[04]	NEON.DOC.005005	NEON Level 0 Data Products Catalog
AD[05]	NEON.DOC.000782	ATBD QA/QC Data Consistency
AD[06]	NEON.DOC.011081	ATBD QA/QC Plausibility Tests
AD[07]	NEON.DOC.000783	ATBD De-spiking and Time Series Analyses
AD[08]	NEON.DOC.000746	Calibration Fixture and Sensor Uncertainty Analysis (CVAL)
AD[09]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[10]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values[1]
AD[11]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products

[1] Note that CI obtains calibration and sensor values directly from an XML file maintained and updated by CVAL in real time. This report is updated approximately quarterly such that there may be a lag time between the XML and report updates.

2.2 Reference Documents

RD[01]	NEON.DOC.000008	NEON Acronym List
RD[02]	NEON.DOC.000243	NEON Glossary of Terms

2.3 Acronyms

Acronym	Explanation
AIS	Aquatic Instrument System
ATBD	Algorithm Theoretical Basis Document
CI	NEON Cyberinfrastructure
CVAL	NEON Calibration, Validation, and Audit Laboratory
DAS	Data Acquisition System
DP	Data Product
FDAS	Field Data Acquisition System
GRAPE	Grouped Remote Analog Peripheral Equipment
Hz	Hertz
L0	Level 0
L1	Level 1
PRT	Platinum resistance thermometer
QA/QC	Quality assurance and quality control

SWE	Surface Water Elevation

2.4 Variable Nomenclature

The symbols used to display the various inputs in the ATBD, e.g., calibration coefficients and uncertainty estimates, were chosen so that the equations can be easily interpreted by the reader. However, the symbols provided will not always reflect NEON's internal notation, which is relevant for CI's use, and/or the notation that is used to present variables on NEON's data portal. Therefore a lookup table is provided in order to distinguish what symbols specific variables can be tied to in the following document.

Symbol	Internal Notation	Description
C_{P0}	CVALA0	Calibration coefficient for LT500 Pressure sensor
C_{P1}	CVALA1	Calibration coefficient for LT500 Pressure sensor
C_{P2}	CVALA2	Calibration coefficient for LT500 Pressure sensor
$u_{A1,P}$	U_CVALA1	Combined, standard calibration uncertainty of the pressure measurement by LT500 sensor (kPa)
$u_{A3,P}$	U_CVALA3	Combined, relative uncertainty (truth and trueness only) of the pressure measurement by LT500 sensor (%)
$E_{Sensor,i}$	Provided by SI&V	Elevation of the sensor measurement location (m – above sea level)
$u_c(E_{Sensor,i})$	Provided by SI&V	Combined uncertainty of elevation of the sensor (m)

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

The Surface Water Elevation related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying file swe_datapub_NEONDOC003794.txt.

3.2 Input Dependencies

Table 1 details the pressure transducer-related L0 DPs used to produce L1 Surface Water Elevation DPs in this ATBD.

Table 3-1: List of pressure transducer-related L0 DPs that are transformed into L1 Surface Water Elevation DPs in this ATBD.

Description	Sample Frequency	Units	Data Product Number
Surface Water Pressure	0.0167 Hz	*kPa*	NEON.DOM.SITE.DP0.20016.001.01379.HOR.VER.000

3.3 Product Instances

Multiple LT500 sensors will be located at each NEON Aquatic Site. LT500 sensors will be located in surface water at stream, river, and lake sites. Data from each LT500 will be sent to the Aquatic Portal by two different methods, which is determined by site type. At stream sites data will be ingested via GRAPE and Ethernet cable. At lake sites data will be ingested via wireless transmission.

3.4 Temporal Resolution and Extent

Surface Water Level will be measured at a rate of 0.0167 Hz (1 per minute) for L0 DPs, and these L0 DPs will be used to calculate the 1- and 30-minute averages of stream level. The sensors deployed within each site will be internally programmed to perform simultaneous measurements. Each sensor will be internally programmed to collect a "burst" of three individual measurements for each measurement parameter over a 15 second interval centered on the scheduled time of the measurement. The sensor will internally compute the average and will report this value as a single measurement in the data stream from the sensor. Retrieval of the individual measurements is not possible from the sensor, so the Level 0 data will be the average of the burst measurements, hereafter considered the instantaneous measurement.

3.5 Spatial Resolution and Extent

A single LT500 will be located inside the aquatic enclosure assembly mounted to the aquatic anchor in the stream at both aquatic sensor set one (S1) and aquatic sensor set two (S2). At river sites, the sensor will be located inside an aquatic enclosure assembly anchored at a static location near the riverbank below the annual mean low flow. At lake sites, the sensor will be located inside an aquatic enclosure assembly mounted to the aquatic anchor in the lake at both the inlet and outlet sensor set locations. The sensor will be located at a known elevation and the surface water level will be determined by the height of the water surface above the sensor elevation.

4 SCIENTIFIC CONTEXT

Surface Water Elevation is a critical physical parameter to measuring hydrology, biogeochemistry and aquatic ecology. Stream discharge is controlled by several hydrologic components as well as physical characteristics of the watershed. Figure 1 shows how stream discharge is determined by precipitation at both the landscape and channel scales, overland flow, interflow, and groundwater flow. Stream discharge is a master variable of the hydrological cycle at the landscape scale and therefore critical to understanding how water moves through the environment. This is necessary to determining how both aquatic and terrestrial ecosystems respond to hydrologic changes. Changes in hydrologic cycles at the landscape and broader regional level are pervasive in the face of changing land use, resource management and climate change.

Tracking the cycle of nutrients through aquatic and terrestrial environment allows scientists to determine structure and function of ecosystems. Stream discharge is necessary to calculate carbon exports and other nutrient fluxes as well as to close the water budget at the watershed scale.

