**OPENWATER – A CITIZEN SCIENCE MONITORING PLATFORM**
Research & Development Report

# 1 INTRODUCTION

This report describes the research and development of the third-generation version of a research quality, relatively low-cost, open-source instrument for measurement of water turbidity in environmental samples. The device is shown in Figure 1.

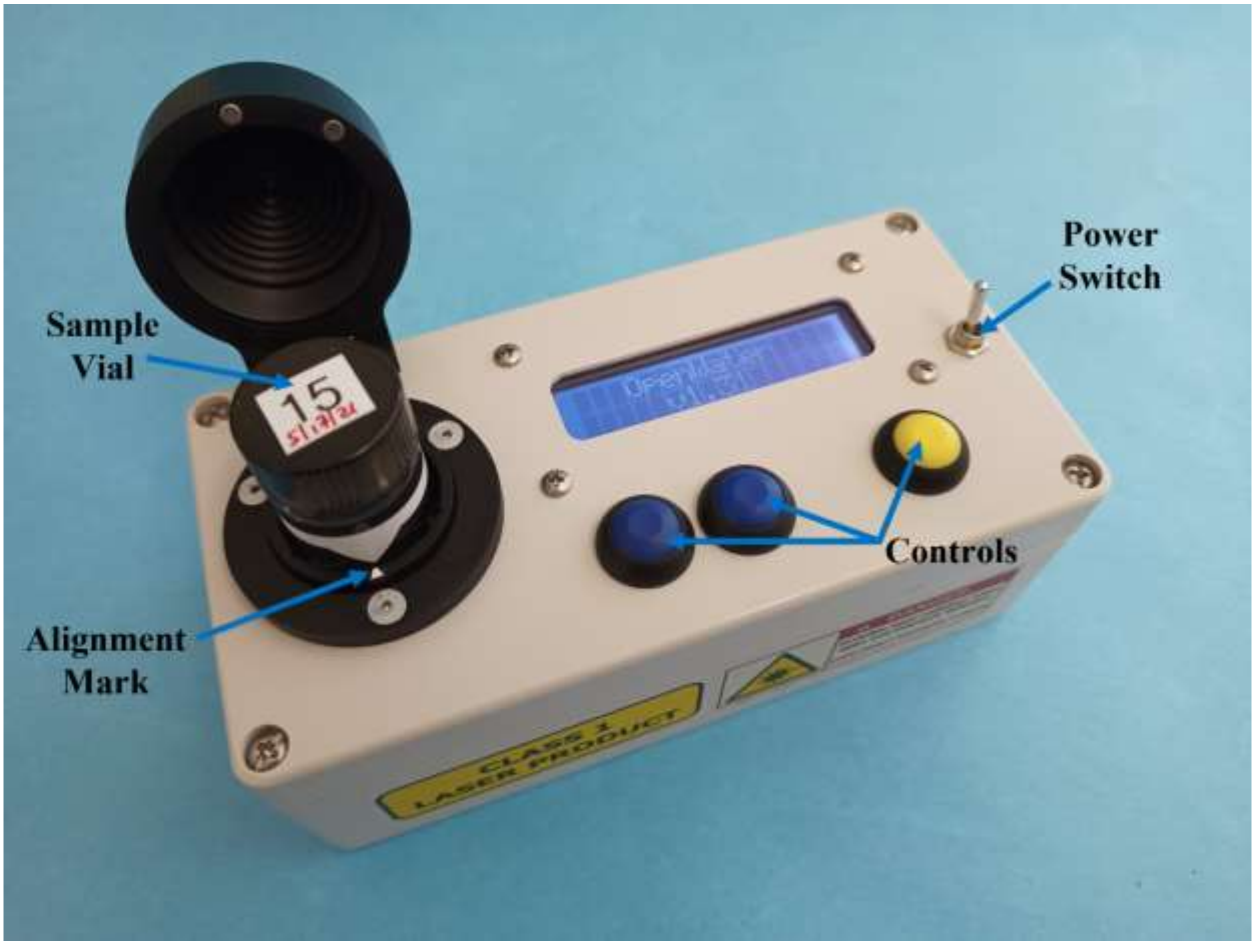


Figure 1. OpenWater Open-Source Turbidity Meter (3rd-Generation Design)

Principle of Operation. The OpenWater turbidity meter is composed of an 850 nm light source oriented at 90° to a light sensor which measures diffuse light scattered by turbidity in the sample. The infrared light source reduces the influence of sample color on turbidity measurements, and results are reported in Formazin Nephelometric Units (FNU). The meter was developed using guidance from Water Quality Standard ISO 7027 (Method c).

## 2 INSTRUMENT DESIGN

Design Overview. The core of the meter is the sample measurement well (Figure 2), which can be fabricated by 3D printing (stereolithography, SLA). The light source is a vertical cavity surface-emitting laser (VCSEL) with a total beam divergence angle (full-width at half intensity) of 4°. The VCSEL is operated in constant current mode to provide uniform light intensity for each measurement. The sensor is a light-intensity-to-frequency converter, which produces a square wave pulse output proportional to the incident light intensity. Pulses are counted during the integration period by a microcontroller which also controls the system.

The inner wall of the sample holder is corrugated to enhance absorption of stray light. A spring-plunger pushes the sample vial against PTFE guide rods in the wall to ensure consistent centering of the vial on the VCSEL. An alignment arrow on the top surface of the vial housing improves consistency of vial alignment. A miniature normally open reed switch placed in series with the laser is used as a safety interlock. A magnet is installed in the lid of the device to close the switch during operation, and the reed sensor is mounted in the sample holder opposite the magnet. Closing the lid actuates the reed switch, allowing the laser to be turned on by the microcontroller.

