HydroSense: An Open Platform for Hydroclimatic Monitoring

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***Abstract*—In the world of water resource management, commercially available hydroclimatic monitoring systems are large, expensive, and disconnected. The current technology is inaccessible to smaller community groups, citizen scientists, teachers, and even university researchers needing to collect real time or high density data. The HydroSense project aims to build an open-source hardware and software framework to enable hydroclimatic monitoring in a more cost effective manner. At present, several prototype system components have been designed, fabricated, and tested. Our design demonstrates that a complete hydroclimatic monitoring system can be deployed at 1/8th the cost of modern commercially available systems. Furthermore, we demonstrate the ability to interface with existing water quality sensors, allowing stakeholders the ability to use instruments they may already own.**

***Keywords*—remote sensing, monitoring, watershed, hydrology, discharge, dissolved solids, innovative technology, environmental chemistry, Chesapeake Bay.**

I. Introduction

The United Nations states that water is at the core of sustainable development and is critical for socio-economic development, healthy ecosystems and for human survival itself [1]. It is vital for reducing the global burden of disease and improving the health, welfare and productivity of human populations. It is central to the production and preservation of a host of benefits and services for people. Water is also at the heart of adaptation to climate change, serving as the crucial link between the climate system, human society and the environment.

Sustainable management of water, both in the United States and around the world, requires the ability for communities to be able to measure key water quality parameters in their local streams, lakes, wetlands, and groundwater aquifers. A crucial element is access to affordable and reliable instruments that can be used to continuously measure basic water quality parameters at sufficient temporal and spatial resolution. Government agencies and universities incorporate these instruments in limited quantities as part of their assessment programs, but most local community groups, citizen scientists, and teachers cannot afford them. With increased monitoring density, pollution can be detected and prevented early or even eliminated entirely. Low-cost monitoring also enables precision conservation and prevention, a hot topic in the Chesapeake Bay Watershed.

Open-source technologies have been identified as the most promising solution to this challenge [2]. As a result, some watershed groups have begun developing their own low-cost monitoring solutions on an as-needed basis [3]. Bucknell University piloted this idea in 2014 [4] and 2015 [5], [6]. In 2014 researchers from Johns Hopkins University and Cornell University published an affordable open-source turbidimeter [7].

By developing a low-cost monitoring framework that is compatible with modern computing systems and open-source development methodologies, we will enable local interest groups, communities, and individuals to readily deploy their own water quality monitoring stations. Data from these stations can be combined to provide quantitative measures of watershed health and help support sustainability efforts. Research centers like the Stroud Water Resource Center [3] and advocacy organizations like the Chesapeake Conservancy [2] are upfront about their needs for precision conservation technologies.

Despite the existence of professional water monitoring technologies, there exist two main hurdles that inhibit the widespread deployment of hydroclimatic monitoring systems. The first hurdle is the reliance on legacy industrial data loggers as the primary sensor interface. These systems are very flexible but as a result are also large, complex, expensive, and power hungry. The second hurdle is the lack of an affordable data collection network. Many systems log data to SD cards or USB sticks which are manually collected. Other approaches rely on costly cellular or satellite connections to deliver relatively small amounts of data to proprietary data collection software. Neither of these solutions promotes widespread hydroclimatic research.

Hydroclimatic parameters such as temperature, flow rate, pH, turbidity, etc. change very slowly relative to the data transmission speed of modern computers and computer networks. The sample rate of these parameters for long-term, continuous monitoring stations is in the scale of a few minutes to hours. The geographic separation between monitoring stations in a watershed depends on the study needs. Detailed investigations may place several sensors in a small area (less than 1 km^2) while other projects may aim to cover a complete watershed with 2-100+ kilometers between sensors. For example, Figure 1 shows the 27,510 mi^2 Susquehanna River Basin. The Susquehanna River Basin Commission maintains a network of 58 monitoring stations in the basin. Each approximately $20,000 station samples water temperature, pH, conductivity, dissolved oxygen, and turbidity every 5 minutes. Data is communicated using a combination of cellular and satellite communications [8]. Although a good starting point, this network only covers a small portion of the Susquehanna River Basin with detailed monitoring as it would be extremely costly to cover the entire basin. The goal of the HydroSense project is to develop a more practical solution to hydroclimatic motioning.

