Low-cost electronic sensors for environmental research: pitfalls and opportunities

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Abstract

Repeat observations underpin our understanding of environmental processes but financial constraints often limit scientists' ability to deploy dense networks of conventional commercial instrumentation. Rapid growth in the Internet-Of-Things (IOT) and the maker movement is paving the way for low-cost electronic sensors to transform global environmental monitoring. Accessible and inexpensive sensor construction is also fostering exciting opportunities for citizen science and participatory research. Drawing on six years of developmental work with Arduino open-source hardware and software and active field research, we outline a series of successes, failures and lessons learned in designing and deploying environmental sensors. Six case studies are presented: a water table depth probe, air and water quality sensors, multi-parameter weather stations, a time-sequencing lake sediment trap and a sonic anemometer for monitoring sand transport. Sensor design and schematics are described alongside an evaluation of pitfalls and future improvements for individual sensors and the workflow process. We show that manual design and construction can produce research-grade scientific instruments for a fraction of the conventional cost. In sharing our collective experiences with build-it-yourself environmental monitoring, we intend for this paper to act as a platform for scientists and educators to delve into low-cost sensor development. This will ultimately lead to superior environmental monitoring at higher spatial and temporal resolution from the local to global scales.

Keywords

Arduino; Data-logging; Environmental monitoring; FreeStation; In-situ measurement; Low-cost electronic sensors; Open-source; Open-source Hardware

I Introduction

1 Hurdles to environmental monitoring

Environmental science is rooted in observation. Long-term measurements of ecological, meteorological and hydrological variables provide the foundation for understanding trends, establishing benchmarks and informing policy (Mishra and Coulibaly, 2009; Tetzlaff et al., 2017). Such data are critical for estimating magnitudes of change in natural systems induced by human activity, such as projected climate warming (Hannah et al., 2011). The ever-increasing sophistication of remote sensing tools and computational models is delivering major advances in environmental science (McCabe et al., 2017). However, alongside increased data gathering by satellites, there has been a concurrent shrinking of conventional ground-based monitoring and measurement. Experimental and field research, for example, is in decline in the hydrological sciences (Burt and McDonnell, 2015) and appetite to support monitoring networks is diminishing amongst funders (Tetzlaff et al., 2017). The global density of hydrological stations has decreased since the 1980s (GRDC, 2018; Hannah et al., 2011) and similar rates of closure of hydro-meteorological stations, especially in Africa and Latin America (WMO, 2009, cited in van de Giesen et al., 2014; Overeem et al., 2013), have been shown to hamper ground-truthing efforts (Lorenz and Kunstman, 2012). This trend is concerning since satellite remote sensing is not without limitations, including the mismatch in spatial and temporal scale between satellite observations and environmental phenomena. For example, the coarse spatial resolution of current satellite soil moisture products does not adequately capture fine-scale variability (Tebbs et al., 2019a; Larson et al., 2008). In addition, many parameters cannot be directly measured from satellite remote sensing (e.g. sub-surface soil moisture, dissolved oxygen). *In situ* measurements are therefore essential for monitoring a full suite of environmental parameters, in addition to their importance for validating satellite products and models.

Time and financial expense are major barriers to collecting ground-based environmental data (Muller et al., 2015; Tauro et al., 2018). Sophisticated instrumentation brings high maintenance costs and a continual need for skilled staff. Increasing the spatial and temporal resolution of repeat measurements demands proportionally greater investment of resources. Even legally mandated national monitoring schemes suffer logistical constraints. The EU Water Framework Directive requires Member States to measure river water quality four times per year, but summed annual loadings are almost certainly underestimates with wide margins of error (Skarbøvik et al., 2012). The arrangement of air pollution monitoring sites across Europe is also regulated (EU Air Quality Directive 2008/50/EC), but the stationary network is unable to pinpoint emission hotspots or their sources, assess the influence of localised meteorology or track plumes (Castell et al., 2016; Thompson, 2016; Rai et al., 2017; Morawska et al., 2018). Though modelling can go some way to filling the void, models such as atmospheric dispersion models are computationally heavy and limited in their predictive capabilities (Kumar et al., 2015).

Alternative monitoring approaches using low-cost instrumentation are gaining momentum across the environmental sciences (Kumar et al., 2015; Muller et al., 2015; Tauro et al., 2018). This is illustrated by the growing prominence of open-source development communities such as the Gathering for Open Science Hardware organization (GOSH), local ‘hackathons’ and public engagement with citizen science initiatives. Low-cost sensor networks have been suggested as a means of improving the spatial coverage of ‘ground-truth’ data for validating satellite products (Tebbs et al., 2019b). A handful of large-scale monitoring networks have been launched, such as the Freestation initiative (www.freestation.org) and the Trans-African Hydro-Meteorological Observatory (www.tahmo.org; van de Giesen et al., 2014). These demonstrate an appetite for low-cost scientific monitoring options by researchers and the wider public.

2 Open-source hardware and the Arduino platform

The open-source movement unfurled in response to the desire for users to “break the black box” and understand how programmes and equipment work. The ultimate aim is usually customisation for specific applications. Customisability heavily depends on the degree to which commercial manufacturers allow their software and hardware be altered by external parties. Open-source describes an alternative approach by which any interested person or team can contribute to machine or software development (Wu and Lin, 2001). Whilst prominent freely-accessible software emerged in the 1980s (GNU) and 1990s (Linux), there has been a proliferation of Open-Source Software (OSS) and Open-Source Hardware (OSH/OSHW) in the last several years (Boisseau et al., 2017). OSH consists of physical technology that can be freely replicated (e.g. circuit boards) or assembled using openly available drawings, schematics and/or circuit board layouts. OSS meanwhile consists of source code or code-snippets again publicly available.

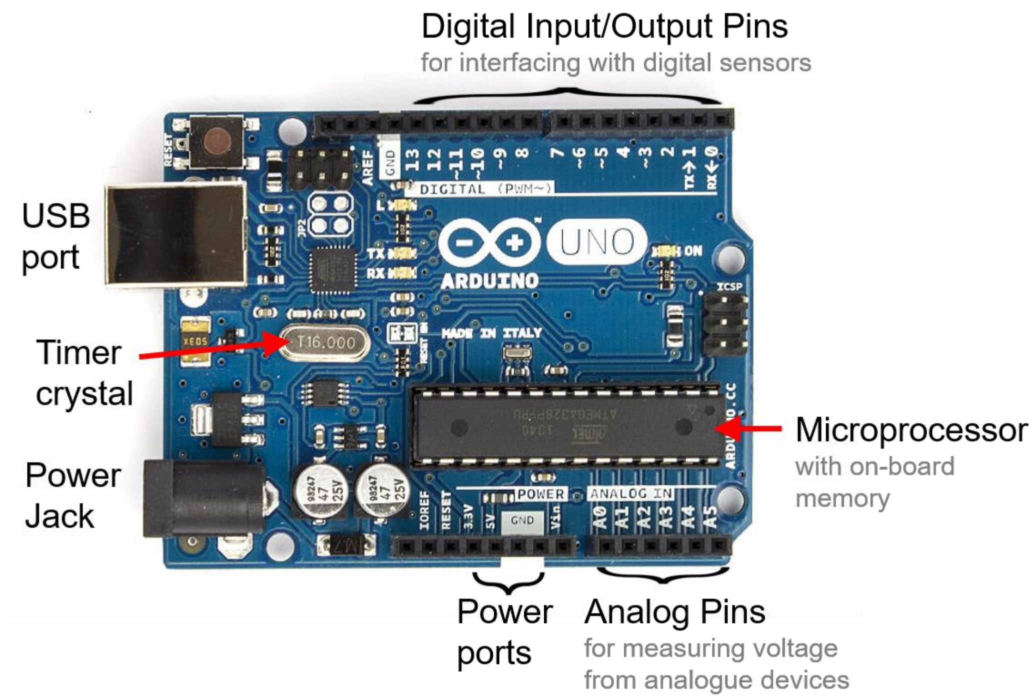
The rise of Open-Source Hardware has been, to a considerable extent, attributable to the rise of the ‘Arduino’ hardware and software platform. ‘Arduino’ is a brand of open-source microcontrollers that may be used for assembling environmental sensors and data loggers, alongside a plethora of other applications (see www.arduino.cc for a sample of practical applications). Commonly referred to as I/O devices due to their ability to simultaneously act as Input devices (i.e. receiving, detecting or measuring electronic signals or voltage levels) and Output devices (i.e. sending electronic signals or varying output voltage levels), microcontrollers typically consist of the components outlined in Figure 1.

Though the development of microcontrollers started many years prior to the emergence of the Arduino brand (notable precursors include PIC and Parallax microcontrollers), the development of Wiring/Arduino was pivotal in transferring micro-controller programming from the hands of specialised engineers to wider audiences. Prior to Arduino, most microcontroller prototyping tools were prohibitively expensive and required steep learning curves (D’Ausilio, 2012; Kusher, 2011). Under the supervision of professors from the Interaction Design Institute Ivrea (IDII), Wiring (the predecessor of the Arduino programming language) was developed as a simplified coding language for programming Atmel microprocessors. Thus, the combination of the simplified, open-source software (the Arduino Integrated Development Environment – hereafter, Arduino IDE) and widespread availability of low-cost hardware (Arduino boards, based on Atmel’s ATMega processors) led to the widespread adoption of microprocessors by hobbyists and the public (Furber, 2017). Through the release of tutorials, troubleshooting forums and continual software and hardware development, the open-source nature of Arduino has diminished the learning curve and created a growing user community of beginners and experts.