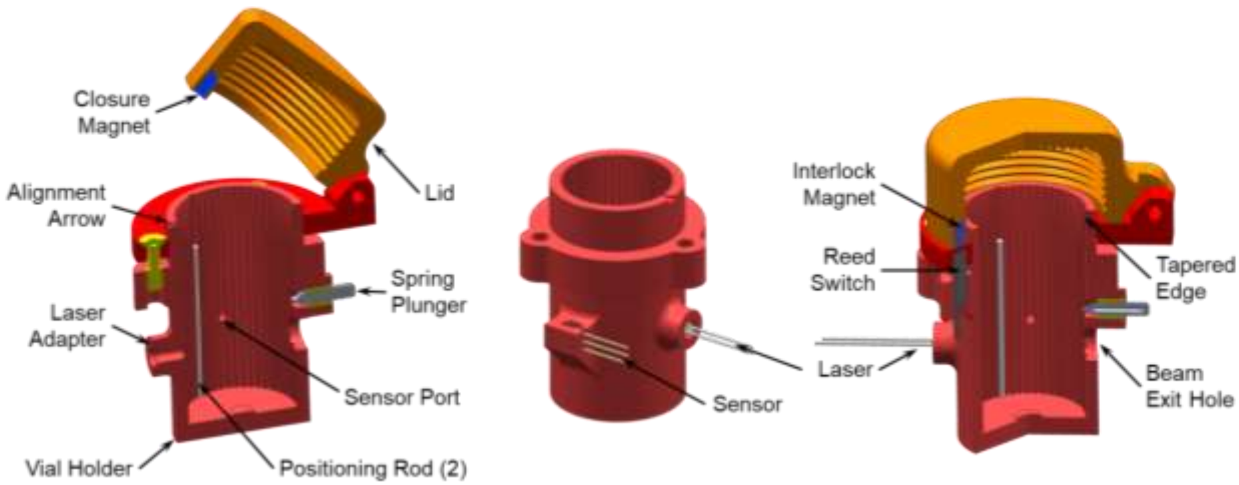


Figure 2. Turbidity Meter Optical System Design. The laser axis is arranged at 90° to the sensor view axis and both are normal to the vial axis. The sensor is mounted at the end of a narrow bore to minimize stray light (left); The light source and sensor are mounted directly on the outside of the sample holder (middle); The spring-plunger aligns the sample vial and laser centerlines (right).

Electronics. The VCSEL light source (TT Electronics, OPV332) is operated in constant current mode. The laser current source circuit is based on the LM-317 regulator, which has low cost, small component count, and stable current regulation. Figure 3 shows the laser control subsystem, including the laser, current regulator, reed switch safety interlock, and transistor interface to the microcontroller.

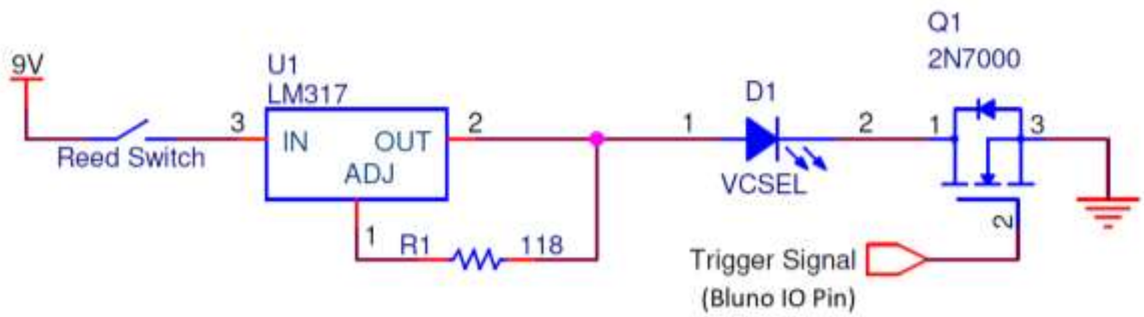


Figure 3. Laser Control Circuit Including Safety Interlock Reed Switch

The laser generates a repeatable signal at low turbidity values with a supply current of 10 mA. However, the voltage supplied by the microcontroller digital outputs is insufficient to drive this current. Therefore, the current source circuit is supplied with 9 V directly from the battery and the microcontroller digital output controls the laser via a 2N7000 transistor. The current source provides stable regulation with mean variability of 4.8 µA and drift between 22 and 50°C of only 0.5%.

The light-intensity-to-frequency converter (AMS, TSL237) only requires one 0.1 µF decoupling capacitor connected across the power supply. The sensor output is connected to an input pin of the 8-bit microcontroller with Bluetooth (Bluno ATmega328P, DFR0267, DFRobot) which controls the system. This board interfaces with an LCD module used for calibration and results display. Figure 4 shows the connections between the microcontroller and the low cost VCSEL and light sensor.