While it is not practical to directly measure discharge continuously at a stream site, discharge is correlated to surface water level. At NEON, surface water level will be used to determine higher-level data products including stream discharge and nutrient flux, metabolism, and reaeration rating curves.

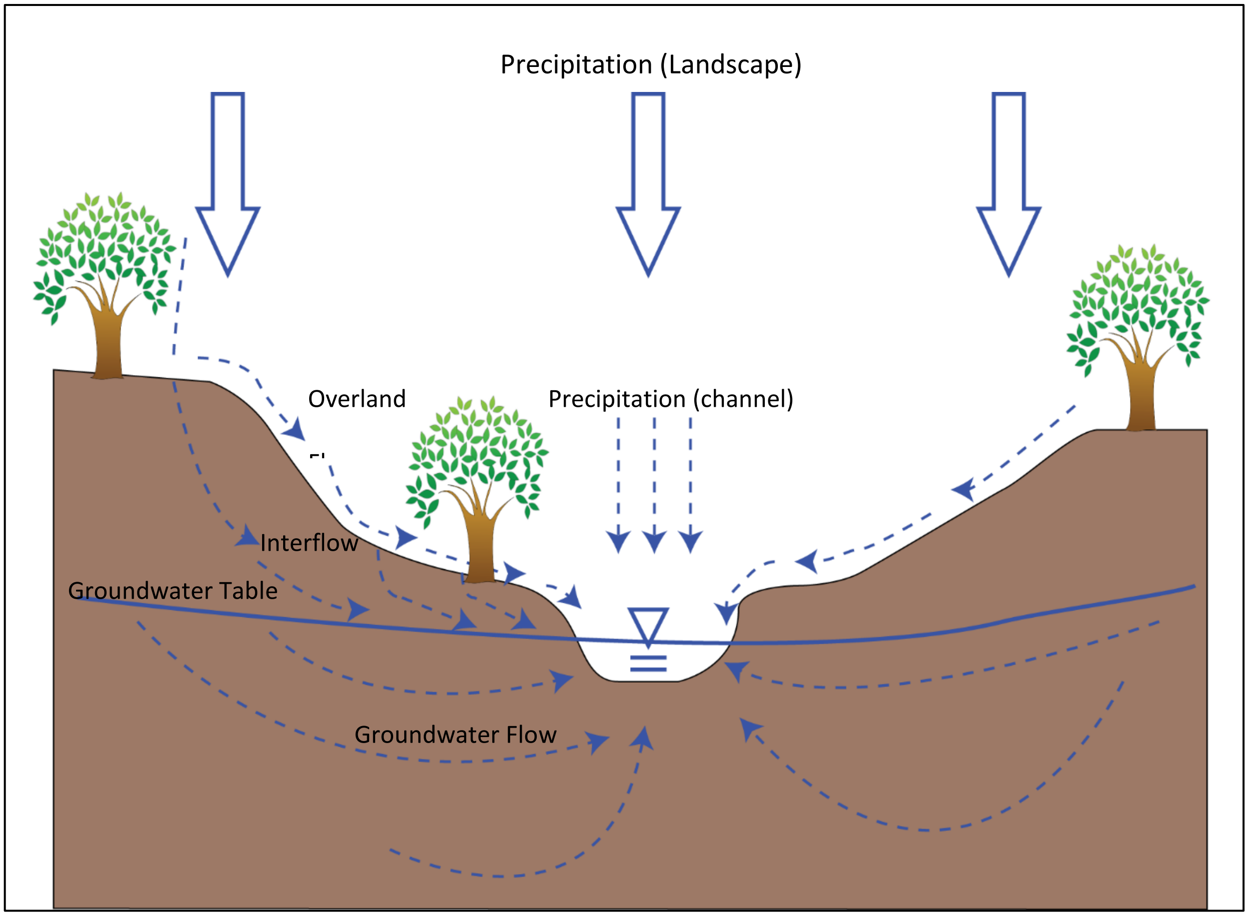

Figure 1. Components of stream flow.

4.1 Theory of Measurement

of pressure gauges to measure surface water elevation has been in use by the USGS for several decades (Rantz and others, 1982), although recent technological improvements have provided commercially available pressure sensors that meat NEON's accuracy and precision requirements (AD[05]).

The LT500 uses a pressure transducer to measure the pressure exerted by water and the atmosphere and uses a silicon bandgap sensor to measure temperature. The LT500 internally converts the analog measurements to digital output, as a result it is not possible to obtain raw analog signals from this sensor. These individual measurements are addressed separately below.

4.1.1 Surface Water Pressure

NEON will report the elevation of surface water based on the measured water level using the pressure guage within the LT500. The pressure gauge senses changes in pressure, measured in force per square unit of surface area, exerted on a strain gauge. Surface Water Elevation is determined by knowing the pressure of the water and atmosphere above the sensor measurement point and the precise elevation of the sensor measurement point.

Figure 2. Photo of a Level Troll 500 with dashed red line indicating the location of the sensing mechanism underneath the nose cone.

This LT500 determines pressure by measuring the slight voltage change that occurs when a variable resistor is compressed due to the hydrostatic pressure of the water. The sensor head is a diaphragm-like impermeable membrane that is in direct contact with the water on one side and vented to the atmosphere on the other side via a small tube that is contained in power and communication cable. The imbalance between the pressure of the water and the air pressure on the two sides of the membrane cause it to be deflected towards the air side. The membrane is part of an electrical circuit and is made of a variable resistor material, which when deflected by the water pressure changes the resistance of the circuit and causes a drop in electrical voltage in the circuit. Through calibrations these changes in electrical voltage can be equated directly to changes in hydrostatic pressure, when the LT500 is spatially fixed. Since changes in atmospheric pressure will directly result in changes in the hydrostatic pressure at a given point in the water column, venting the sensor to the atmospheric pressure changes eliminates the need to compensate for the pressure of the atmosphere in the measurement stream.