3 Applications for environmental science education and citizen science

Open-source software and hardware has long been seen as a key tool for shifting computer technology education from prescribed learning (Selwyn, 2007). By cracking the ‘black box’ of software code or literally opening up scientific hardware for modification, students and lecturers can adapt technology to their own needs. This pragmatism lies at the heart of John Dewey’s constructivist theories of understanding as applied to learning (Koohang and Harman, 2005). In particular, the focus on knowledge construction (not reproduction) and the provision of authentic contextualised instruction in a real-world, case-based setting (Jonassen, 2006). Thus, Alimisis (2013, p.67) explicitly refers to Arduino as promoting the paradigm shift from ‘black box’ to ‘white box’ understanding, with learners as “makers” rather than simply “consumers”’. From our pedogological experience, physical geography projects using Arduino OSHW cultivate strong student engagement. Success (or failure) is clearly visible (i.e. does the device perform as intended) and learning through troubleshooting leads to more critical consideration of the resulting environmental data. Hands-on sensor development creates ownership of the process and the learning outcomes. This ownership and voice in the learning process is a key goal in constructivist learning environments (Honebein, 1996).

Accessible and inexpensive OSHW such as Arduino has also evolved citizen science (research conducted by amateur scientists) into what some now term ‘Extreme Citizen Science’ (Stevens et al., 2014). In these exemplary situations, participants help devise and operate their own scientific equipment, democratising participation in environmental research and arming citizen groups with the data required to address potential concerns. This combination of citizen scientists with technology facilitates a form of ‘participatory science’ where lay-people may contribute data to a project, collaborate on refining a method or co-create research from concept to analysis (Bonney et al., 2009).



Component	Description and function
Microprocessor	An embedded chip consisting a processor and hardware controller.
USB port and programmer	Provides a means to interface with a computer. This is both for uploading (or ‘flashing’) the program to be run and communicating results. Some microcontrollers require an independent programmer which must be plugged and unplugged.
Dedicated Ports	Connection ports for easily connecting/disconnecting periphery devices
Analog Ports	For measuring varying voltages from analogue devices
Digital Ports	For interfacing with digital sensors and devices.
Voltage regulators	Converts (or ‘regulates) voltages from power sources to the voltage required by the microprocessor and periphery devices
Other componentry	Microprocessor boards often incorporate other critical componentry, e.g. timer crystal, capacitors, memory.

Figure 1. Arduino Uno anatomy with components and functionality common to many microcontrollers labelled. Source: oomlout (CC-BY 2.0).

4 Purpose of the paper

This paper aims to catalyse and accelerate the take-up of low-cost sensors for environmental research. It draws on six years' experience developing, testing and deploying a range of Arduino-powered, low-cost environmental sensors by staff and students of the Department of Geography at King's College London. The impetus for each project has varied: some were geared towards research advancements while others were initially developed as teaching activities. In each case, numerous unforeseen challenges have helped us develop smooth, effective workflows and reliable, research-grade data is now rapidly emerging. The following sections explain the core components of an Arduino environmental data logger before presenting six case studies: 1) a water table depth probe; 2) an air quality monitor; 3) an aquatic water quality multi-probe; 4) a customisable multi-parameter weather station; 5) a time-sequencing sediment trap; 6) a sonic anemometer for monitoring wind-blown sand dynamics. We then outline our workflow for best practice during development and deployment of low-cost environmental sensors to avoid potential pitfalls we frequently encountered. We intend this paper to act as a transformative platform and the key reference for physical geographers (and geoscientists more broadly) looking to move into low-cost environmental monitoring. In our view, careful adoption of open-source environmental sensors will deliver step-change improvements to global environmental monitoring and management.

II Environmental sensors

1 Background to Arduino open-source hardware and software

Arduino is a type of microcontroller with its own processor and memory that uses code to control electronic devices (Karvinen and Karvinen, 2011). The Arduino programming language is based on C/C++ that is accessed via a user-friendly IDE. An enormous online community provides technical support as well as an extensive list of existing libraries (collections of code that provide bespoke functionality for individual sensors). Despite their versatility, microcontrollers are on their own inadequate for formal scientific environmental monitoring. Core components required for most sensors are described in Table 1. Though these components can be connected via breadboards and jumper wires, bespoke printed circuit boards (PCB) can be used to simplify construction and minimise connectivity issues such as loose wiring or poor soldering. Most components can be easily acquired from UK and overseas sellers. Costs are usually lower from suppliers in China, but at the expense of lengthy delivery times and long-distance transport emissions.

Table 1. Key components for an environmental data logger.

Component	Function	Version	Typical cost (£ GBP)
Arduino board	Microcontroller to interface sensors, clock and memory	Pro Mini or Nano	3.00
Breadboard	Prototyping or solderless circuits	400-point	1.50-3.50

Solderboard	A solder-able breadboard for robustness	PTH-protoboard-30	4.00
Real Time Clock	High-accuracy time-keeping and power-saving by utilising in-built alarm functions	DS3231, DS3234, 1 PCS data logging shield	2.00-14.00
(Micro)SD Card & shield	Portable data storage and handling	Any	Varies with storage size
Battery holder, connector and batteries	Power supply	We prefer unwired holders and leads with press stud contacts	Holder = 1.00, lead = 0.50

2.1 Water table depth probes

Tropical peatlands are one of the most carbon (C) dense ecosystems in the world, storing 3% of global soil C on 0.25% of the total land area. However, over the past few decades, peatlands in Southeast Asia have been deforested and subjected to different land-uses, mainly by employing drainage and fire, resulting in their conversion to a net source of C (Evers et al., 2017). These disturbances not only result in loss of vegetation structure but also enhance peat oxidative decomposition. To assess the impact of deforestation, drainage and fires on peatland CO_2 emissions (e.g. through gas chamber flux measurements), it is necessary to supplement flux measurements with water table and soil temperature monitoring. An ongoing CO_2 and CH_4 flux monitoring site in the tropical peatlands of Belait District, Brunei, consists of 10 sampling sites with bored water table monitoring wells. Conventional water depth sensors (e.g. Van Essen Diver) are relatively expensive at $750 per unit. Authors Smith and Chan developed low-cost water table depth sensors that can be supplemented with water and/or soil temperature sensors.

Our initial approach was to use a differential pressure sensor (e.g. NXP MPX5010DP) coupled with an ADC and standard Arduino logging components (outlined in Table 1), housed inside a weather-proof junction box. The differential pressure sensor consists of two tube connections, allowing for one tube to be submerged in the well (sensing water head pressure and atmospheric pressure), with the other tube exposed to atmospheric pressure only. The difference in pressure may be used to calculate the water depth. Advantages of this setup are that only the tube needs to be submerged in the well, with all electronics housed at the surface; the differential nature of the measurement allows for very high precision; and there is no need for a separate measurement of atmospheric pressure. The major disadvantage of the setup was the need to have a tube exposed to atmospheric pressure, leaving the housing exposed to humidity and insects, resulting in the failure of most units and heavy degradation of others.

Our second, and more successful approach, used a single pressure sensor (e.g. TE Connectivity ms5803-02ba). Here we use a 2-bar sensor (up to ~10 m water depth, though other variants are available for deeper, or better precision for shallower, applications). The sensor and Arduino components are housed inside a water-proof aluminium tube (Figure 2) with two screw-threaded caps at each end, which must sit inside the well. The space-constraints of the tube necessitates direct-soldering of short wires onto components and the Arduino, with connection wires also directly soldered onto a small lithium ion battery (there is a lack of space for a battery holder). The challenging assembly of this design is its main disadvantage. The sensor is delicate, but needs to be exposed to water pressure, while its electronic connections need to be waterproofed. Our solution to this was to attach a small section of rubber tubing fixed to the protruding pressure sensor; this tubing was fed through a drilled hole in one end of the tube housing, before an epoxy coating was applied to the tube cap, fixing the sensor and rubber tubing in place, isolating the exposed sensor from the electronic components. The necessity for short wires and direct-soldering also affected ease-of-assembly and increased the likelihood of misconnections/ripped wires when screwing the caps on the tube housing. Thread seal tape was used on the screw threads for the housing to ensure waterproofing. A separate atmospheric pressure sensor was needed for the calculation of water depth. Code was leveraged from the sensor (MS5803) library. Our Arduino-based pressure sensor was deployed alongside the Van Essen Diver at one of the ten wells in Brunei, showing strong performance over a two-month period (Figure 3).

Figure 2. A set of water table depth loggers designed following the second, more successful approach using a single pressure sensor (see text for details).