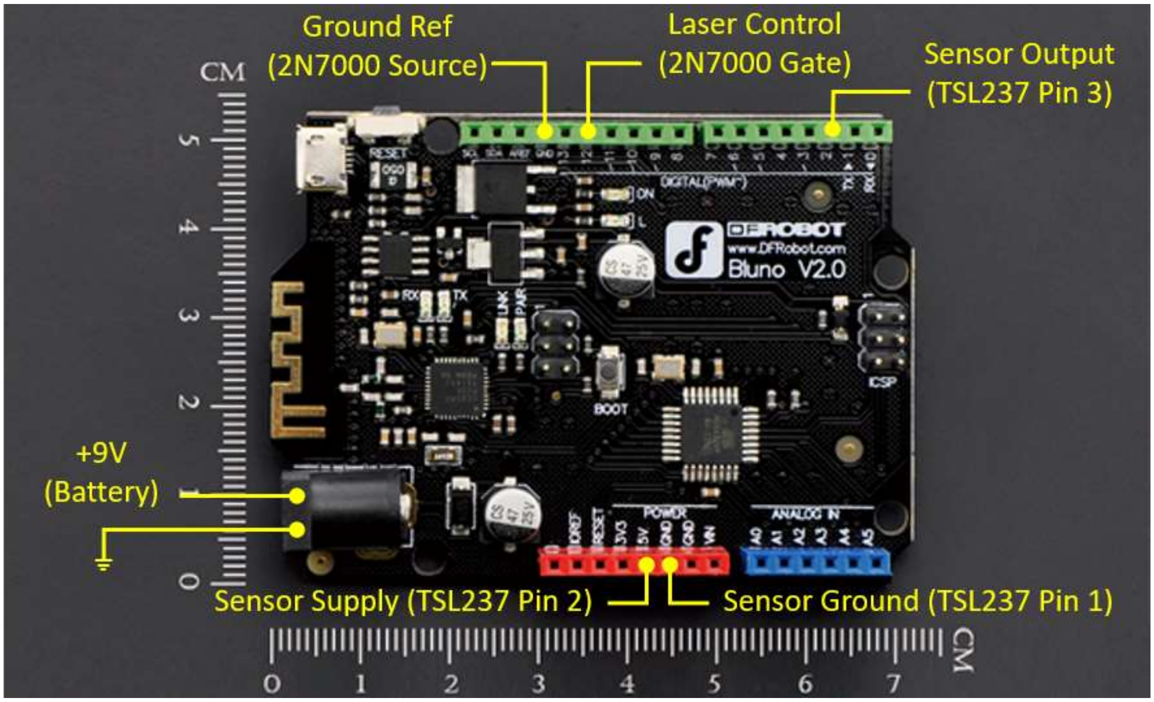


Figure 4. Bluno Microcontroller Connections to Light Source and Sensor

Enclosure. A commercial splash-resistant plastic enclosure (090816060, Rose Enclosures) is used for the third-generation prototype. The box measures 160 mm L x 80 mm W x 55 mm H (6.3 x 3.2 x 2.2 in.), providing ample space for the sample holder, microcontroller, LCD display, and battery pack. The lid of the enclosure is modified to accommodate the system components, as shown in the drawing in Figure 5. A piece of adhesive-backed Velcro (loop side) is installed on the inner wall of the enclosure base, opposite the laser beam exit hole in the vial holder. This simple, low-cost, absorptive material reduces the background count (light intensity measured at 0 NTU) by 30 percent and increases the ratio between counts at 0 and 20 NTU by 25 percent.

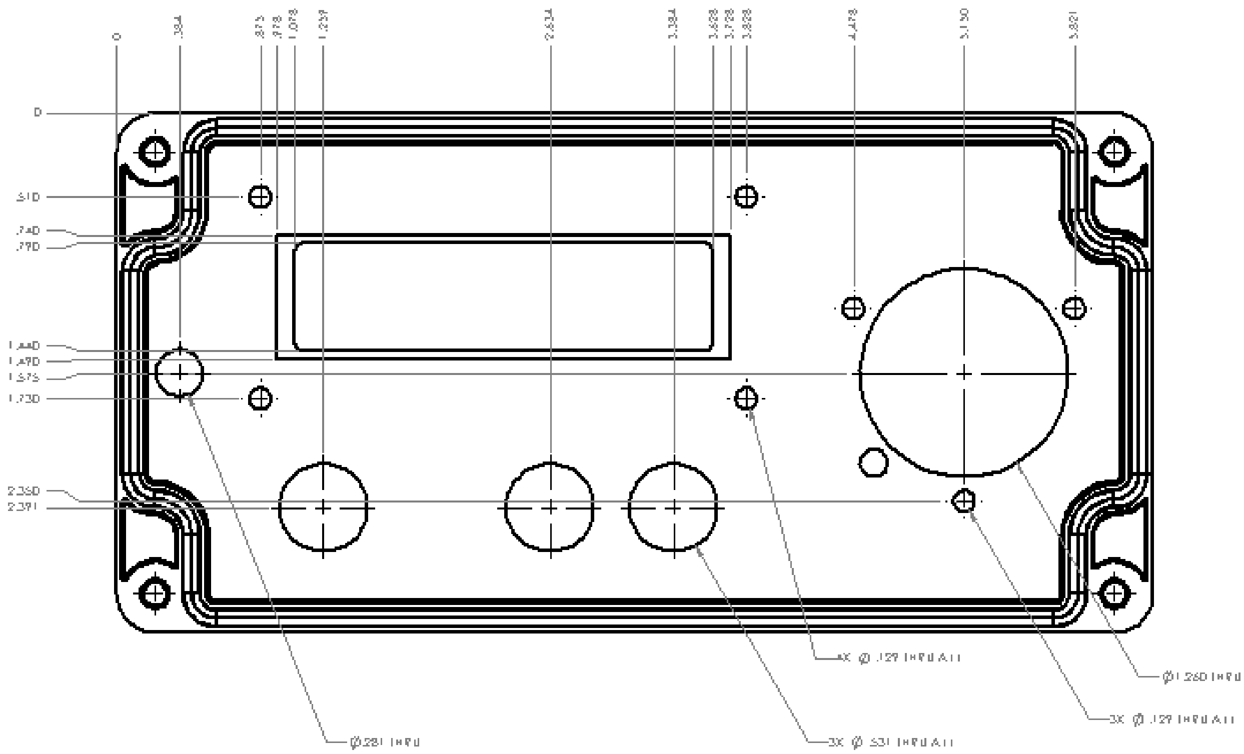

Figure 5. Modifications to the Commercial Enclosure

Safety. The turbidity meter contains a laser device that produces invisible radiation at 850 nm. If the laser is operated with a current greater than the recommended maximum (i.e., in an overcurrent failure mode at 30 mA), it will produce class 3B laser radiation. Class 3B devices have beams that are normally hazardous when a direct exposure occurs within Nominal Ocular Hazard Distance (NOHD). The IEC 60825-1 laser safety standard specifies an NOHD of several meters for class 3B devices.

There is no danger of harm due to the radiation from the laser in this instrument when it is used according to the instructions in the user manual. The following turbidity meter design features are meant to protect the user from potentially harmful infrared radiation:

- An interlock switch connected in series with the laser prevents operation while the lid is open.

- A warning label is placed over the seam of the enclosure to remind users not to open the enclosure while the device is powered on.
- The laser is operated in constant-current mode, below the recommended maximum current (<12 mA).
- The axis of the laser beam is oriented parallel to the base of the measurement well so that laser light is not directed towards the user.

Firmware. The OpenWater sensor uses an Arduino-type microcontroller with an integrated Bluetooth radio (Bluno, DFRobot). For the third-generation design, the system is controlled either by using buttons and an LCD display on the front panel, or via Bluetooth. In addition to the power switch, the front panel includes Up/Down buttons for scrolling through menus, and an Enter button for accepting settings (Figure 6). The calibration routine allows for selection of the integration time for each reading and the number of readings that are averaged for each measurement. The user can also select the value of each of the calibration points (typically 0 and 20 FNU).