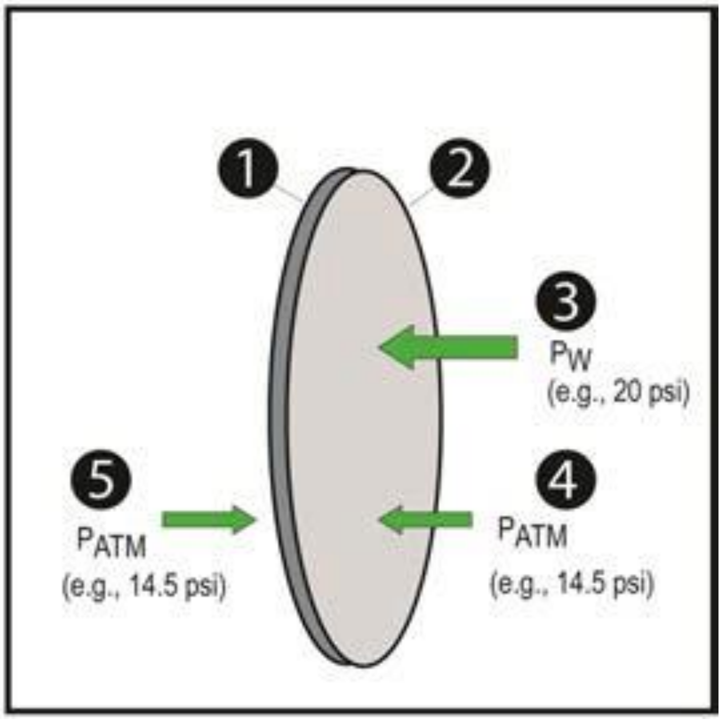

Figure 3. Illustration of forces measured by the pressure transducer, where 1) Sensor back; 2) Sensor front; 3) Water pressure; 4) Atmospheric pressure; 5) Atmospheric pressure.

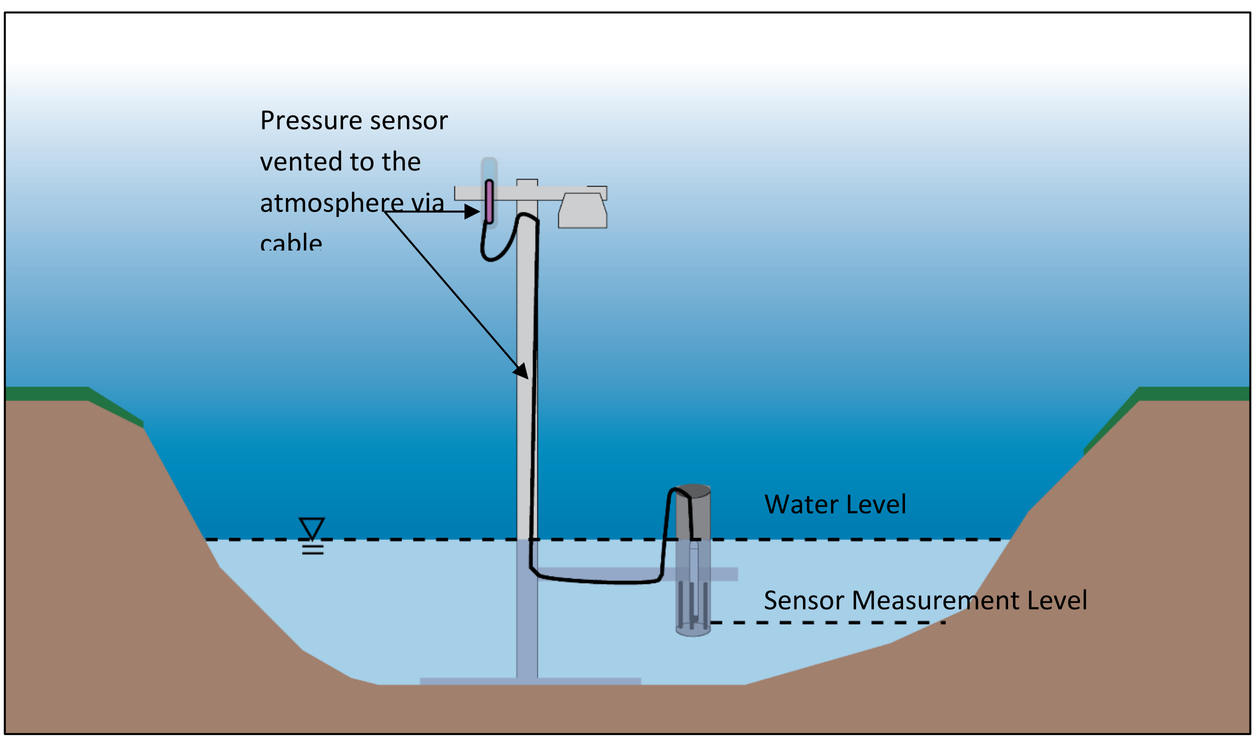

Figure 4. Cross-section of a stream illustrating the location of the sensor compared to the water level; sensor is vented to the atmosphere via a tube within the cable assembly.

4.1.2 Surface Water Temperature

The temperature measurements from this sensor are not the primary temperature measurement for the Surface Water Temperature data product, but rather will be used in a consistency analysis as part of automated quality control algorithms for the primary Surface Water Temperature data product. There fore the temperature measurement from this sensor is NOT converted to an associated L1 DP. For more discussion of the implementation of the LT500 L0 temperature measurements refer to (AD[13]).