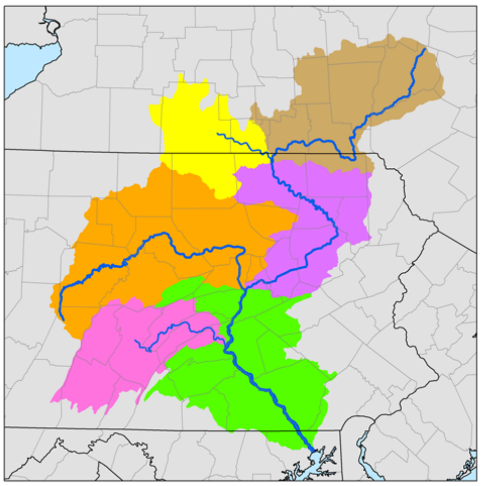

Fig. 1. A map of the 27,510 mi^2 Susquehanna River Basin.[1]

II. Water Quality Parameters

To provide maximum utility, six fundamental monitoring parameters were selected for initial support. Each of the supported parameters, along with a brief statement of their significance and measurement approach is detailed below.

Water Temperature is widely considered to be the most fundamental parameter. In addition to being needed for temperature corrections of pH, conductivity, and other sensors, temperature has significant biological and industrial importance. Temperature affects metabolic rates in organisms, oxygen concentration in water, and even compound toxicity. Furthermore, thermal pollution from power plants and industrial sites can seriously affect watersheds, increasing the need for monitoring of areas near their discharge. Water temperature can accurately measured with a simple thermistor.

Water Depth or **stage** is a critical parameter in relation to flood conditions, effects of precipitation, and as a marker of water body volume [9]. Water depth can be accurately measured using widely available pressure sensors with either a vented cable or a second reference pressure sensor above the surface of the water.

pH measures acidity or alkalinity. Serious fluctuations in pH can be dangerous for humans, but more minor fluctuations directly correspond to the viability of biological organisms. The Colorado River Watch Network states young fish and insect larvae are especially sensitive [10]. Those concerned with pollution monitoring often study pH fluctuation from acid rain and other chemicals. Commercial glass-electrode pH probes are relatively inexpensive and widely available. The glass-electrode produces a millivolt potential proportional to the pH difference to a reference electrode (usually with a pH of 7).

Oxidation Reduction Potential or **ORP** measures the ability to transfer electrons. It is important for water potability as pathogens like E. coli can only survive for 10 seconds in water with ORP of greater than 665mV [11]. The measurement approach is similar to the glass-electrode pH sensor. The sensor itself contains two electrodes; one for sensing and another for reference. The potential difference between the electrodes is proportional to the ORP.

Dissolved Oxygen or **DO** is the amount of oxygen present in the water. It is particularly relevant to biologists as it is how aquatic organisms subsist. Oxygen is diffused into a body of water from the atmosphere, but also comes from photosynthesis of aquatic plants [9]. Dissolved oxygen can fluctuate during the day as a function of surface wind and solar radiation, making extended temporal monitoring of DO especially relevant for fish and wildlife agencies or other stakeholders monitoring aquatic life. Dissolved Oxygen can be measured with a polarographic or galvanic sensor probe. Both contain polarized electrodes isolated by a semi-permeable membrane [12]. Galvanic probes do not require an external voltage while polargraphic probes do. Both types produce an output current ($< 2\mu A$) proportional to the amount of DO present. The low-level current signal can be converted by a transimpedance amplifier to a usable voltage level for a standard analog-to-digital converter.

Specific Conductance describes the ability of the water to conduct electricity. Minerals and other dissolved compounds increase the conductivity, especially in high flow conditions when sediments are washed into a body of water from the surface runoff. Conductance is correlated to total dissolved solids and turbidity [9]. Specific conductance sensor probes are widely available. When performing a measurement it is important to avoid DC signals which can cause chemical changes through electrolysis. Some approaches use alternating current signals but a simpler approach uses an easier to generate short-duration square-wave signal [13].

III. System Overview

A diagram of the the HydroSense components is shown in Figure 2. There are four key components: 1) a datalogger to store measurement data, 2) a water sonde (monitor) to interface to the various water quality sensors, 3) a weather sensor interface to interface to common weather sensors, 4) a 900 MHz long-range radio for communication, and optionally, commercial off-the-shelf SDI-12 digital sensors.