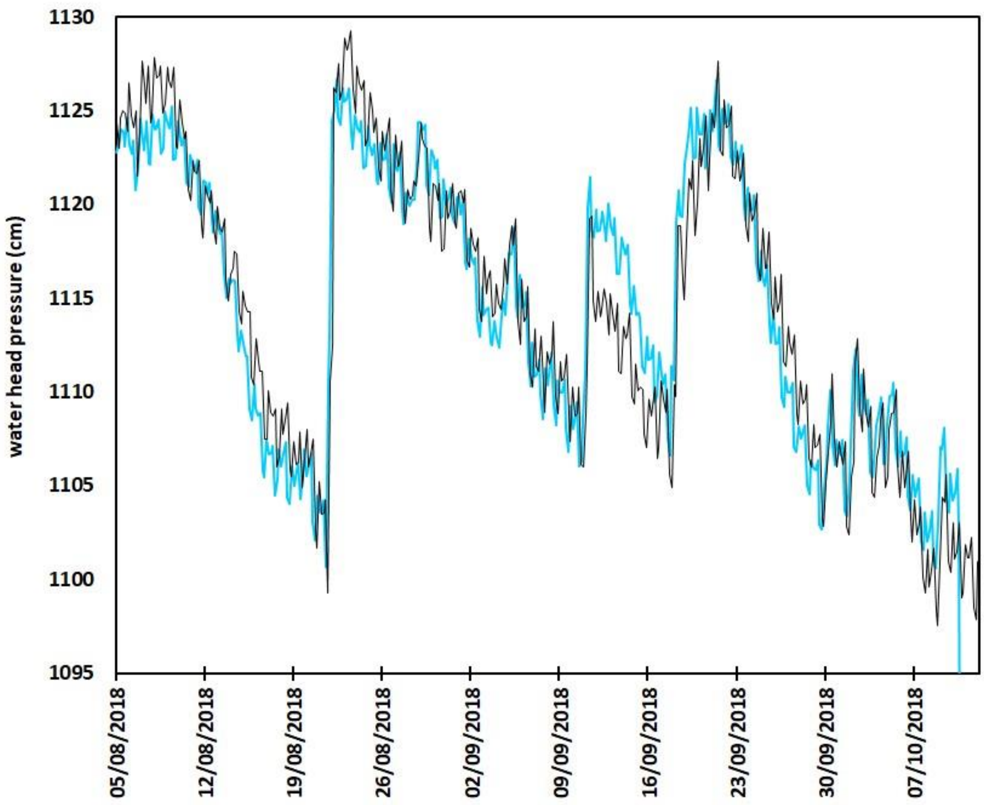


Figure 3. Comparison of head pressure as measured by the Arduino (blue line) against a commercial equivalent Van Essen Diver, ~$750; black line). Both loggers were deployed in the same well for two months. Values have not been corrected for atmospheric pressure.

2.2 Air Quality loggers

The pervasive threat of poor air quality in urban settings and its acute physiological effects are becoming clear (Atkinson et al., 2016). Gaseous and particulate emissions have been linked to greater risk of child obesity (Kim et al., 2018), adverse effects on foetal growth (Smith et al., 2017) and more frequent incidences of dementia in London (Carey et al., 2018), for example. In urban areas, the particulate component is predominantly derived from vehicles through combustion emission, braking and tire abrasion as well as domestic wood burners (Vicente et al., 2015) while the gaseous fraction is primarily released during fossil fuel combustion. Urban air quality is typically monitored using fixed, ground-based stations. Costs of such configurations run to many thousands of pounds per instrument (Mead et al., 2016) and stationary infrastructure is less suitable for pinpointing emission point-sources and assessing personal exposure and localised risks. Low-cost air pollution sensors offer valuable granularity and portability with initial studies showing promise (Mead et al., 2016; Piedrahita et al., 2014). We have developed Arduino sensors to measure particulate matter (PM_1, $PM_{2.5}$ and PM_{10}) and trace gases (NOx, O_3 and VOCs), which showed good performance when calibrated against London Air Quality Network (LAQN) stations.

For particulate matter, we determined the most effective sensor to be the *Plantower PMS-5003* sensor (~£18 GBP), an optical, laser scattering sensor that achieves high accuracy (98% counting efficiency of PM ≥ 0.5 μm (Plantower, 2016). Its rapid measurement response time (≤10 seconds) allows reliable measurements to be made in transit. Tests of cheaper (£10 GBP) *Sharp GP2Y1010AU0F* sensors showed inferior performance and the need for self-calibration. Electrochemical gas sensors manufactured by Alphasense have been used to measure NO, NO_2 and O_3, with reported accuracies below 1, 0.5 and 0.5 ppm, respectively (Alphasense, 2017). We adapted two designs: one incorporates a pump, air flow circuitry and filter system that keeps separate the PMS 5003 inlet and outlet before removing particulates prior to entering the gas chamber (Figure 4). We ensured sampling intervals were programmed to mimic the instrument's inhalation and exhalation cycle. The second fixes the PM and gas inlets and outlets to separate holes drilled through the housing. We usually mount a Bosch *BME280* that measures temperature, humidity and barometric pressure or a *BME680* (also samples volatile organic compounds) alongside the *Plantower*.

We calibrated the Arduino air quality sensors against the LAQN kerbside monitoring station on Marylebone Road, a major arterial route through west London. Both the Plantower (R^2 = 0.75, RMSE = 4.29) and Alphasense (R^2 = 0.88, RMSE = 12.63) showed strong performance over seven-day calibration periods (Figure 5), capturing both variation between weekday and weekend traffic density as well as rush-hour peaks. Our sensors produced promising research-grade data and allowed new questions to be explored at the local or community level. For example, one deployment showed the installation of an ivy green screen at a primary school in central London decreased NO_2 concentrations during peak traffic congestion by 35%, whilst another confirmed that choosing an optimal form of public transport to minimise personal exposure presents a predicament: particulate matter is high when walking, cycling, or on the Underground, but time inside buses and cabs increases exposure to NO_x.

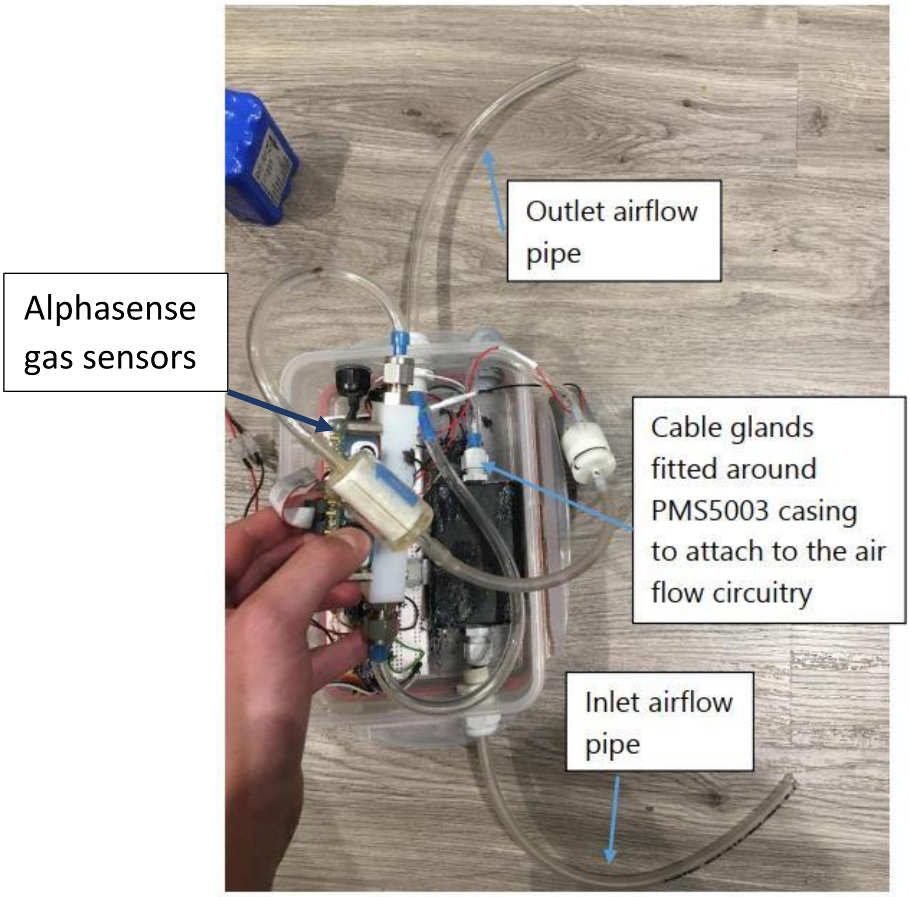


Figure 4. Air quality sensor array comprising a Plantower PMS5003 and a set of Alphasense gas sensors.

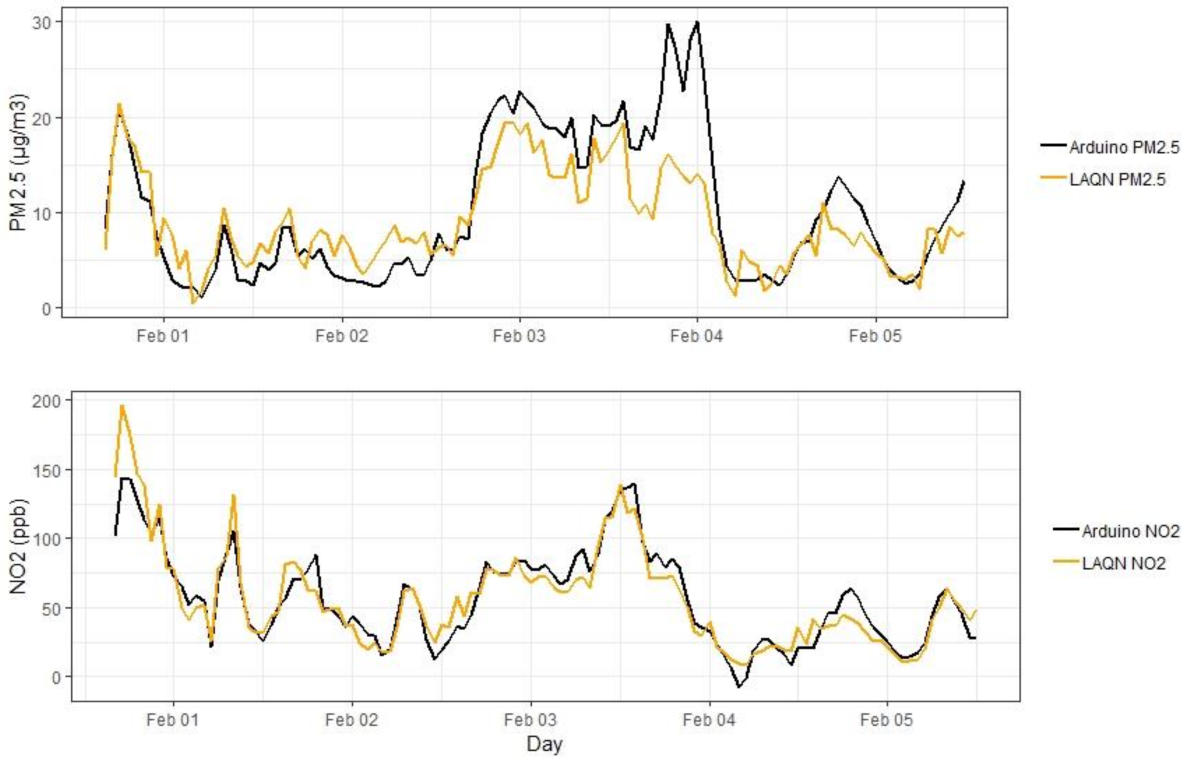


Figure 5. Data comparison of $PM_{2.5}$ and NO_2 measurements made by an Arduino sensor and the London Air Quality Network's (LAQN) Marlyebone monitoring station over a five-day period in February 2018. The Arduino sensor sits on top of the station to ensure measurements are made at similar heights.