4.2 Theory of Algorithm

Surface water pressure will be used to determine surface water elevation. Non-vented pressure measurements are useful in vacuum testing, in short-term testing when atmospheric pressure would not be expected to change, in very deep aquifers where the effects of atmospheric pressure are negligible, and in unconfined aquifers that are open to the atmosphere.

With vented or “gauged” pressure sensors, a vent tube in the cable applies atmospheric pressure to the back of the strain gauge. The basic unit for vented measurements is PSIG (pounds per square inch “gauge”), measured with respect to atmospheric pressure. Vented sensors thus exclude the atmospheric or barometric pressure component.

The difference between absolute and gauged measurements may be represented by a simple equation (see also Figure 3 above):

$$P_{gauge} = P_{absolute} - P_{atmosphere} \tag{1}$$

4.2.1 Surface Water Elevation Algorithm

Calibrated surface water pressure will be used to calculate the surface water elevation. Surface water pressure will be determined by applying the calibration coefficients, supplied by CVAL, to the “raw” sensor output as follows:

$$P_{SW,i} = C_{P2} * P_i^2 + C_{P1} * P_i + C_{P0} \tag{2}$$

Where:

P_{SW,i_i} = Individual (0.0167 Hz) surface water pressure (kPa)
C_{P2} = Calibration coefficient provided by CVAL ((kPa)$^{-1}$)
C_{P1} = Calibration coefficient provided by CVAL (unitless)
C_{P0} = Calibration coefficient provided by CVAL (kPa)
P_i = Individual (0.0167 Hz) pressure output from sensor (kPa)

Surface Water Elevation is calculated using the pressure measurement and a reference location. The elevation of the sensor measurement location is required to calculate the Surface Water Elevation. The Surface Water Elevation is calculated by converting the water pressure over the sensor to a length term by:

$$E_{SW,i} = E_s + 1000 \times (P_{SW,i} / (\rho_{water} \times g)) \tag{3}$$

Where:

$E_{SW,i}$ = Individual surface water elevation measurement (m-asl)
E_s = Elevation of sensor (m-asl)
$P_{SW,i}$ = Individual pressure measurement (kPa)
ρ_{water} = Density of water = 999.0 (kg/m^3)
g = Acceleration due to gravity = 9.81 (m/s^2)
*m-asl = meters above sea level

During the construction of each aquatic site, the in-stream infrastructure will be surveyed and the precise geospatial locations of the LT500 will be determined. SI&V will create an xml file based on this as-built survey that will include the latitude, longitude and elevation (E_{Sensor}) and its associated combined uncertainty ($u_C(E_{Sensor})$). This information will be transferred to CI in an xml file for ingest into the geospatial database. Based on the design of the deployment infrastructure, removal of the sensor from the mounting disc should not interfere with the ability to replace the sensor in the same location in the stream.

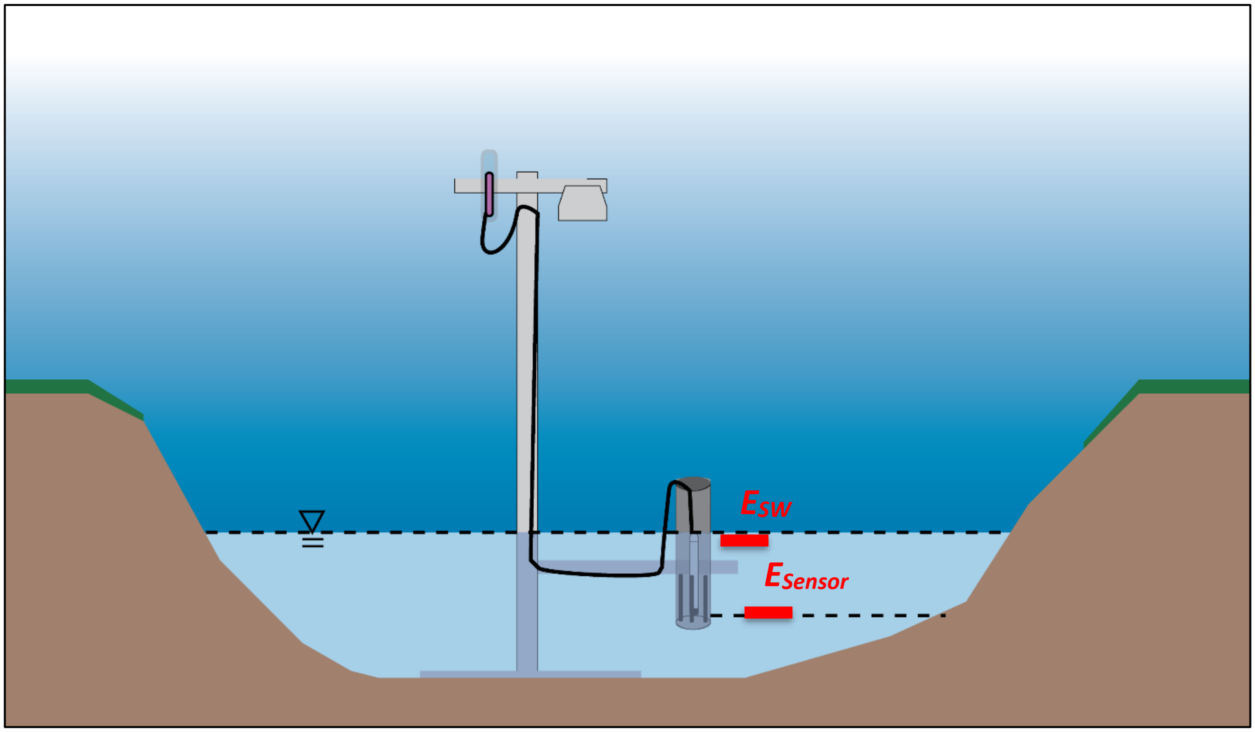

Figure 5. Illustration showing the location of the Elevation of the sensor (E_{Sensor}) which is measured by SI&V and the calculated Surface Water Elevation (E_{SW}).