In addition to the hardware, open-source software libraries for Arduino and Raspberry Pi computers are being developed. We hope that by providing open access to this protocol, researchers and hobbyists alike can easily use and expand on the system. HydroSense provides a complete foundation for

[1]Creative Commons CC-BY-SA 2.5 by Wikipedia user Kmusser

deploying low-cost hydroclimatic monitoring stations, both on the datalogger and sensor sides.

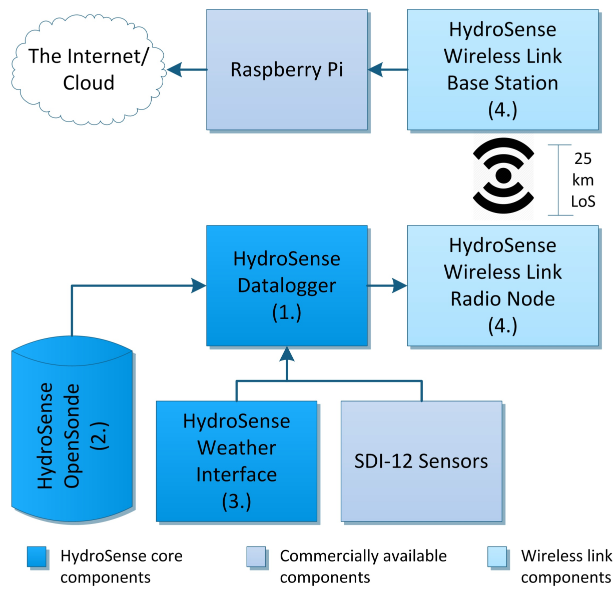

Fig. 2. The four key components of the HydroSense system.

The primary communication between the components is by a SDI-12 bus. This protocol is well suited to remote sensors because it requires a total of only 3 wires to communicate and supply power: +12 VDC, ground, and a bi-directional serial data line. It is widespread in use, with the U.S. Geological Survey employing over 4,000 SDI-12 sensors in its data collection networks. The SDI-12 bus can connect up to 62 sensors over a distance up to 2,000 ft [14]. The protocol was designed for low power applications of low system cost with multiple sensors on one cable. Coupled with the many off-the-shelf SDI-12 compatible sensors available for weather and hydroclimatic monitoring, this protocol was the obvious choice around which to base our system.

Basic operation is driven by the datalogger which periodically polls the OpenSonde, weather interface, and other SDI-12 sensors. As data is received on the SDI-12 bus, it is stored on the SD card and simultaneously transmitted to the wireless base station. The base station can store the data locally, to a remote, or cloud-based database such as MySQL or MongoDB.

A. HydroSense Datalogger (1.)

The datalogger, shown in Figure 3, is at the center of the HydroSense system. It is responsible for powering, sampling, storing, and reporting data from the connected sensors. It is deployed on the river bank near the HydroSense OpenSonde or other sensors. To enable users to easily install new sensors, communication methods, or implement custom logic, the datalogger is based on the familiar Arduino Leonardo platform.

It is fully compatible with the Arduino Integrated Development Environment (IDE) and complies with the Arduino standard shield interface. With PCB and supplemental parts included a single datalogger can be deployed for less than \$200. (See Table I)

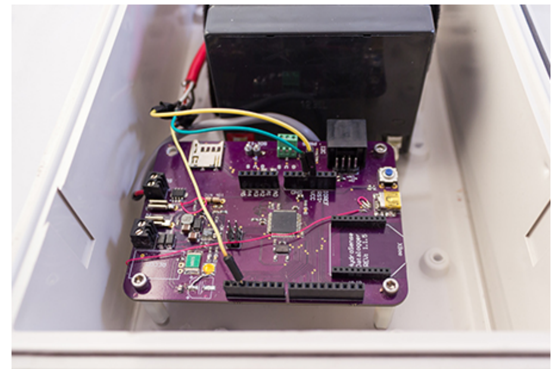

Fig. 3. The HydroSense Datalogger and sealed lead acid battery installed in a waterproof enclosure.

B. HydroSense OpenSonde (2.)

An underwater instrument is needed to measure water-quality parameters. In the field of water quality monitoring this instrument is referred to as a Sonde, the French word for probe. A robust enclosure is required to survive the underwater conditions. The enclosure is constructed from low-cost readily-available parts. The body is a clear 4 inch PVC tube. Liquid-tight cord grips are used to seal measurement probes to the bottom plate. A single water-tight connector provides the 3-wire SDI-12 interface.