2.3 Water Quality loggers

Threats to water quality and aquatic biodiversity from human activities are a global issue. Despite widespread acknowledgement that pollution is a major threat to the sustainable management of aquatic environments (Vorosmarty et al., 2010, Rockström et al., 2014), local and regional scale initiatives are constrained by the limited availability of real-time, on-the-ground data (Behmel et al., 2016). Alongside warnings of "data-rich but information-poor" scenarios around water quality monitoring networks (Ward et al., 1986), the temporal and spatial scale of water quality testing is largely determined by finance and logistics, particularly due to the expense of commercially available monitoring systems. We suggest Arduino-based hardware can be used to develop bespoke, robust aquatic monitoring instruments. This approach offers notable advantages to the scientific community in terms of cost, replicability, and scalability. Here we present our efforts to develop a multi-parameter probe for water quality monitoring. Following global monitoring efforts (World Health Organisation, 1996; 2004), we choose to focus on temperature, conductivity, and dissolved oxygen due to overall cost and likelihood of producing accurate readings (Wagner et al., 2006).

Temperature influences most water quality parameters (WHO, 1996). Not only do temperatures in water bodies vary over 24 hours, but their daily averages change throughout the year (Brümmer et al., 2003). An OMEGA thermistor (£10 GBP), which uses resistance to extrapolate the temperatures for a range of 0-100°C (OMEGA, 2017), was selected for its accuracy, low cost and low power consumption. Dissolved oxygen (DO), an indicator of aquatic biological health, is related to the photosynthetic and metabolic activity of aquatic organisms. Given DO is affected by temperature and there are noticeable diurnal and seasonal variations, temperature and DO are monitored simultaneously (Kannel et al., 2007). We chose the Atlas Scientific DO kit due to its accuracy, compatibility and robustness and a cost of £260 GBP (Atlas Scientific, 2017). The associated shield for computer communication also allowed more straightforward calibration and programming. The shield directly calculates actual DO values from the voltage, saving time when writing the code and calibration. Conductivity is a commonly measured water quality parameter (Wagner et al., 2006) and long-term monitoring can be useful for tracking pollution sources (Morrison et al., 2001). We used the DFRobot electrical conductivity probe and shield (£50 GBP) to achieve an optimal balance between cost and accuracy. The glass design protects the sensitive electrode, providing additional durability (DFRobot, 2017). The selected product works with a dedicated shield that converts analogue readings to voltage, meaning only a simple calibration equation is needed to obtain the conductivity value. The datalogger consists of an Arduino Pro Mini 3.3v microcontroller, SD card, real-time clock and power supply. The attached sensors operate at 5v, however, so a 5v regulator and capacitor were added to the circuit to cope with the power transformation.

The River Brent, London, has a long history poor water quality and river restoration efforts are on-going (Thames21, 2019). We deployed Arduino loggers (Figure 6) in two locations along the River Brent - a river restoration and an unrestored site – for one week in February 2018 (Lavelle et al., 2019). We also deployed a commercial logger (HOBO U26-001) measuring temperature and DO at the unrestored site to facilitate performance evaluation. All loggers were placed in the middle of the river on wooden stakes, hammered 15-cm deep into the river bed and protected with rocks for security.

Arduino-based DO and temperature time series at the two sites are similar to the Hobo logger (Figure 7a and 7b). Temperature was measured particularly effectively (R^2 = 0.97, RSME = 0.29). DO was satisfactorily calibrated (R^2 = 0.87, RSME = 1.73) but an offset is evident, with the Hobo logger giving readings ~20% higher. Nevertheless, given the temporal similarities, calibrating each Arduino DO sensor should produce reliable readings. Conductivity was much different, however, leading us to suspect issues with probe accuracy. Difficulties with conductivity calibration persist despite extensive lab testing.

A major pitfall in the construction of these probes was an underestimation of the time it would take to troubleshoot errors and complications. Eliminating electrical interference associated with using multiple sensors was an unexpected but major technical challenge. Difficulties with water leakages were predicted yet producing a waterproof sensor was enormously time consuming. We experimented with many designs to maximise its watertightness and ruggedness for aquatic deployment while attempting to keep the project "low-cost". The number of prototype probes we produced gives some insight into the time commitment: four models of the sensor were iteratively produced, which were the result of six documented field tests and numerous in-laboratory undocumented trials. In addition to two successful multiprobes, five others were tested and failed because of calibration inaccuracy, water intrusion, faulty parts or short-circuiting. This repeated replacement of parts and calibration chemicals is a hidden cost. Nevertheless, the Arduino multiprobe still represents an economically competitive alternative to commercial equipment and further work to find the right external housing should yield a reliable device.

Each individual sensor requires calibration and associated coded algorithms. We found this to be straightforward with the thermistors but ensuring accurate readings was much more complicated for conductivity and DO. The daily means did differ between Arduino loggers and the commercial probe, which could have resulted from multiple sources of error including the calibration process or erroneous signals introduced by electrical interference. Low readings and instability may also reflect the inaccuracy of the selected sensors in general (Siragusa and Galton, 2000).

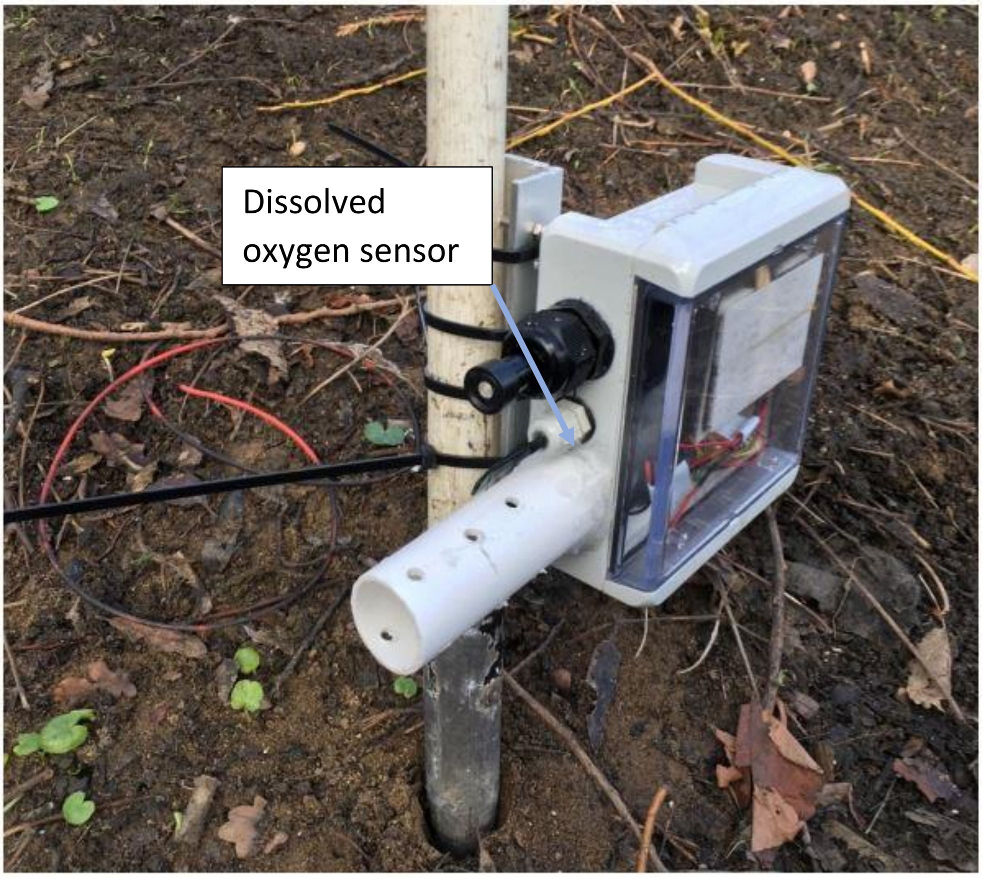
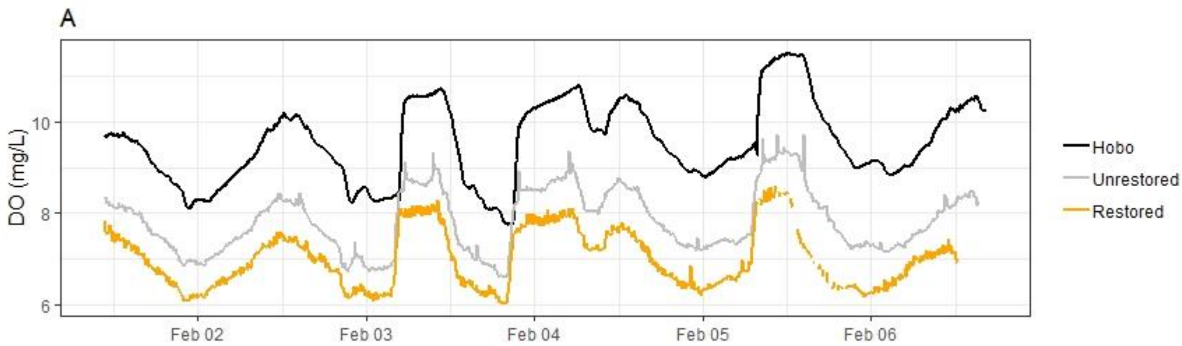


Figure 6. Deployment configuration of the water quality multiprobe.