Figure 6. Front Panel Controls of the OpenWater Turbidity Meter

Bluetooth Low Energy service is included with the Bluno firmware. Table 1 shows the acceptable commands that control or request data from the device. These Bluetooth commands enable the mobile application to wirelessly execute turbidity measurements and calibrations.

| Table 1. Turbidity Meter Commands (Firmware v1.31) | | | |
|---|---|---|---|
| **Command** | **Description** | **Data Returned** | **(Format)** |
| 00 | Execute Measurement | None | |
| 01 | Read Last Reading Mean | Mean FNU | (X.XX) |
| 02 | Read Last Reading Std. Dev. | Std. Dev. FNU | (X.XX) |
| 03 | Read Number of Averages | Number | (XX) |
| 04 | Read Integration Time | Time | (XX.X) |
| 05 | Read Calibration Slope | FNU / Count | (XXX.XX) |
| 06 | Read Calibration Intercept | FNU | (XXX.XX) |
| 07 | Read Last Reading Mean Counts | Mean Counts | (XXXX) |
| 08 | Read Last Reading Std. Dev. Counts | Std. Dev. Counts | (X.XX) |
| 09 | Read All Parameters | See Note 1 | |
| 10 | Read Stored Calibration Date | Unix Epoch Time | |
| 11<date> | Write Calibration Date | None | |
| 12<date> | Execute Calibration | None | |
| 14 | Read is Measuring Status Flag | Status | (0 or 1) |

Note 1: The “All Parameters” command returns a comma-separated string of values in the following order: Last Reading Mean, Last Reading Std. Dev., Number of Averages, Integration Time, Calibration Slope, Calibration Intercept, Mean Counts, Std. Dev. Counts, Calibration Date.

# 3 DATA SHARING

Mobile Application. A mobile device app called WeatherCitizen may be used for OpenWater device control and data dissemination (described in detail at https://weathercitizen.org/). WeatherCitizen consists of a mobile application and a cloud database that enables collection and sharing of geolocated environmental measurement data. Measurements can be displayed on an interactive map in near real-time or downloaded by any user. Photographs and additional observations can be added to the data record to assist with interpretation by other users.

Figure 7 shows how the user navigates through the application to make a measurement with the OpenWater turbidity meter. First, the main menu allows the user to connect to an external device from a list of those available. Then, after selecting “Make an Observation” from the Home screen, the Snapshot button starts the process (at this point the application sends an Execute Measurement command). The application allows a photograph to be taken or added from storage, and various observations and notes can be recorded. Once all the metadata is provided, the observation is submitted. If the smartphone is not connected to the network, the observation is stored locally on the phone and uploaded to the remote WeatherCitizen database and web map display when connection is restored.

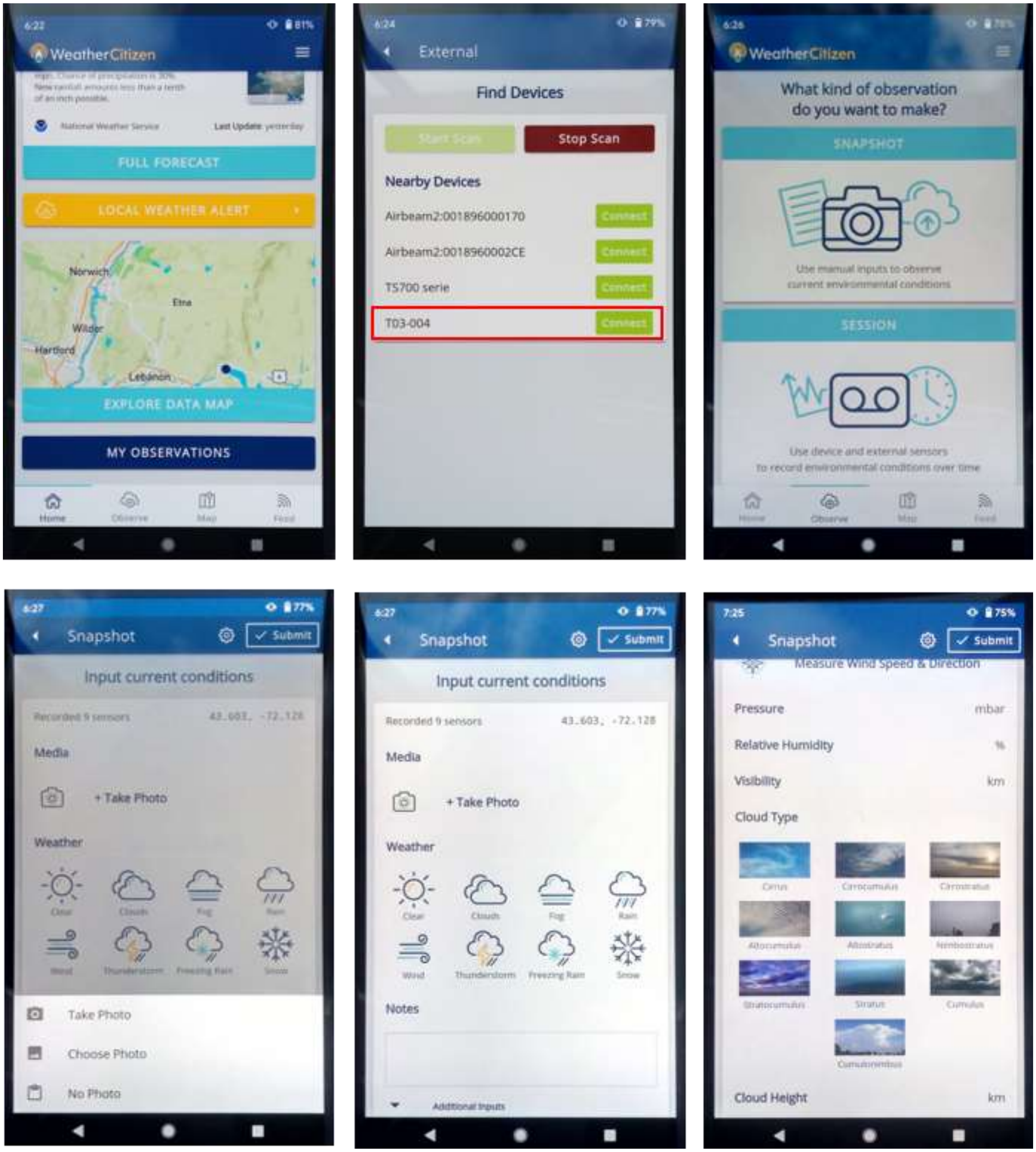

Figure 7. Screenshots of the Mobile Application Being Used with the OpenWater Meter: Home screen (upper left); Selecting a device to connect (upper center); Making an observation (upper right); Adding a photograph (lower left); Adding weather observations and notes (lower center); and Adding additional information (lower right).