Surface Water Elevation is reported as a 5-minute and a 30-minute average. The 0.01667Hz instantaneous L0 measurement ($E_{SW,i}$) shall be used to calculate the 5-minute average as:

$$\overline{E_{SW5}} = \frac{1}{n}\sum_{i=x}^{n} E_{SW,i} \tag{4}$$

Where for each 5-minute average, *n* is the number of measurements in the averaging period and $E_{SW,i}$ is the calibrated surface water elevation calculated from the 0.0167 Hz measurements according to equations 2-3 above during the 5-minute averaging period. For a 5-minute average, n = 5 if all points are included [0,5).

The 0.0167Hz instantaneous L0 measurement ($E_{SW,i}$) shall be used to calculate the 30-minute average as:

$$\overline{E_{SW30}} = \frac{1}{n}\sum_{i=x}^{n} E_{SW,i} \tag{5}$$

Where for each for a 30-minute average, n = 30 if all points are are included [0, 30).

4.2.2 Surface Water Temperature Algorithm

The temperature measurements by the LT500 are not used to produce the primary water temperature data product and are not transformed to L1 DP. Therefore there is no discussion of such transformation within this document. All processing the LT500 temperature data stream, such as the application of calibration coefficients and the calculation of averages is presented in (AD[13]).

5 ALGORITHM IMPLEMENTATION

Data flow for signal processing of L1 DPs will be treated in the following order.

1. Calibration coefficients will be applied to instantaneous 0.0167 Hz surface pressure value (P_i) according to Eq. (2).
2. Surface water pressure values will be converted to surface water elevation according to Eq. (3) using the pressure from the sensor and the elevation of the sensor.
3. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[07].
4. Signal de-spiking and time series analysis will be applied to the data stream in accordance with AD[08].
5. 5-minute and 30-minute averages for surface water elevation will be calculated using Eq. (4) and (5) respectively.
6. Descriptive statistics, i.e. minimum, maximum, and variance, will be determined 30-minute averages.
7. QA/QC Summary (Q_{sum}) will be produced for 30-minute averages according to AD[09].

QA/QC Procedure:

1. **Plausibility Tests** – All plausibility tests will be determined for surface water pressure (AD[07]). Test parameters will be provided by AQU and maintained in the CI data store. All plausibility tests will be applied to the sensor's L0 DP and an associated quality flags (QFs) will be generated for each test.

2. **Signal De-spiking and Time Series Analysis** – The time series de-spiking routine will be run according to AD[08]. Test parameters will be specified by AQU and maintained in the CI data store. Quality flags resulting from the de-spiking analysis will be applied according to AD[07].

3. **Placeholder for Consistency Analysis** (see section 7 for future implementation).

4. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[09] – If a datum fails one of the following tests it will not be used to create a L1 DP, ***range***, ***persistence***, and ***step*****.** α and β QFs and QMs will be determined using the flags in Table 5-1. In addition, L1 DPs will have a QA/QC report and quality metrics associated with each flag listed in Table 3 as well as a final quality flag, as detailed in AD[09] Ancillary information needed for the algorithm and other information maintained in the CI data store is shown in Table 5-2.

Table 5-1: Flags associated with surface water pressure measurements.

Tests
Range
Persistence
Step
Null
Gap
Signal Despiking
Alpha
Beta
Final quality flag

Table 5-2: Information maintained in the CI data store for surface water pressure

Tests/Values	CI Data Store Contents
Range	Minimum and maximum values
Persistence	Window size, threshold values and maximum time length
Step	Threshold values

Tests/Values	CI Data Store Contents
Null	Test limit
Gap	Test limit
Signal Despiking	Time segments and threshold values
Calibration	CVAL sensor specific calibration coefficients
Uncertainty	AD[14]
Final Quality Flag	AD[16]

6 UNCERTAINTY

Uncertainty of measurement is inevitable (JCGM 2008, 2012; Taylor 1997). It is crucial that uncertainties are identified and quantified to determine statistical interpretations about mean quantity and variance structure; both are important when constructing higher level data products (e.g. L1 DP) and modeled processes. Uncertainty related to the Surface Water Pressure Transducer and associated data products is provided in detail in the Aquatics Uncertainty Document AD [15], which serves to identify, evaluate, and quantify sources of uncertainty relating to L1 surface water pressure and L1 surface water temperature DPs. It is a reflection of the information described in AD[11] and is explicitly described for the level sensor in AD [15].

6.1 Uncertainty of Surface Water Elevation

Uncertainty of the LT500 assembly is discussed in this section. The section is broken down into two topics. The first informs the sources of *measurement* uncertainty, i.e., those associated with *individual pressure, temperature and conductivity measurements*. The second details uncertainties associated with temporally averaged data products. A diagram detailing the data flow and known sources of uncertainty are displayed in Figure 6.