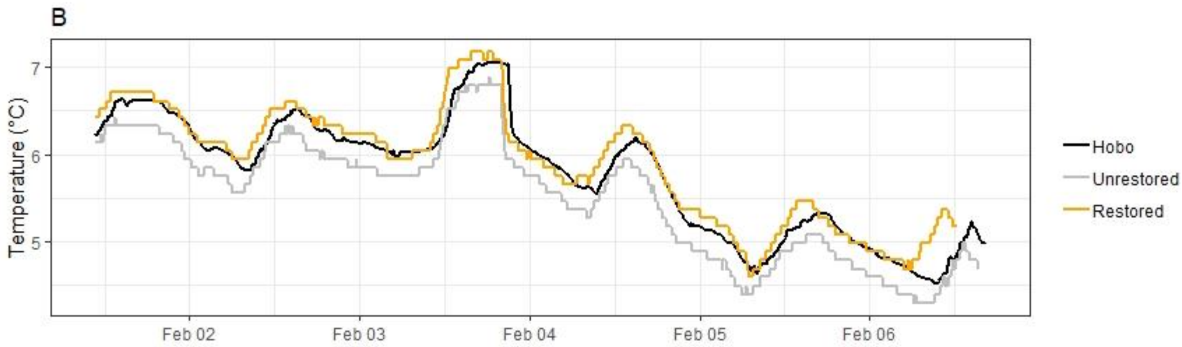


Figure 7. Time series from 02 – 07 February 2018 of (a) dissolved oxygen and (b) water temperature measured at an unrestored (Arduino and Hobo loggers) and restored (Arduino only) river site.

One of the most exciting aspects is that the technology allows for multiprobes to be customised for specific studies, such as the inclusion of nitrogen, phosphorous, nitrate, colour or chlorophyll sensors to monitor eutrophication in freshwater systems (Ferreria et al., 2013). *In situ* water quality monitoring is complicated because a complete and precise assessment cannot be reached unless several interacting parameters are measured simultaneously, which still poses a technological challenge to this monitoring approach. Nevertheless, low-cost, continuous water quality loggers offer a rare method for broadening the spatial coverage of routine monitoring, which could go a long way to identifying specific environmental pollution sources while providing long-term records of baseline conditions.

2.4 Automated Weather Stations

Basic meteorological data is fundamental to climatic, hydrological, ecological and geomorphological research. Multivariable weather stations are the standard system for monitoring meteorology, with >47,000 locations globally officially recording precipitation and >24,000 recording mean monthly temperature (Hijmans et al., 2005), though many more unofficial (amateur) weather stations now exist. A weather station normally measures air temperature, atmospheric humidity and pressure, precipitation, solar radiation, and wind speed and direction. These variables allow an assessment of surface energy and water balances and horizontal fluxes of air. Automatic weather stations can measure sub-hourly but usually aggregate data to hourly or daily averages or totals before recording. Depending on specification, commercial multivariate stations can be priced in the thousands of pounds (https://www.campbellsci.com/aws-meteorology) before specialist installation and maintenance is factored in, and are thus out of scope for many research, educational or community projects. As a result, in low-income countries, weather stations are few and far-between and their state of maintenance can be poor, threatening the value of long-term records, at a time when longitudinal data are critical in understanding climate change and its impacts.

Since 2014, *www.FreeStation.org* has developed open-source designs for a range of low-cost instrumentation and loggers. These include standalone and web-connected automatic weather stations (AWS) based on Arduino and Particle microprocessors. The stations are designed to be easily built from accessible components as well as accurate, robust and easy to transport and install. More than 219 stations are currently collecting data at 43 sites in 15 countries and the design has evolved significantly over time, guided by deployments in a range of environments. The stations are used by research projects in environments from desert to tropical forest as well as by schools, NGOs and some governmental authorities. FreeStation AWS have a component cost 3-6% the cost of a commercial station and require 2-4 hours of unskilled labour to build using the detailed build instructions at www.freestation.org/building. This opens monitoring capacity to a much wider range of organisations, enabling more stations to be deployed, providing redundancy but also enabling better understanding of spatial heterogeneity of weather and climate. The FreeStation *Meso* station includes precipitation, temperature, humidity, pressure, wind speed and direction and solar radiation (Figure 8a). It reads instruments every 10 minutes and writes hourly summaries to an on-board microSD card. The *Meso* can use an Arduino Pro-mini, a Particle Photon, or RedBear microprocessor. The *MesoLive* (Figure 8b) has the same instrumentation on a smaller footprint with cellular connectivity and access to data via a simple web API.

(a) (b)

Figure 8. (a) The FreeStation Meso Automatic Weather Station (AWS). **(b)** The FreeStation MesoLive AWS.

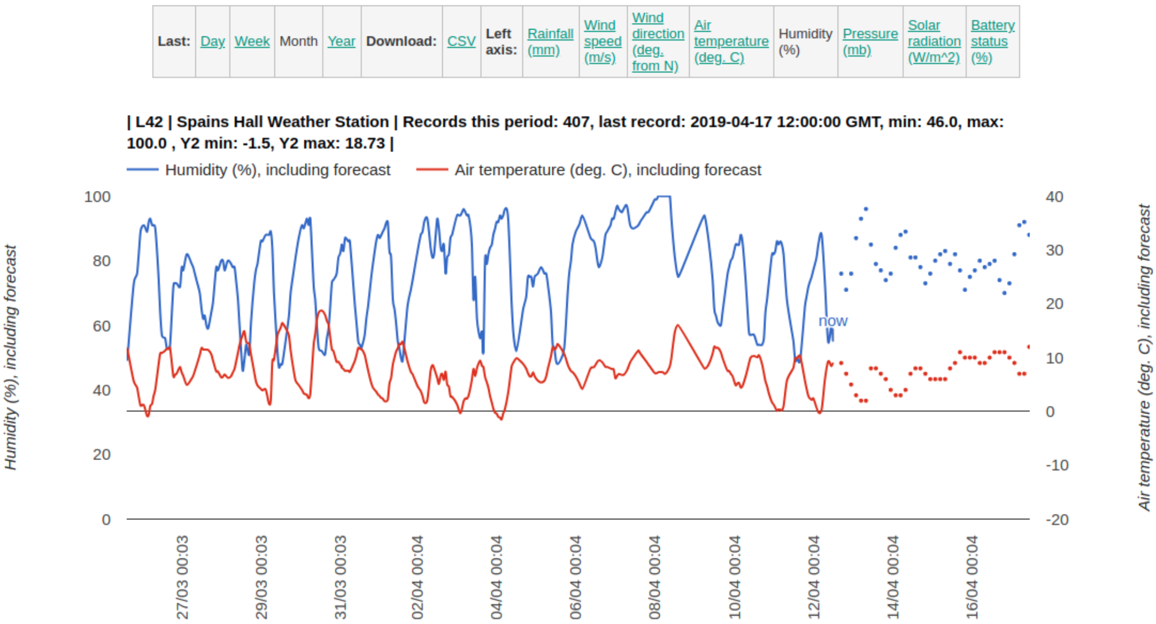


Figure 9. An example of the live data stream from a UK Freestation weather station, including forecast data (Freestation, 2019).

FreeStations are built around the FreeStation PCBs and FreeStation firmware which allow "plug and play" connectivity of a variety of sensors through standard RJ45 and RJ12 cables (commonly known as ethernet and phone cables). They are designed to be buildable by students with no electronics knowledge or interest in microprocessors. Key challenges have been working within the constraints (power and programmable memory) of the Arduino platform, making designs easy to build, transport, and deploy whilst managing the data streams emerging from multiple deployments. Calibration against commercial instrumentation has shown these instruments to be of acceptable accuracy if properly built and deployed. Whilst detailed training information is available, challenges remain in having novices build these to a high standard, though with care and practice, this is easily possible. Data streams are managed through a web platform and API (Figure 9) which is capable of quality control, combining incoming data streams with forecasts, early warning and direct connection to web-based modelling and policy support tools such as WaterWorld and Eco:Actuary (www.policysupport.org). This kind of integration of real-time data streams with web-based models has significant potential in environmental forecasting and management.

As part of the Pathways out of Poverty for Reservoir-dependent Communities in Burkina Faso (POP-BF) project (www.sites.google.com/view/pop-bf), a range of Freestations have been installed that monitor local weather, water levels in reservoirs using sonar and soil moisture. These stations are connected to the WaterWorld policy support system to deliver nowcasts and short-term forecasts (communicated via on-board switches and lights) on reservoir volume and soil moisture to advise irrigation and harvest planning. The simplicity of the technology and output has created a locally-owned reservoir monitoring system that will continue beyond the lifetime of the project.

The project has worked with students, extension workers and government technicians to develop local capacity in operating the automatic weather stations. Importing the build materials and components has been a challenge, however. Many of the Freestation components are sourced from the web and direct postage has been problematic, with lengthy delays at customs. Bringing parts and stations from the UK as personal baggage during research visits has proved easier, but this is not a long-term option. The hot and dry environment and intense dust production in Burkina Faso has also required modifications to the housing. Tighter seals have had to be installed around the electronics housing and cabling and the solar panels require regular cleaning. More unusually, we believe one sensor was lost to crocodiles who live in the reservoirs, highlighting the need to consider local wildlife!