Web-Based Data Repository. Sensor measurements collected using WeatherCitizen are stored in a web-based data repository. Several different background base map types, including street, satellite, contour, and nautical maps can be used to visualize data. Map symbols show the location of citizen observations, and they are color-coded based on the value of the underlying measurement parameter. Underlying data can be viewed in chart form (both time series and multi-variate scatter plots) or exported in CSV format for use by other software. In addition to turbidity measurements, the repository also incorporates data from other available sensors (weather, tides, and buoy-based water quality monitoring systems) allowing data from these fixed sensors to be viewed in conjunction with the citizen scientist observations. Figure 8 shows an example of a series of turbidity measurements that were collected along with water temperature, photographs, and weather observations from several water bodies in Enfield and Canaan, NH. In addition to selecting the parameter to display, the data and time range for observations can be adjusted.

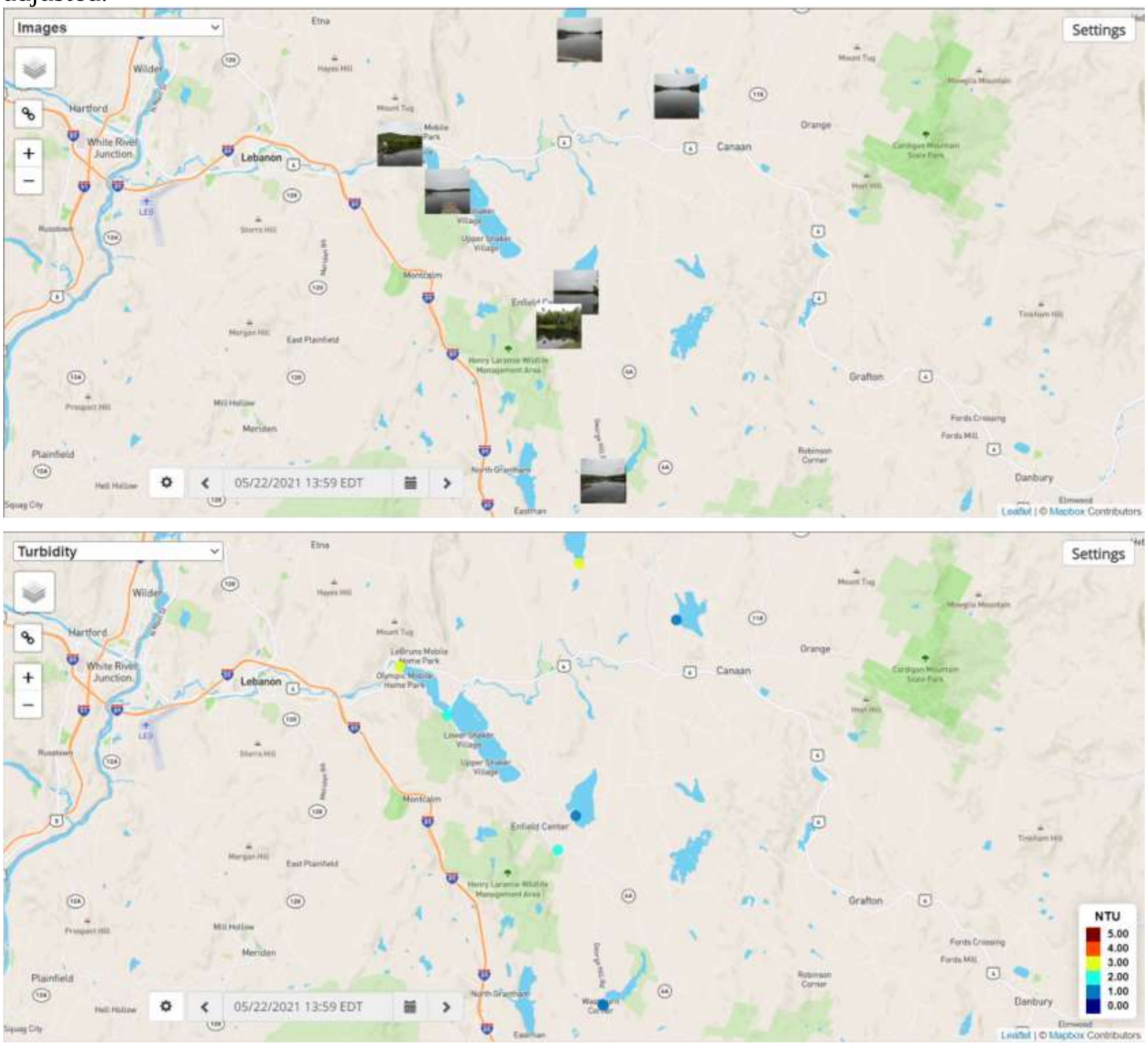


Figure 8. Map Views from Web Application: Images are pinned to the locations where observations were made (upper) and turbidity results that were measured at each site are displayed as dots with color scale indicating the magnitude of the measurement (lower).

Figure 9 shows the detail page that is displayed when the user selects one of the observation locations on the map. The page shows images and metadata associated with the observation.

