



ADAPT-NP Stakeholder Needs and Future Directions Workshop Report.

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Southampton.

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1. Executive Summary

The ADAPT-NP project is funded by the NERC Innovation in Environmental Monitoring programme and seeks to develop, and field test a novel multi-nutrient sensor and integrate adaptive monitoring. The sensor will build on the single nutrient sensor developed by SouthWestSensors, using micro-fluidic technology to monitor Nitrate, Nitrite, Ammonium and Phosphate at almost real-time frequency. Adaptive monitoring will involve end-users determining triggers or environmental thresholds which increase the frequency of the nutrient measurements in a bid to improve “event” monitoring, reduce costs and improve data output quality. Finally, the project seeks to co-design sensor specifications with end-users, with this report detailing an important component of this work. An inception workshop was held on Friday 27th September with stakeholders from government bodies, water industry, aquaculture and research centres spanning research and practice in the field of water quality monitoring. This report details the discussions of that workshop which included the current experience of sensor end-users (stakeholders herein) and their thoughts on what the future challenges or opportunities in nutrient monitoring may be. The aim of this work was to identify the major challenges of those responsible for maintaining and reporting sensor water quality data to understand where innovation may be best placed and how the ADAPT-NP project may address these challenges.

Many end-users of water quality sensors reported common experiences in sensor maintenance and data usage. Currently, sensors are not deemed to produce data reliable enough to be used in compliance and statutory monitoring and cannot report absolute values due to the low sensitivity and range of some determinands (i.e. Ammonium) and difficulty in interpreting “noisy” data. As such, most stakeholders report or visualise data by summarising trends or changes over a threshold. The pressure on staff time from the activities involved in sensor use such as maintenance to data cleaning and analysis was raised throughout the workshop. There was a sense that whilst sensors are promoted as a tool to reduce staff pressures and costs, invariably this is not the case and a greater recognition of this is needed. There was also a demand to improve best practice and quality assurance particular in terms of data cleaning, which is often subjective and requires statistical expertise. Finally, users all agreed that sensors needed to be better able to integrate with other sensors, with a common goal to create sensor networks within a catchment. Often different sensors will have their own software which prevents integration of other sensors and their datasets, despite this being imperative for the holistic understanding of the environment. Specifically, there is a need to be able to view and analyse water quality data alongside hydrological and meteorological data in a more accessible manner so that managers can be more reactive to sensor output.



Following on from current sensor experiences was a stakeholder discussion regarding the future opportunities and needs of high-frequency water quality monitoring. Most discussion centred on iterations and developments of environmental legislation which is increasing the demand for high-frequency monitoring of nutrients in surface waters, and how best sensors could support this work in a sustainable way. There was also interest in being able to reliably monitor nutrients in extreme weather conditions as the climate becomes more variable and unpredictable and in other more difficult environments such as estuarine systems. Finally, being able to integrate and develop high-frequency nutrient monitoring alongside ecological monitoring was a shared aspiration to those involved in statutory monitoring. It was felt that this would enable more rapid forecasting and response to ecological impacts of nutrient pollution such as algal blooms.

The workshop finished with a showcase of SouthWestSensors single nutrient sensor and introduction to adaptive monitoring, with a question-and-answer session with the engineering and data science team responsible for these activities. Stakeholders were interested in the sensitivity and range the sensors could detect nutrients and interoperability with other sensors, all of which will be developed and trialled as part of the ADAPT-NP project. The benefits of this unit include self-diagnostics and drift correction, as well as automated calibration. A cartridge system will contain the reagents, calibration standards and waste effluent will ensure contamination to the environment is minimised. As well as laboratory tests, these sensors will undergo three field tests to assess the applicability and ease from deployment to operation. The adaptive sampling component will develop the data tools such as an R script which will interact with the sensor to trigger an increase in monitoring according to pre-defined conditions set by the end-user with stakeholder feedback noting interest in shifting flow conditions in moving surface waters and temperature/dissolved oxygen in lakes. This requires an interactive, interoperable, and intuitive data platform, which again will be developed and trialled as part of this work. Stakeholders will be kept updated on the ADAPT-NP project by a stakeholder newsletter and invited to attend a second workshop further into the project which will likely comprise a showcase of the prototype multi-nutrient sensor and opportunity for feedback.