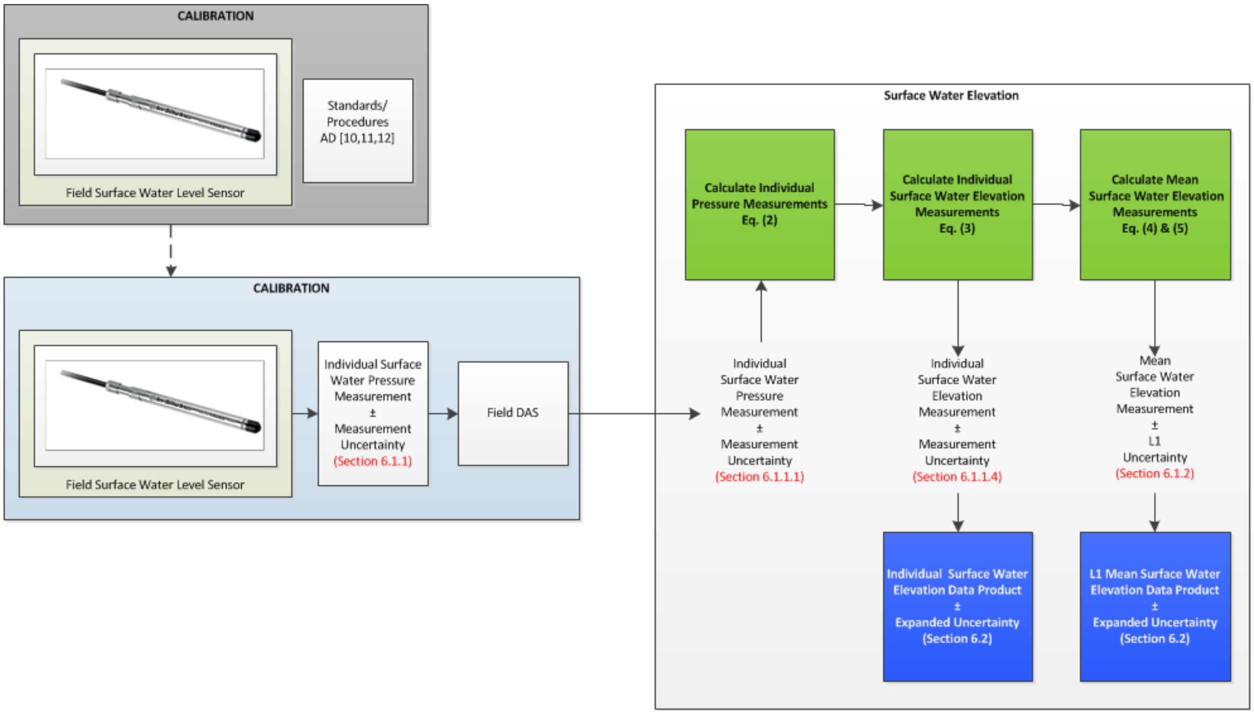

Figure 6. Displays the data flow and associated uncertainties of individual measurements of surface water elevation (from pressure) and associated L1 DPs.

6.1.1 Measurement Uncertainty

The following subsections present the uncertainties associated with *individual observations*. It is important to note that the uncertainties presented in the following subsections are *measurement uncertainties*, that is, they reflect the uncertainty of an *individual* measurement. These uncertainties should not be confused with those presented in Section 6.1.2. We urge the reader to refer to AD[11] for further details concerning the discrepancies between quantification of measurement uncertainties and L1 uncertainties.

NEON calculates measurement uncertainties according to recommendations of the Joint Committee for Guides in Metrology (JCGM) 2008. In essence, if a measurand *y* is a function of *n* input quantities

$x_i \ (i = 1, \dots, n),\ i.e., y = f(x_1, x_2, \dots, x_n)$, the combined measurement uncertainty of *y*, assuming the inputs are independent, can be calculated as follows:

$$u_c(y) = \left(\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \right)^{\frac{1}{2}} \tag{6}$$

where

$\frac{\partial f}{\partial x_i}$ =partial derivative of *y* with respect to x_i

$u(x_i)$ =combined standard uncertainty of x_i.

Thus, the uncertainty of the measurand can be found be summing the input uncertainties in quadrature. For surface water pressure measurements, the sources of uncertainty are discussed below.

6.1.1.1 DAS

The In-Situ LT500 sensor has an internal Analog to Digital (A/D) converter and outputs data in digital form. Therefore, no data conversions occur within the DAS, and uncertainty introduced by the DAS can be considered negligible.

6.1.1.2 Calibration

Uncertainties associated with the calibration process of the LT500 for surface water pressure and temperature measurements will be provided by CVAL as individual standard combined uncertainty values. These uncertainties $\{u_{A1}\}$ (see Section 2.4) represent i) the repeatability and reproducibility of the sensor and the lab DAS and ii) uncertainty of the calibration procedures and coefficients including uncertainty in the standard (truth). Both are constant values that will be provided by CVAL, stored in the CI data store, and applied to all *individual pressure, temperature and conductivity measurements* (that is, the uncertainty values do not vary with any specific sensor, DAS component, etc.). A detailed summary of the calibration procedures and corresponding uncertainty estimates can be found in AD[11,12].

6.1.1.3 Surface Water Elevation

This section details the measurement uncertainty relating to the individual *Surface Water Elevation* measurements. Figure 7 shows the variables necessary to calculate the sensor elevation (E_{Sensor}). These will be measured by SI&V during sensor installations at each sensor location.