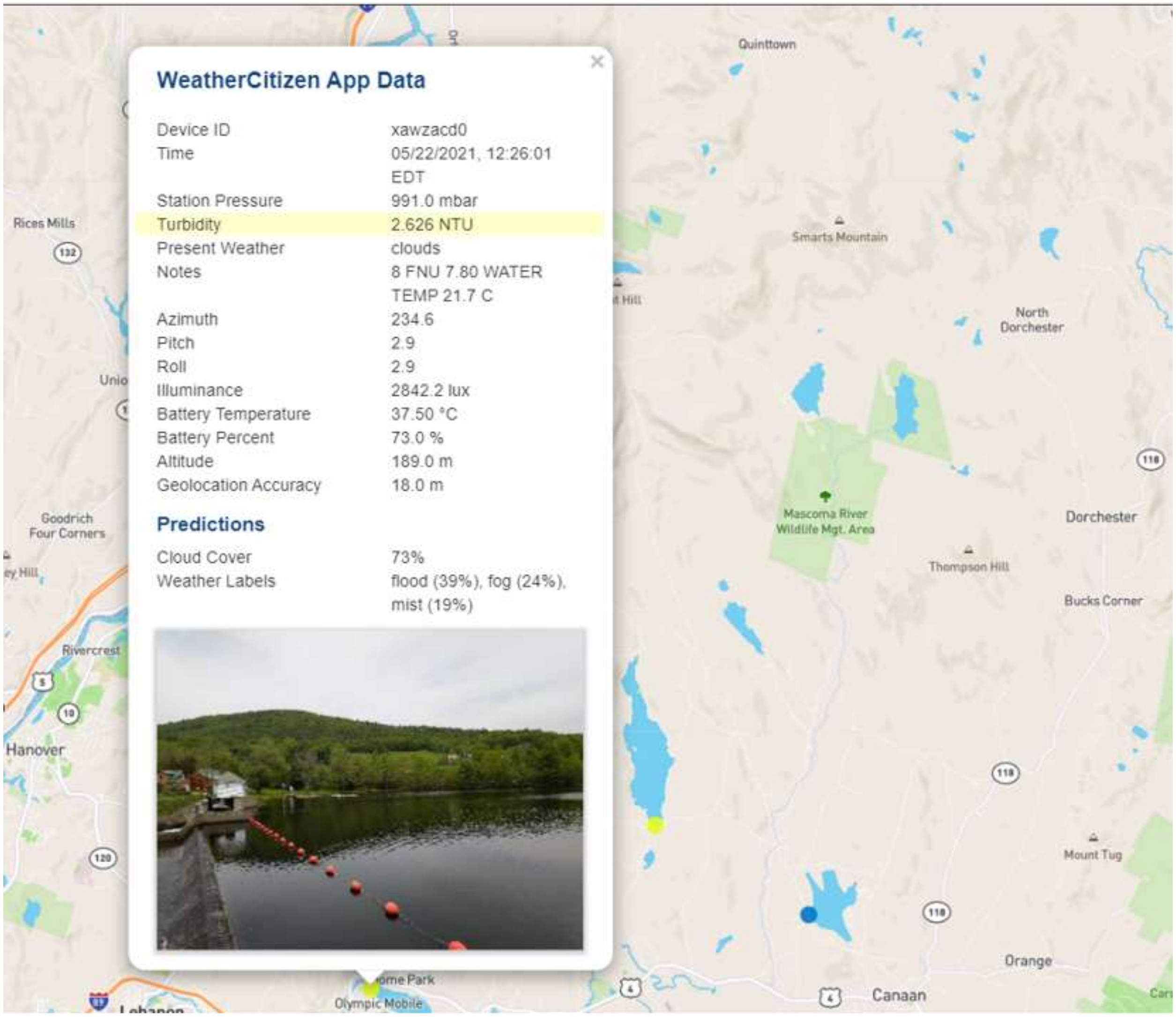


Figure 9. Observation Display Window in Web Application. Clicking on the map location of an observation opens the detail window.

## 4 CALIBRATION & VALIDATION

Measurement Units. A U.S. Geological Survey naming convention provides different turbidity units based on the design of the measurement instrument. Formazin Nephelometric Units (FNU) are used for meters having a monochromatic light source between 780–900 nm and with a detector placed at 90° to the incident beam. The more common Nephelometric Turbidity Units (NTU) and FNU have the same magnitude and are therefore comparable.

Calibration Procedure. The turbidity meter may be calibrated using liquid AMCO Clear primary calibration standards. Four sample vials are selected with similar background readings (when filled with DI water) to create a matched set for calibration and sample measurement. Vials are filled with 0, 5, 8, and 20 FNU standards. Prior to each measurement, vials are gently inverted (not shaken) and carefully wiped using a lint-free cloth. The instrument measures light scattered from the 0 and 20 FNU vials and calculates a slope and offset for the calibration curve. Subsequent measurements are background corrected using the offset and quantified using the slope. Turbidity measurements at 0, 5, 8, and 20 FNU must fall within ±0.5 FNU of the true value to validate the calibration. The vial containing the 5 FNU standard is subsequently emptied and used for sample measurements and the 8 FNU standard is used for continuing calibration verification. The 0 and 20 FNU standards are retained for recalibration of the instrument in the field if necessary (for example, if a large drift due to high ambient temperature occurs). Settings and results of a typical calibration are shown in Table 2.

| Table 2. Turbidity Meter T03-004 Initial Calibration | |
|---|---|
| Calibration Values | 0, 20 FNU[1] |
| Replicate Readings | 3 |
| Integration Time | 3.0 Seconds |
| Mean Dark Counts | 6 |
| Background Counts (0 FNU) | 826 |
| Calibration Slope | 130 counts/FNU |

Note: [1]Formazin Nephelometric Units (FNU) are used for infra-red source meters.