The HydroSense OpenSonde board is installed into the OpenSonde enclosure and interfaces to the underwater sensor probes. The sensors are monitored by the OpenSonde and the current values are stored in memory. The datalogger can poll the OpenSonde to retrieve the latest measurements. Like the datalogger, the OpenSonde PCB is based on the familiar Arduino Leonardo platform. This allows users to use the standard Arduino IDE and libraries to customize operation of the OpenSonde.

Including the PCB, enclosure, and sensors, a sonde can be deployed for less than \$1100. (See Table I)

C. HydroSense Weather Interface (3.)

Weather has a strong impact aquatic conditions. Therefore, it is important to capture these parameters in the vicinity of the hydroclimatic monitoring stations. To accomplish this with HydroSense we have developed an interface to standard low-cost weather sensors similar to the sonde interface (except above the water). The analog sensors are sampled and stored in memory on the weather interface. The datalogger can then poll the weather interface to retrieve the stored readings.

Like the datalogger and sonde, the weather interface is based on the Arduino Leonardo platform. This allows users to use the standard Arduino IDE and libraries to customize operation of the Weather Interface.

Including the PCB, and sensors, a weather module can be deployed for less than \$600. (See Table I)

D. HydroSense Wireless Link (4.)

Often the goal of hydroclimatic monitoring is to assess the health of an entire watershed covering many thousands

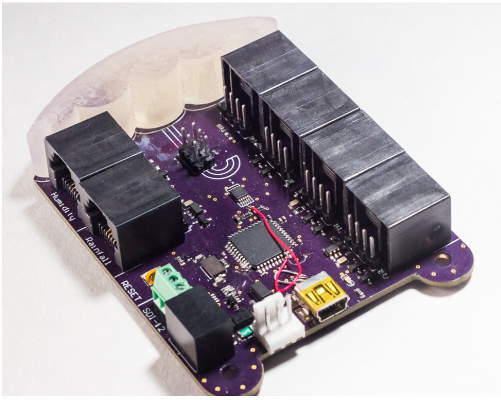

Fig. 4. The HydroSense Weather Interface PCB.

or tens of thousands of square miles with relatively few monitoring stations. The HydroSense Wireless Link achieves long-range communications at the cost of low-datarate. The radio uses the CC1120 narrowband radio with CC1190 front-end providing 27 dBm output in the 900 MHz ISM band. Due to the low-datarate, a cellular model is used to avoid congestion caused by ad-hoc packet forwarding. Each radio network cell is managed by a base station node running on a Raspberry Pi computer with Internet access via DSL, cable modem, or cellular network. The expected communication range is 2 km - 25+ km depending on antenna height and terrain. A time and spatially synchronized network protocol (TDMA/SDMA) is being developed to allow efficient use of the limited network bandwidth and reduce the power consumption on each node by allowing very low duty cycles of the radio (e.g., $\ll$1%).

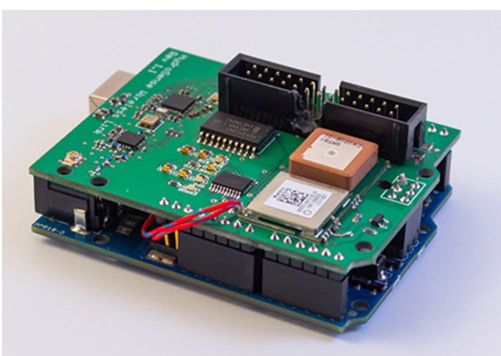

Fig. 5. Prototype HydroSense Wireless Link atop an Arduino Uno (without antenna). RF components are on the left side of the board, while peripherals are towards the right.

The HydroSense Wireless Link board includes a global positioning system (GPS) receiver for time synchronization and position awareness and a real-time clock to maintain precise timing without GPS. The board has a novel dual interface to provide compatibility as an Arduino Shield or a peripheral for a Raspberry Pi (models A/B and generations 1/2). This dual interface allows sensor nodes and gateway nodes to share the same wireless link board, reducing cost and development time. The base station nodes uses a Raspberry Pi to provide connectivity between the 900 MHz network and a WiFi or wired Ethernet Internet connection. Low-level hydroclimatic sensing applications are more suited to the Arduino platform due to its flexible hardware interface, improved timing, and lower power consumption. The assembled PCB cost is $100 in low-volume.