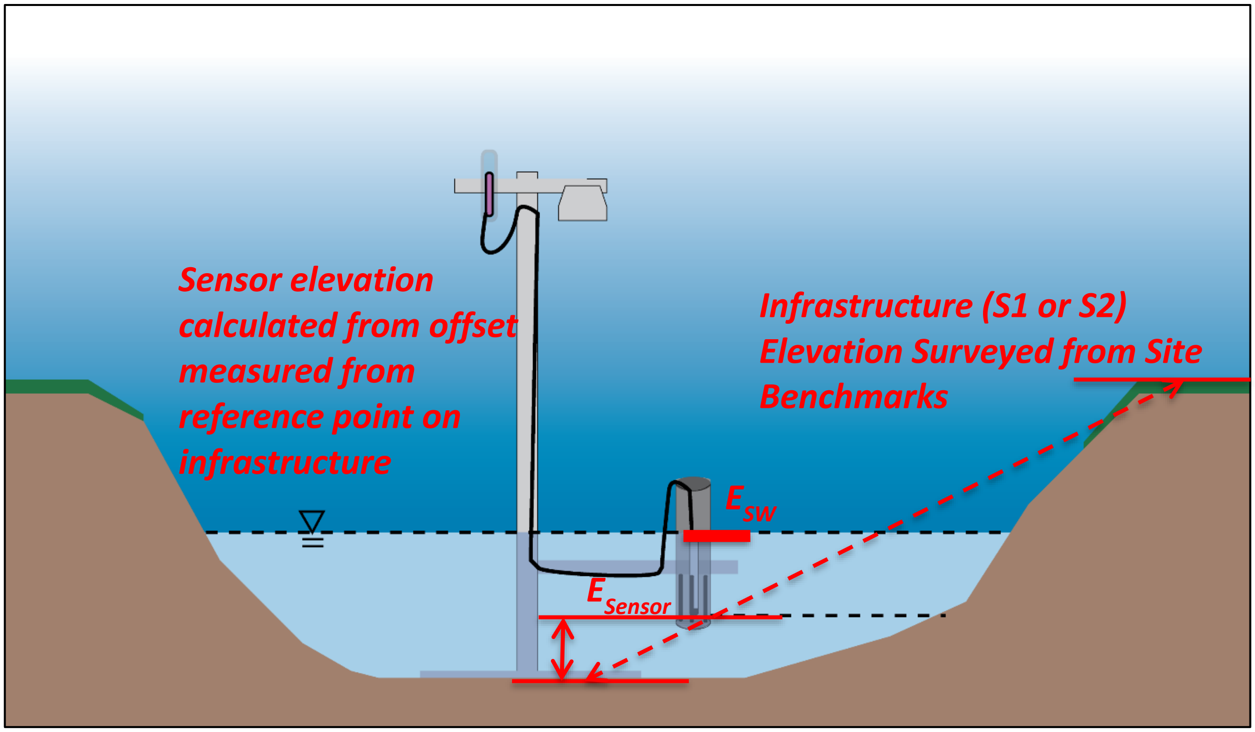

Figure 7. Illustration of the points measured by SI&V during installation in order to calculate the sensor elevation.

6.1.1.3.1 Ground Surface Elevation

Spatial error is a principle source of uncertainty in the calculation of the surface water elevation. The precise location and elevation of the sensor as well as the ground surface elevation at each infrastructure location will be determined after installation by surveying the site. Spatial error will combine the uncertainty of the permanent survey marker at a site and the error associated with surveying the elevation at each aquatic infrastructure location. These errors will be quantified for both the permanent benchmark and the ground surface elevation at the in-stream infrastructure location according to the survey process.

The combined uncertainty of the ground surface elevation for all sensor locations will be determined by SI&V based on the technique used across all sites. This is discussed herein for informative purposes only. CI will not need to utilize this constant (See next section).

These values are given as the accuracy of the measurements during surveying and will be passed from the surveyor to SI&V and determined as a constant value for all instances.

6.1.1.3.2 Sensor Elevation

The sensor elevation is given as a physical measurement with uncertainty that is based on the resolution of the measurement equipment. This should be resolved to the millimeter and there the input value is considered a constant that does not significantly contribute to the combined uncertainty beyond the topographical survey.

6.1.1.3.3 Density of Water

Density of water is a function of temperature, pressure and dissolved ions (conductivity). The density of pure water at 4°C is 1000 kg/m^3. Conductivity over the range expected in the freshwater systems within the NEON Project will have a negligible effect on the density of water. Temperature of the typical range of 5-20°C can affect the density by up to 1 kg/m^3. The density of water is part of the calculation of surface water elevation as shown in Eq. (3). A change of 1 kg/m^3 in density translates to an error of nearly 4mm. This is well below the 1 cm accuracy requirement, therefore the error associated with using the precise density of water is considered negligible. The density of water will be considered constant at 999.0 kg/m^3.

6.1.1.4 Combined Measurement Uncertainty

Temperature:
Because the only known quantifiable uncertainties are those provided by CVAL, the combined uncertainty of temperature is simply equal to the standard uncertainty values provided by CVAL (See Section 2.4).

Pressure:
Because the only known quantifiable uncertainties are those provided by CVAL, the combined uncertainty of actual conductivity is simply equal to the standard uncertainty values provided by CVAL (See Section 2.4).

Surface Water Elevation:
Because surface water elevation is derived from the pressure measurement and the known elevation of the sensor, the combined uncertainty for individual measurements takes into account the positional uncertainty provided by SI&V and the measurement uncertainty provided by CVAL according to Eq. 14.

$$\boldsymbol{u_c(E_{SW,i}) = \left[u_c{}^2(E_{sensor}) + u_{A1,P}^2\right]^{\frac{1}{2}}} \tag{7}$$

6.1.2 Uncertainty of the L1 Mean Data Products

The following subsections discuss uncertainties associated with temporally averaged, i.e., L1 mean data products. As stated previously, it is important to note the differences between the *measurement uncertainties* presented in Section 6.1.1 and the uncertainties presented in the following subsections. The uncertainties presented in the following subsections reflect the uncertainty of a time-averaged mean value, that is, they reflect the uncertainty of a distribution of measurements collected under non-controlled conditions (i.e., those found in the field), as well as any uncertainties in the form of *Truth* and *Trueness* related to the accuracy of the field assembly.