Precision and Accuracy. The accuracy goal for the low-cost meter is ±0.5 FNU below 10 FNU and ±5% above 10 FNU. Results from 30 measurements of standards at 1 and 15 FNU in the laboratory and at 8 FNU in the field were analyzed, to make an estimate of instrument accuracy and precision (Table 3). The accuracy was calculated as the mean absolute deviation of the measurements as a percentage of the standard value. The uncertainty was calculated as the standard deviation of the measurements as a percentage of the mean measured value. These results demonstrate that the instrument accuracy was well within the target value of ±5% throughout the measurement range.

| Table 3. Accuracy & Precision of Turbidity Standard Measurements | | | |
|---|---|---|---|
| Standard Value | 1 FNU | 8 FNU | 15 FNU |
| Mean Absolute Deviation | 0.19 FNU | 0.15 FNU | 0.14 FNU |
| Mean Absolute Accuracy | 19% | 1.9% | 0.9% |
| Precision (Std. Deviation) | 0.04 FNU | 0.16 FNU | 0.12 FNU |
| Relative Uncertainty | 3.1% | 2.1% | 0.8% |

Calibration Verification. After calibration, the linearity of the OpenWater meter was compared to that of a HACH 2100Q-IS in the range of 0–40. Serial dilutions of Formazin were prepared and measured on each device. The correlation coefficient of the linear regression equation was >0.999 in both cases (Figure 10). The small difference in offset between the two instruments was likely due to their individual calibrations.

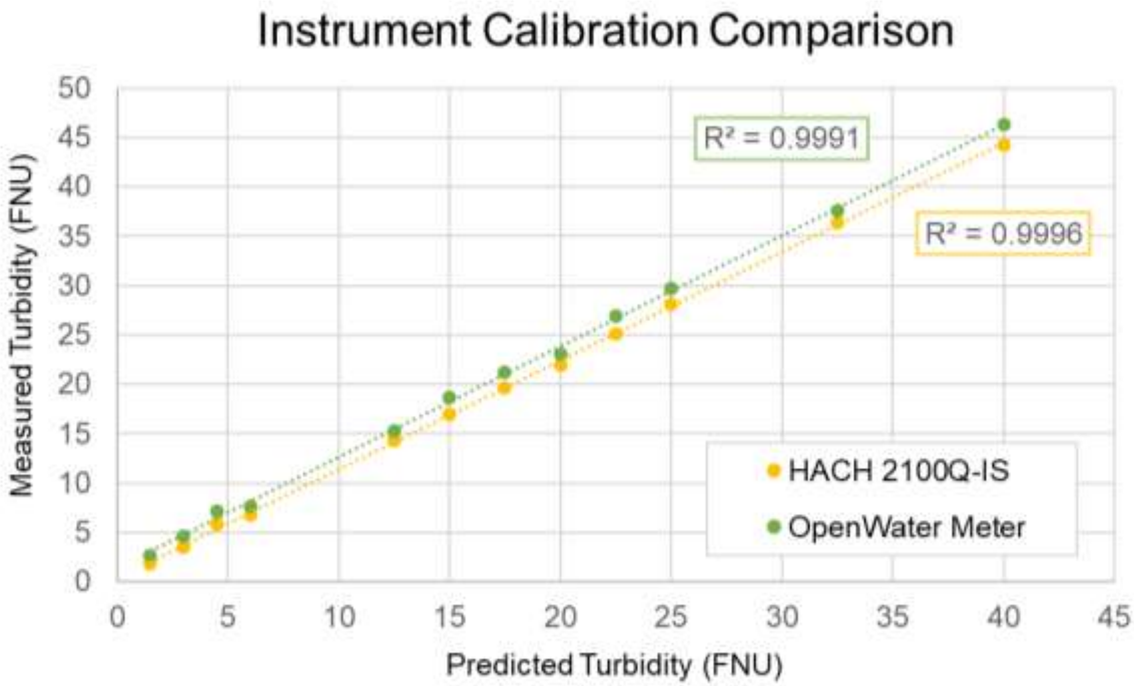


Figure 10. Laboratory Assessment of Instrument Linearity Using the OpenWater and HACH 2100Q-IS turbidity meters.

## 5 CASE STUDY

Long-term Comparison Study. Thirty samples were collected in October and November 2019 (almost daily) from Mascoma Lake in Enfield, New Hampshire. Sample turbidity was measured using the OpenWater and research-grade HACH instruments. Samples were collected from the town dock while it was present prior to its off-season removal (about half of the collection period) and by carefully wading to a depth of approximately 1 foot after it was removed. During each collection, a sample vial was filled and measured for water turbidity together with quality control samples using both meters. A 10 FNU standard (supplied by the manufacturer) was used as a calibration check for the 2100Q-IS meter, and all measurements fell between 9 and 11 FNU (±10%). An 8 FNU standard was used as a continuing calibration check for the OpenWater meter because it is closer in value to most of the environmental samples, and all measurements fell between 7.5 and 8.5 FNU (±0.5 FNU). Figure 11 shows data collected using both meters, and the ambient water temperature at the time of sample collection. The elevated turbidity results coincided with days on which significant wave action was observed. The measurement difference between the two meters does not appear to be related to the water sample temperature.