2.5 Time-sequencing lake sediment traps

Sediment traps installed in lakes capture particles settling through the water column. Long-term, high-frequency monitoring offers insight into the biogeochemical functioning, sedimentation regime and seasonal changes in biodiversity that cannot be replicated in laboratory experiments (Bonk et al., 2015; Chmiel et al., 2015). Static trap deployment is common but requires manual retrieval, severely restricting sampling frequency, especially at remote sites. Time-sequenced instruments which open separate containers at pre-programmed intervals provide valuable temporal resolution. Commercial versions are costly (>£10,000 GBP). Bespoke designs exist (e.g. Muzzi and Eadie, 2002) but require moderate expertise in mechanical and electrical engineering. A reliable, low-cost sequencing sampler will transform particulate monitoring in lakes, particularly given funding pressures on long-established initiatives.

Initially an undergraduate project, we swiftly appreciated the research potential of an Arduino-powered sequencing sediment trap. Our original design comprised three main components: (i) two 3D-printed carousels (d = 187 mm) holding twelve 60 mL NalgeneTM polyethylene bottles, fixed by threaded rod to a stepper motor (Figure 10(a)); (ii) cylindrical PVC downpiping that feeds a funnel sitting over the carousel hole (d = 33 mm) and (iii) an IP67-rated enclosure housing the stepper motor and Arduino electronics. Bottle lids were fixed in carousel holes with epoxy resin and holes bored equivalent to funnel diameter.

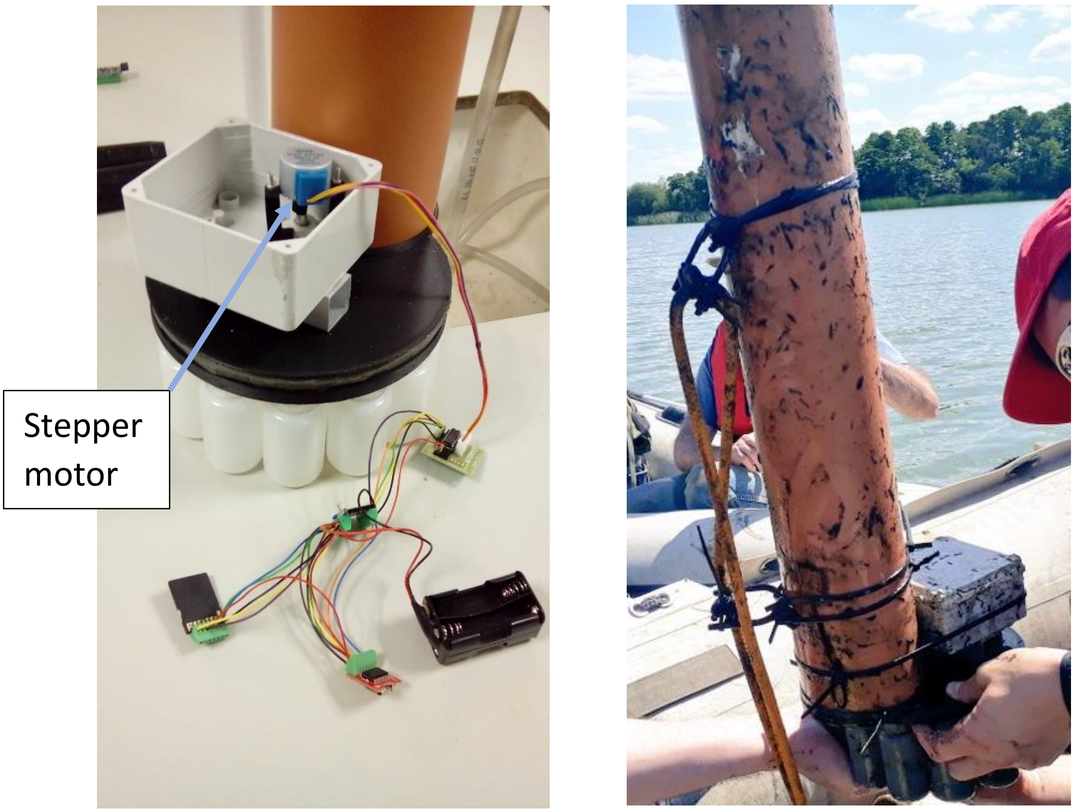


Figure 10. (a) Internal hardware components. (b) Post-deployment. An improved version will seal the stepper motor separately to the electronics, thereby minimising the risk of water ingress.

The downpipe (h=75cm, outer diameter=110mm) aspect ratio of 6.8:1 follows recommendations of Bloesch and Burns (1980) to ensure representative sediment capture in small lakes. The unipolar 28BYJ-48 stepper motor is cost effective (£1-2 GBP) while offering high-precision rotation at low speeds. Although the stepper motor draws 5v, testing confirmed a 3.3v ProMini provided adequate power for 30-day rotation. Different time-steps are easily programmed for alternative applications.

A twelve-month test deployment in Crose Mere, Shropshire (52.86°N, 2.84°W) successfully recovered sediment each month. Trap installation involved fixing the downpipe using D-clasps to 5mm wire held between a basal 20-kg weight and buoys: one larger suspended below the annual minimum lake level to maintain taut deployment and a small coloured float at the surface. The design is operationally effective but water seepage into the housing, most likely through the cable gland during rod rotation, remains a concern. Trap recovery highlighted two further issues: biofouling (Figure 10(b)) and abrasion of bottle labels. The volumes of trapped sediment dispel concerns that 60 mL containers are too small, at least in eutrophic, productive lakes.

An improved version is under construction with improved watertightness the key objective. Although costlier, the stepper motor and electronics will be enclosed in separate IP68-rated cases, greatly reducing the exposure of internal electronics to water. A model boat shaft seal (with a sealed internal drive rotating shaft) will be used and, following Muzzi and Eadie (2002), o-rings and nylon inserts will be inserted between the rotating carousel and upper fixed plate at each bottle hole to reduce biofouling, friction and water intrusion.

2.6 High-frequency measurement of wind-blown sand

Research on sand transport by wind includes a rich variety of electronic sensors for measuring and recording physical processes and flows at relatively high frequencies (Sherman et al., 2013). Typical field instrumentation includes sonic anemometers for monitoring wind characteristics, electronically weighing sand traps, sand-grain impact sensors, and laser interference instruments for detecting saltating sand transport rates, and additional equipment such as continuous soil-moisture probes and further meteorological sensors. The acquisition and data storage of high-frequency time-series of wind and sand transport measurements is crucial to investigating the relationship between turbulence in the airflow and the spatio-temporal variability of sand transport, displayed particularly by the ubiquitous presence of streamers (also known as sand snakes) in wind-blown sand (Baas & Sherman, 2005; Baas, 2008). Sensors are positioned in close proximity and data outputs of different types are acquired and need to be stored synchronously as well as at the original high measurement frequencies. This poses significant challenges to traditional data loggers but provides opportunities for custom-built (and low-cost) Arduino systems.

Our latest research combines sonic anemometry with laser-counter sensors, which have been integrated with an Arduino logger system. A Gill R3-50 sonic anemometer provides 3D wind vector measurements at 50Hz, output via an RS232 serial ASCII data stream and a Wenglor laser counter detects sand grains flying through a narrow laser beam, outputting a 100 µs voltage pulse for each interruption (Davidson-Arnott et al., 2009). Traditional dataloggers struggle with these data output and recording requirements; simple and low-cost loggers exist for pulse signals, but typically do not possess RS232 input capabilities and are often restricted in temporal resolution to logging at >1Hz. High-end dataloggers on the other hand can handle RS232 input, but have only a few dedicated pulse counter input channels and can be weighty. Our Arduino solution is based on a Due micro-controller board, which operates an 84 MHz processor and can accommodate several dozen count channels as well as RS232 input via an RS232-to-TTL adaptor. The ASCII stream from the sonic anemometer is read and stored into an accruing string in the memory, one character at a time. Pulses from the Wenglor are counted via an external interrupt routine. The anemometer sends a termination character after each output of a wind vector measurement stream (every 0.02 seconds) and receipt of this character at the Due triggers appends to the memory string: the total pulse count at that moment, a time-stamp, and a carriage return (or 'new line'), while the pulse counter is reset to zero. After storing 200 lines (i.e. 4 seconds worth) of data the memory is then written to a micro-SD card attached to the Due. The temporary memory storage is crucial because the SD writing process is comparatively slow and so writing direct to the SD card at the 'raw' data rate of 50Hz is not feasible. The code for the running loop in the Arduino processor is very short and efficient, minimising the processor overhead.

This Arduino data collection system has been lab tested using a rotating disc with a series of holes mounted on a multi-speed bench drill for providing calibrated and steady rates of Wenglor laser beam interruptions (counts). The tests show that the system can easily measure and record pulse rates of at least 4500 counts per second (as well as the 3D airflow data) at the required 50 Hz. This exceeds the tested capabilities of commercial logger combinations (Bauer et al., 2018). A pilot field deployment has demonstrated success and portability of the system (Figure 11) and its compatibility with application of Large-Scale Particle Image Velocimetry (LSPIV) equipment (Baas & Van den Berg, 2018). The Arduino hardware costs ~£50 GBP.