6.1.2.1 Repeatability (Natural Variation)

To quantify the uncertainty attributable to random effects, the distribution of the individual measurements is used. Specifically, the *estimated standard error of the mean (natural variation)* is computed. This value reflects the repeatability of measurements for a specified time period:

$$u_{NAT}(\bar{X}) = \sqrt{\frac{\sigma^2}{n}} \tag{8}$$

Where

X = measurement, *e.g. surface water pressure*
$u_{NAT}(\bar{X})$ = standard error of the mean (natural variation)
σ = experimental standard deviation of individual observations for a defined time period
n = number of observations made during the defined period

6.1.2.2 Calibration

he calibration uncertainty for a L1 mean DP is similar to that described in Section 6.1.1.1. However, the uncertainties provided by CVAL (see Section 2.4) do not account for i) individual sensor repeatability, or ii) the variation of sensors' responses over a population (reproducibility). These components estimate the uncertainties due to the accuracy of the instrumentation in the form of *Truth* and *Trueness*, a quantity that is not captured by the standard error of the mean. Both values (i.e. temperature and pressure) are constant values that will be provided by CVAL and stored in the CI data store. Please refer to AD[10] for further justification regarding evaluation and quantification of this combined uncertainty.

6.1.2.3 Combined Uncertainty

The combined uncertainty for L1 AT200 data products are computed by summing the unceratinties from Section 6.1.2.1 and the CVAL provided uncertainties in quatrature:

$$\boldsymbol{u_c(\overline{P_{SW}}) = \left[\, u^2_{NAT}(\overline{P}_{SW}) + u^2_{A3,P}\right]^{\frac{1}{2}}} \tag{9}$$

6.1.2.4 Surface Water Elevation

The combined uncertainty for surface water elevation includes the combined uncertainties for sensor depth and ground surface. These are discussed above in Section 6.1.1.3.

Surface Water Elevation:

$$\boldsymbol{u_c(\overline{E_{SW}})} = [\boldsymbol{u_c}^2(\boldsymbol{E_{sensor}}) + \boldsymbol{u_c^2(\overline{P_{SW}})}]^{\frac{1}{2}} \tag{10}$$

6.1.2.5 Communicating Precision

L1 mean groundwater surface elevation data products will be reported to 0.01 m. This digital sensor is capable of measuring pressure at a resolution of 0.005% of full scale, which in this case is 0.03 KPa. This pressure sensitivity equates to 0.0035m in water height. The largest source of uncertainty is related to the positioning of the sensor. The reported resolution is consistent with our scientific requirement for accurate determination of the water level.

6.2 Expanded Uncertainty

We assume the measurement variability is normally distributed (Gaussian). The combined uncertainty represents plus or minus one standard deviation or a confidence interval of 68%. This confidence level is below the industry standard and is therefore expanded to a 95% confidence interval. This is typically calculated by multiplying the combined uncertainty, $u_{c,r}(y)$, by a coverage factor, k_p.

$$\boldsymbol{U_p = k_p\, u_{c,r}(y)} \tag{11}$$

Where $k_{95} = 1.96$ for $p = 95$ for a given degrees of freedom. k_p is approximated by a t-distribution with an effective degrees of freedom, v_{eff}, obtained from the Welch-Saterwaite formula:

$$\boldsymbol{v_{eff}} = \frac{\boldsymbol{u_c^4(y)}}{\sum_{i=1}^{n}\frac{\boldsymbol{u_i^4(y)}}{\boldsymbol{v_i}}} \tag{12}$$

The coverage factor then becomes $k_p = t_p(v_{eff})$, where $t_p(v_{eff})$ is obtained from a table.

However to simplify the calculations further, we can conservatively estimate the expanded uncertainty at a 95% confidence level to be two times the combined uncertainty.

$$\boldsymbol{U_{Expanded} = 2 \times u_c} \tag{13}$$

This expansion is to be applied to all combined uncertainties for the L1 DP described herein.

6.3 Uncertainty Budget

The uncertainty budget is a visual aid detailing i) quantifiable sources of uncertainty, ii) means by which they are derived, and iii) the order of their propagation. Uncertainty values denoted in this budget are either derived within this document or are provided by other NEON teams (e.g., CVAL), and stored in the CI data store.

Table 6-1 Uncertainty budget for individual measurements. Shaded rows denote the order of uncertainty propagation (from lightest to darkest).

Source of Measurement Uncertainty	**Measurement uncertainty Component $u(x_i)$**	**Measurement Uncertainty Value**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$
Pressure	$u_{A1,P}$	AD[11]	n/a	n/a

Table 6-2 Uncertainty budget for L1 mean DPs. Shaded rows denote the order of uncertainty propagation (from lightest to darkest).

Source of Uncertainty	**Uncertainty Component $u(x)$**	**Uncertainty Value**	$\frac{\partial f}{\partial x_i}$	$u_{u_{x_i}}(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$
Pressure	$u_c(\bar{P}_{SW})$	Eq. (11)	n/a	n/a
Calibration	$u_{A3,P}$	AD[11]	n/a	n/a
Natural variation	$u_{NAT}(\bar{P}_{SW})$		n/a	n/a
Surface Water Elevation	$u_c(\bar{E}_{SW})$	Eq. (12)	n/a	n/a
Pressure	$u_{A3,P}$	AD[11]	n/a	n/a
Sensor Elevation	$u_c(E_{sensor})$	Site metadata	n/a	n/a

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream and included in the QA/QC summary DP ($Qsum_{5min}$) that summarizes any flagged data that went into the computation of the L1 DP.

It is planned that a QA/QC flag for data consistency will be applied according to a developed consistency analysis (AD[05) and a pass/fail flag will be generated to reflect this activity. Pressure at each surface water level measurement location in at a given NEON aquatic site will have the time series data compared against the measurement variance other wells. If a difference between the measurements is less than the defined limits, provided by AQU and maintained in the CI data store, then the sensor will have passed the consistency analysis. Alternatively, a difference outside the defined limits will result in a failed test, and will be flagged as such. L1 DPs that fail the consistency analysis will continue to be reported, but will have an associated failed flag that will be include in the QA/QC summary.

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