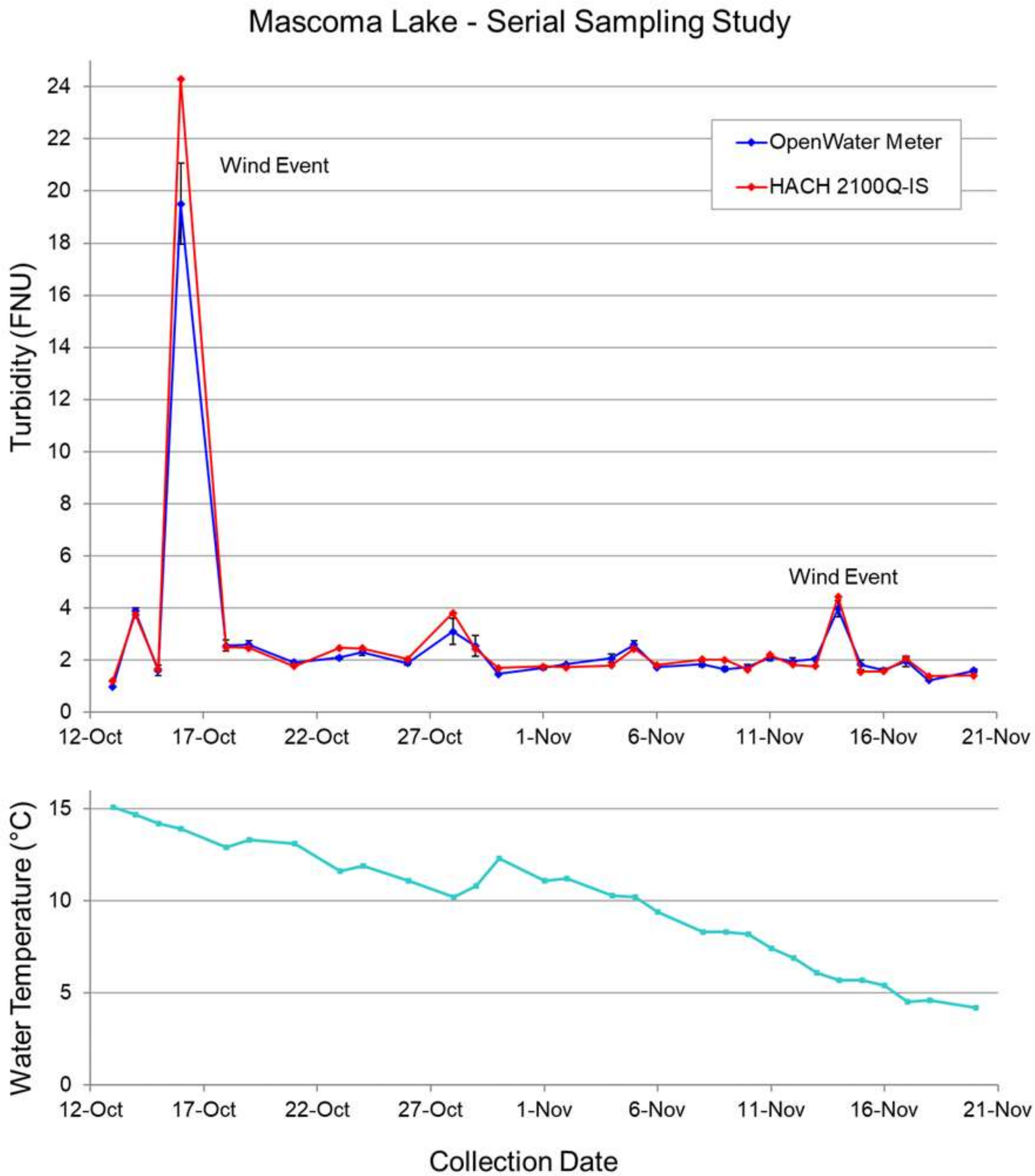


Figure 11. Turbidity Measurement Data Collected at Mascoma Lake Using the OpenWater and HACH Instruments. Error bars for OpenWater data represent the standard deviation of the 3 readings within each measurement.

Figure 12 shows the correlation between the two meters, with the ideal 1:1 relationship (solid blue line) and ±0.5 FNU bounds (dashed blue lines). The mean value of the absolute difference between the two meters was 0.05 FNU. Almost all measurements made with the OpenWater meter fell within ±0.5 FNU of the value measured with the 2100Q-IS meter.

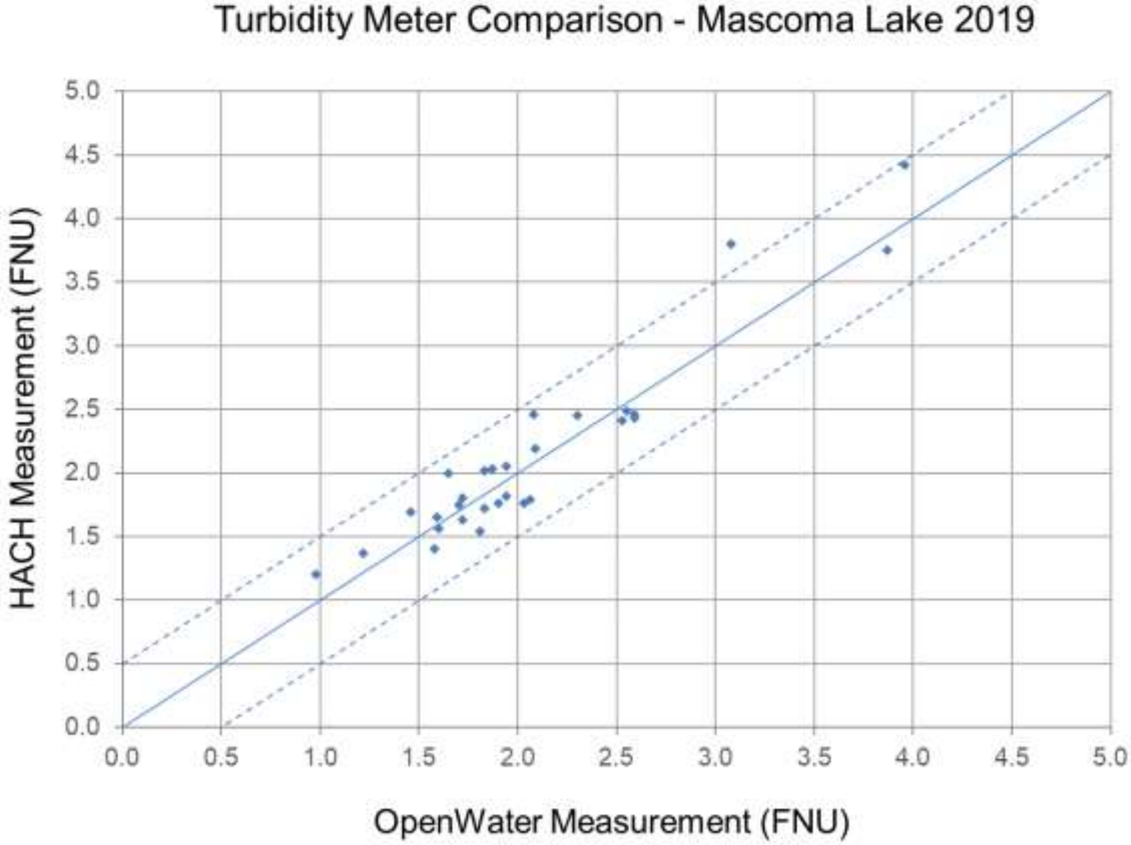


Figure 12. Correlation Between the OpenWater and HACH Turbidity Meters. A linear 1:1 relationship (solid line) and ±0.5 FNU deviation (dashed lines) are shown. The high result from October 16 was omitted for clarity.