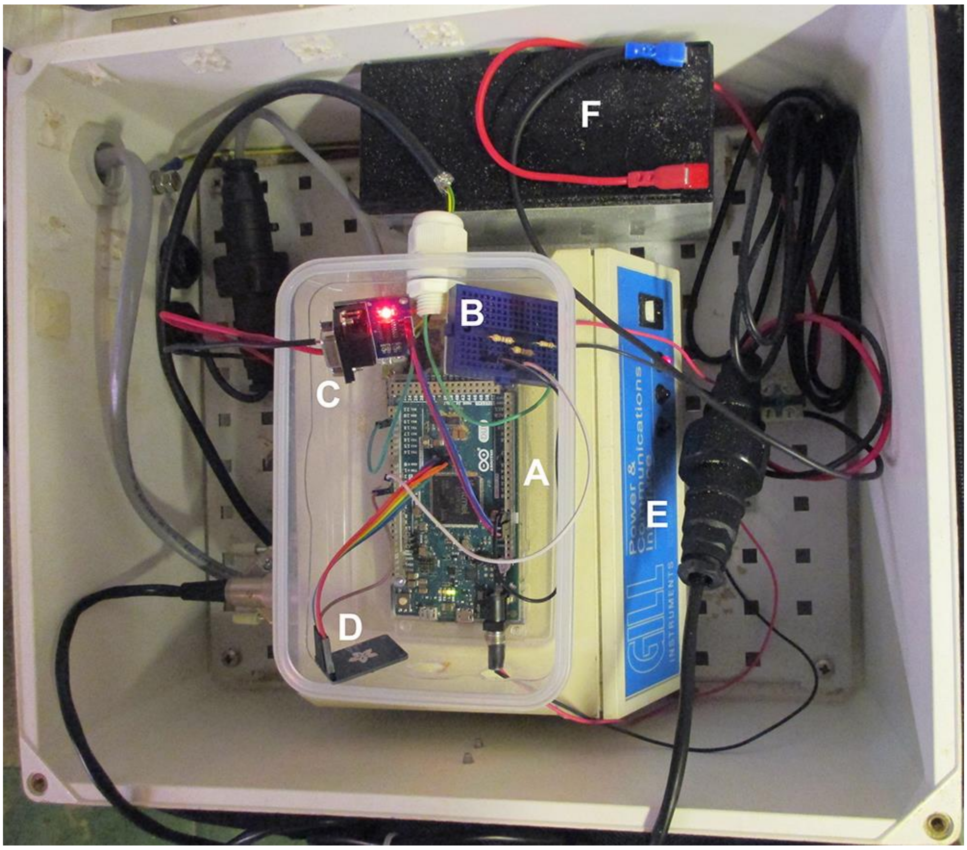


Figure 11: Data acquisition system used for synchronous recording of Gill Sonic and Wenglor laser-counter measurements, housed in a portable environmental enclosure. Components: A) Arduino Due micro-controller board, B) voltage divider to reduce the ~11VDC output from the Wenglor to <3VDC input to the micro-controller board, C) RS232 input from the Gill Sonic communication unit, D) mini-SD card 'shield' for storing the data, E) Gill sonic communication unit, F) 12 VDC battery power supply.

III Lessons Learned

1 Major advances and successes

Our cumulative experience has highlighted the following key considerations from which we've developed a set of best-practice guidelines.

Standardised designs and bespoke circuit boards

While Arduino offers near-limitless adaptability, a key aspect of our streamlined workflow is having core design frameworks. For example, we now have a standard design for ultra-low-power loggers (important for long-term monitoring) that can be readily adapted to most sensors. Similarly, we have developed replicable methods of incorporating a solar panel onto most designs. While we regularly use solderless breadboards for prototyping and as teaching aids, soldered wires are near-essential to minimise the possibility of loose wires and short-circuits. Poor or incorrect wiring is the most common malfunction, in our experience. We are increasingly making use of bespoke PCBs, led by the Freestation project. Designing PCBs in conjunction with OSHPark is cost-effective, simplifies the electrical assembly and minimises wiring faults while maximising customisability for multi-sensor applications. They can also accommodate web-integrated cellular boards such as the Particle Electron or Photon (https://docs.particle.io/electron/).

Documentation

Developing low-cost environmental sensors does not require prior expertise with electronics or programming, though experience in the latter is beneficial. What is crucial, however, is documenting every stage of the design and testing process. We host build notes, schematics and 'sketches' on a shared Google Drive, and students are asked to upload their code and schematics as part of their dissertation submission. The requisition log is also shared, facilitating rapid price comparisons and bulk orders, minimises excess purchasing and highlights reliable suppliers. When writing code, best practice including version control and in-line commenting is strongly recommended (Goodliffe, 2007). Sharing designs widely is core to the Arduino open-source platform. The Freestation website fully documents the build steps and component list and displays live data, for example.

Price

A core benefit of Arduino technology is the vastly reduced cost of components compared to conventional commercial instruments. Low-cost environmental sensor networks have particular potential given funding pressures in science. An estimate for open-source medical technology found the return on investment for funders to be hundreds or thousands of percent (Pearce, 2015). Low financial and technical costs also provide the capacity for schools, NGOs and governmental authorities in parts of the world with limited infrastructure to expand environmental monitoring efforts. Nevertheless, we have learned that a careful assessment of costs is a necessary precursor for each project. Sensors tend to be the most expensive component, followed by commercial housings, especially where a high degree of sealing effectiveness is required. Our testing of various air quality sensors showed cost-benefit analysis is important. Whilst there is an incentive to source the lowest cost components, it is worth considering the advantages of higher quality sensors, particularly if these incorporate standardised calibrations. A Sharp GP2Y1010AU0F is two-thirds the price of the Plantower PMS series but is significantly more sensitive to temperature fluctuations and requires manual calibration. We therefore deemed the Plantower worth the added outlay. Component costs also vary between suppliers, especially between UK and overseas, and there is a trade-off between delivery time and cost, especially when ordering from China. The construction of multiple (failed) prototypes brings unexpected costs that we now build into our workflow.

Workflow recommendations

Our streamlined workflow is presented in Figure 12. Designing a reliable sensor is a highly iterative process from sketch to successful deployment. Log and photograph each wiring configuration and housing assembly; it will help others and may be useful for a future project. Think carefully from the outset about research priorities: which components are essential? Each addition heightens risks of hardware or software incompatibility. Testing must replicate real-world deployment conditions as closely as possible, both in terms of environmental conditions (sufficient solar power supply, for example) and length of deployment. Sensors successfully tested at minutely or hourly resolution under laboratory conditions frequently failed when re-programmed to daily intervals for deployment. We strongly recommend verifying data quality after a short deployment phase but keep in mind that not all libraries are designed to automatically re-start if the SD card is removed.

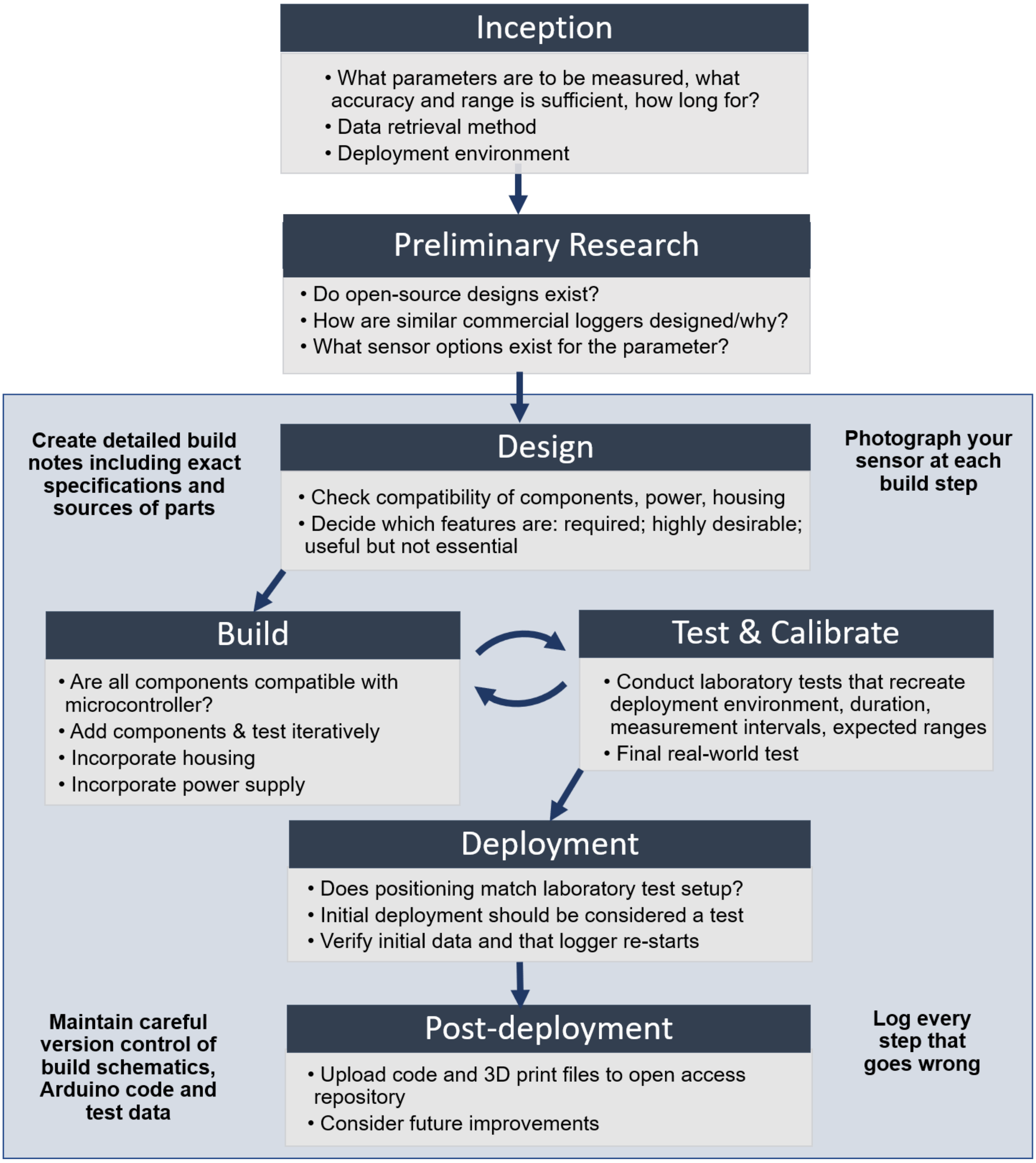


Figure 12. A schematic visualisation of our workflow for developing low-cost environmental monitoring devices and key considerations at each stage.