E. HydroSense SDI-12 Software Library

SDI-12 is a text-based protocol which provides a digital interface to up to 62 wired sensors. Each command begins with the address specified by a single alphanumeric ASCII character, followed by a command string, and an exclamation point specifying the end of the command. The sensor is required to respond within a timeout period and ends its response with a carriage return and line feed. An example of a *Send Data* transaction is shown below.

```
aD0!
a+119+25.3+302<\CR><\LF>
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For the *Send Data* transaction, the response data string is comprised of the sensor address ('a'), depth (119 mm), temperature (25.3 C), and conductivity (302 μS/cm). All values except the sensor address are preceded by the appropriate sign (either + or −); the sign characters serve as delimiters to separate each parameter.

The HydroSense SDI-12 library allows users to communicate with any SDI-12 sensor system within the Arduino IDE. It is the only open-source library that implements SDI-12 over the Arduino *HardwareSerial* class, exposes the sensor side of the protocol, provides a hardware-independent abstraction layer, and grants a simple API to the end user. For the HydroSense datalogger, we have hardware (UART) controlled and software emulated interfaces.

The datalogger side uses an asynchronous paradigm. This allows for multiple remote sensors to be efficiently queried on the same bus. The library handles all data transactions, detects when a measurement is ready to be collected, and converts the text responses to binary data. The communication medium is selected on instantiation and automatically configured by the controller.

The sensor side uses an asynchronous event-handler paradigm, allowing the user to handle measurement requests while taking care of the low-level protocol requirements.

We designed this library for use in our own datalogger and sonde but it abstracts away the communication protocol from the hardware implementation. The interface *SDIStream* expands on the Arduino Stream interface, providing I/O control and begin and end calls. Only an implementation of the *SDIStream* interface is required to port the library to new hardware. We hope that by designing our library in this way, we provide an interface that is easy for others to use in their own projects.

IV. System Testing

The HydroSense system is still under active development for field deployment in the summer of 2016. The electronic subsystems have been tested in isolation and our testing has focused on the software libraries.

An important functionality of the HydroSense system is the ability to accept third-party sensors. A research group may already own SDI-12 sensors or require specialized sensors outside the scope of the HydroSense system. Furthermore, these third party sensors are application-specific and come with certificates of calibration. For testing the functionality of third-party sensors with the HydroSense Datalogger we selected the Decagon Devices CTD-10 sensor. The CTD-10 measures water temperature, depth, and conductivity, useful for studies with groundwater wells.

To test our SDI-12 library we used a hybrid approach. Initially we used our own fork of *arduino-mock*[2], Google's GMock and GTest libraries for high-level unit testing. From there, we individually tested protocol functions using a protocol analyzer, verifying the proper timing and data format. Finally, we validated the library using a Decagon CTD-10, validating we were recieving consistently correct results while maintaining proper communication with the sensor.

V. System Cost

The total cost for a HydroSense monitoring station is shown in Table I using the cost information from the initial prototypes. The prototype system is able to monitor six fundamental water-quality parameters, very similar to the $20,000.00 stations currently deployed for water-quality monitoring. Not included in this cost are materials required for deployment (mounting, anchors) and cabling. Including a generous budget for these items, it is clear that a HydroSense monitoring station can be deployed for less than $1/8$th of the cost of the current approach ($2,500.00).

TABLE I. Cost Breakdown of the prototype HydroSense monitoring station.

Component	**Cost**
Datalogger	$83.70
Radio Link	$102.03
Weather Interface	$76.82
Weather Sensors (solar radiation, anemometer, wind vane,humidity/temperature, and rain gauge)	$465.00
Enclosure, 12 V battery, 15 Watt solar panel	$105.00
OpenSonde	$110.00
OpenSonde Enclosure	$86.66
OpenSonde Sensors (PH, ORP, DO, temperature, pressure, and conductivity)	$865.00
TOTAL	1,894.21

VI. Conclusions and Future Work

Commercially available hydroclimatic monitoring equipment is supplied by well-established manufacturers at significant cost. Further, most of these systems rely on proprietary hardware and software interfaces. These factors make it impractical for small community groups, citizen scientists, and teachers to monitor local hydroclimatic parameters of interest. In this paper we present HydroSense, a complete open-source Arduino-compatible platform for hydroclimatic monitoring. Through our initial prototype, we have validated the primary functions of the system and demonstrate the total system cost is less than $1/8$th of commercial systems. All of the developed hardware and software components are freely available on our website, http://hydrosense.net/. We believe this open-source approach will help to fuel a new generation of hydroclimatic research.

[2]https://github.com/Hydrosense/arduino-mock

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