2 Common pitfalls

Testing and calibration

Unsurprisingly, testing and calibration is crucial. Our experiences show that testing must follow the deployment protocol as closely as possible. This has implications during the build and programming phases. For example, a sensor that successfully logs at one-minute intervals during lab testing offers no guarantee that switching to, say, 30-minute intervals upon deployment will be faultless. Some libraries helpfully supply one line of code to set measurement intervals but we found more substantive edits were often required. In other cases, this meant designing elaborate apparatus in a laboratory to mimic real-world conditions (e.g., the wind-blown sand laser counter; Section 2.6). Calibration checks under final deployment conditions are highly recommended (Rai et al., 2017) but may be logistically problematic. Tight regulations mean testing in the River Thames, for example, is non-trivial despite our geographical proximity. On the other hand, we are fortunate that London Air Quality Network allow our Arduino sensors to be tested and calibrated at their flagship Marylebone station. Calibration additionally should not be considered a one-time job. Componentry and sensor materials are subject to degradation as they age, introducing *drift* in reported results and potentially hampering accurate measurements (Bourgeois et al., 2003; Artursson et al., 2000). Where calibration is not possible, post-processing can be implemented to correct for sensor drift through measuring standard quantities or cross-calibration against other more recently calibrated and/or accurate sensors.

We recommend testing also be carried out at the component level – i.e., prior to sensor assembly -- as visual and electronic inspection can reveal flaws in purchased components. Wires are often mounted differently to supplied sensor schematics, for example, potentially short-circuiting the Arduino board and, at worse, posing a fire hazard. Arduino components can usually be replaced - certainly more easily than commercial loggers - but early testing saves on time, expense and frustration.

Time

Our experience shows clearly that every stage in a new project takes longer than expected. Publications showcasing the “do-it-yourself” approach often present the methodology and schematics for a functioning sensor, followed by a brief reflection on accuracy and future applications (e.g., Khanfar et al., 2017; Beddows and Mallon, 2018, Metzger et al., 2018). These guides rarely comment on the time commitment. While this will depend on the level of technical competence and experience of the designer, the trial-and-error nature of the technology exacerbates this issue. The water quality sensor (Section 2.3) development process illustrates this pitfall: four models of the sensor were produced, which were the result of six documented field tests and numerous in-laboratory undocumented trials. Two successful probes were eventually produced but five others were tested and failed because of calibration inaccuracy, water intrusion or conflicting libraries when wiring multiple probes. Repeated builds also induces an unexpected cost element.

Sensor housing

Robust external housing is critical. The deployment environment will dictate the sealing effectiveness and purchasing casings with appropriate Ingress Protection (IP) ratings is a start but preventing water and/or dust ingress is a challenge that we underestimated repeatedly. Housing dimensions also need to accommodate sensor power draw. Battery packs constitute up to two-thirds of the space requirements for some of our sensors so a belated realisation that more power is necessary could necessitate a wholly new housing. We increasingly manufacture 3D-printed containers to optimise protection and streamline the design process, especially for housing smaller components. Filling gaps in commercial casings with epoxy is extraordinarily time consuming, for example. Loose wires are a common malfunction; we advocate soldered wire connections, PCBs and the plug-and-play approach of the Freestation to maximise durability. Experience has shown that it is very difficult to make watertight housing to research-grade standard whilst keeping the project “low-cost” and diagnosing the source of leakages is a particular challenge. In our view, the microprocessor, SD card and clock should be housed separately and securely from other components wherever possible to minimise leak points. The stepper motor will be fixed separately to the electronic on the updated sediment trap, for example, as the rotating axle is a weak point for water ingress.

Power

We have grappled at length with ensuring adequate power supply and maximising longevity. Think carefully about minimum measurement intervals, which will be guided by research objectives. Will a 30-minute or 60-minute wake-up interval provide appropriate data? We now have a standard core design for ultra-low power sleeping loggers and increasingly incorporate solar-powered, rechargeable lithium ion batteries. Shaded deployment sites along riverbanks and obtaining adequate exposure in built-up areas have proved difficult. Integrating components that draw 3.3v and 5v is another complication. Conversely, testing showed a 3.3v Arduino Nano could drive the 5V stepper motor on the sediment trap, which aided compatibility. There have also been notable developments around power saving in recent years across the Arduino community, involving new hardware and scripts (Beddows and Mallon, 2018). Lastly, removing obsolete LEDs from the Arduino and connected shields using a hot soldering iron or carefully slicing tracks with a sharp blade can reduce power draw substantially.

Sensor and library compatibility

Progressing from a complete assemblage of sensor(s), board and wires to an operating, reliable instrument is easily underestimated. One of the biggest hurdles we repeatedly encounter is a lack of compatibility between sensors and Arduino libraries when designing multi-probes. Each additional component introduces a non-linear degree of added complexity, with conflicting libraries a common occurrence. Individual sensors can be accurately calibrated but daily means did differ when integrated into a single instrument. We attributed these issues to electrical interference, which requires targeted compensation (Siragusa and Galton, 2000) and significantly longer build and testing times. Similarly, whilst most PM sensors use laser scattering, internal differences between manufacturers produce unique biases. These are rarely clear in supplied documentation.

Deployment Considerations

We also emphasise that deployment protocol is a non-trivial aspect that is rarely afforded due consideration. After the more arduous task of designing, building and calibrating low-cost environmental loggers, deployment seems the simple and exciting job. This is a particular issue when sensors are handed from makers – who may know the particularities of the logger and sensor setup – to fieldworkers. Without adequate consideration of the deployment criteria of specific sensors (e.g. under what conditions does the sensor accurately measure? What periodic maintenance is required? Where specifically should the sensor be mounted?) results may due a disservice to the effort expended in design and development. This reinforces the need to share understanding of the sensors, loggers and fieldwork conditions between makers/electronic engineers and fieldworkers. General good-practice guidance for attaining accurate measurements of the particular environmental parameter should also be adhered to.

IV Attribution and intellectual properties

Despite the open-source revolution, scientific research necessarily requires attribution, both to ensure we as researchers are recognised for our contribution and that the conceptual and theoretical development of research can be understood. While instructions or design descriptions are generally included in methodological sections of journal articles, alternative methods are required for storing 3D-design files, board designs and code. Helpfully, an increasing number of suitable online repositories are now available that create a Digital Object Identifiers (DOIs), with some journals now offering similar online repositories. A DOI is a unique alphanumeric string assigned by the International DOI Foundation and associated registration agencies (e.g. Crossref). We would encourage academic authors to host build instructions and materials on public-facing open-source sites wherever possible. Common domains include: Github (github.io), the Open Science Framework (OSF.io), PublicLab, Thingiverse, Zenodo, Figshare and the Open Hardware Repository.

Awareness of open-source licences is also useful in sensor development. The open hardware and software community have grown to embrace this aspect but navigating the options can be puzzling. Arduino has adapted the Creative Commons Attribution-ShareAlike 3.0 (CC BY-SA 3.0), which in brief means anyone can make use of material it hosts online provided the CC BY-SA 3.0 licence is always re-used. This equally applies to adaptations; the same licencing must be adapted when utilising code snippets, for example. A range of CC licences do exist, with the most common provided by Apache 2.0, GPLv3 and CC0. Each has specific rules and instructions for re-use; collating this information goes beyond the scope of this paper but we recommend two useful resources: "The legal side of open source": https://opensource.guide/legal/ and https://choosealicense.com/ .

V Summary

In this paper we have showcased the ability of low-cost sensors to transform environmental monitoring of aquatic, terrestrial and atmospheric systems around the world. We intend this paper to act as a catalyst for the uptake of low-cost sensors by geographers and environmental scientists. Deriving insight from six varied case studies including experimental sensors and global operational networks such as our Freestation project (www.freestation.org), we have demonstrated the benefits of using low-cost sensors powered by Arduino across a wide range of disciplines including atmospheric science, Earth System Science, ecology, geomorphology and hydrology. By drawing on six years' experience, we have also highlighted potential pitfalls in design and construction, recommendations for best practice have been proposed and a workflow for developing new sensors and overcoming technical challenges has been presented. Importantly, in this paper we have confirmed that electronic sensors designed and constructed for a fraction of the conventional cost can deliver research-grade data. Given global funding pressures in science, developing and deploying low-cost sensor networks has the potential to deliver enormous benefits, including improved representation of spatial and temporal variability. Other key advantages include customisability – i.e. the opportunity to develop bespoke sensors that are tailored to a particular research need or environment. We have also witnessed the value of using Arduino sensors as a tool for teaching in Geography, for citizen science, and for enthusing the public and our students about the importance of active monitoring to better understand environmental change. Our experience has demonstrated that the Arduino and Internet-of-Things technology and support communities are sufficiently developed to allow geographers and environmental scientists with no background in electronics and limited coding experience to develop and customise new sensors. The potential for sensor development is essentially limited only be imagination, as examples of open-source Geiger counters and Arduino-based CubeSat satellites demonstrate (SeedStudio, 2011; Geeroms, 2015). The workflow presented in this paper, along with tools for web integration as demonstrated by Freestation, provide a framework that can enhance environmental monitoring and management from the local to global scales.

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