2. Introduction

ADAPT-NP is developing and field testing an adaptive multi-nutrient sensing system. The aim of the project is to create and test a novel microfluidic based multi-nutrient analyser and integrated adaptive monitoring systems for cost-effective high frequency analysis of nutrients in freshwater through three objectives. 1) Improving the temporal resolution of nutrient monitoring in water, high-frequency measurements across environmental variables, and 2) using adaptive sampling approaches to optimise data collection and maintenance procedures, reducing



sampling and analysis costs, ensure data quality is maintained, and usable data summaries and visualisation are produced. Finally, 3) co-designing the sensing system and testing scenarios alongside end-users and other project partners, followed by conducting three trial deployments to test different aspects of the combined system capability. Considering the third objective, the first stage in the co-design process is to understand current sensor user or stakeholder experiences and identify their future needs for these types of freshwater monitoring systems. In doing so, this project may address current challenges encountered by stakeholders and develop innovative and reliable monitoring approaches to ultimately help better understand and manage our freshwaters.

This report details the key emerging themes which arose via the discussion sessions held within the stakeholder inception meeting of the ADAPT-NP project, part of the NERC Innovation in Environmental Monitoring programme on Friday 27th September 2024 and several interviews with individuals thereafter. The meeting was held in two locations; UKCEH Lancaster and University of Southampton who were connected virtually. The first section details the current experiences of stakeholders with sensors used for water quality monitoring, revealing universal challenges or themes around sensitivity, maintenance and data management. The second section details the future directions of the ADAPT-NP project and how it might address the future needs of water quality monitoring for multiple stakeholders.

3. Current experiences with water quality sensors

The workshop consisted of stakeholders from research organisations, government agencies and water industry personnel involved in the practice and research of water quality monitoring using high-frequency sensors or sondes. In England and Wales, statutory reporting of water quality in freshwaters relies on accredited laboratory analyses of water samples with sondes used mainly for bespoke water quality investigations. One of the most common brands of sondes used by stakeholders are YSI probes ([YSI](#)), with others using Proteus developed by RS Hydro ([RS Hydro](#)), a newer brand on the market. The most common determinands measured include Temperature, Conductivity, pH, Turbidity, Dissolved Oxygen, with Ammonium being the most common nutrient. Other determinands used but not in a universal manner include Chlorophyll, Blue green algae, Fluorescent Dissolved Organic Matter, Biological and Chemical Oxygen Demand, Total Organic Carbon, with water industry sensors monitoring *E*-coli and Total Coliforms. Below details the discussion with stakeholders around their experiences of sensor practice, from calibration to data processing.

3.1 Sensitivity and range

Most statutory monitoring in northwest England is conducted in low nutrient systems, which differs to the more populated regions or urban centres of the UK where water quality and nutrients are in typically higher concentrations. Contrary to manufacturers specifications, experience from real-world deployments is that sensors are not sensitive enough at the lower nutrient concentration ranges and so, cannot provide reliable quantitative data. Ammonium for example, uses an ion selective electrode, and measures to 0.1mg/L with a quoted accuracy of +/- 2 mg/L. This low level of accuracy, results in low sensitivity in low nutrient environments where concentrations are typically >0.1mg/L ([State of the water environment: long-term trends in river quality in England, 2024](#)). This sensor technology is also subject to considerable drift over the timescale of days to weeks and therefore requires regular calibration. The result is that absolute values of Ammonium concentrations are not considered accurate enough to use in compliance reporting, but rather general patterns are used to give an indication of changing nutrient conditions and the identification of potential pollution events.

Turbidity, a measure of the relative clarity of water, is another problematic determinand to interpret. This is because the sensor output for Turbidity is typically noisy, with low values for much of the data record and temporally short-lived rapid increases in turbidity or 'spikes' in values. To assess whether these spikes are valid, it's necessary to visualise and cross-reference them with other water quality measures. Frequently these spikes do not correspond with changes in other water



quality determinands or high flows. Spikes not associated with actual suspended sediment 'events' can be due to material blocking the sensor or measurement outliers i.e. sensor error. In this instance, interpretation of the data is challenging at a quantitative level and again, there is less confidence in reporting this determinand.

Chlorophyll which is measured using a fluorescence sensor can also be problematic as readings can be influenced by biofilm development with regularly cleaning needed to reduce biofilm development. Some sensors have wipers associated with the optical probes, but these can increase power usage.

3.2 Reliability

Whilst sensor reliability can be improved via deployment and routine calibration and maintenance, other factors can lead to a reduction in reliability. For instance, one investigation which used Phosphorus sensors did not return trustworthy results, with issues from lower temperatures affecting the readings. Improving the reliability of sensors in a range of conditions would improve their value to stakeholders wishing to report their output in statutory monitoring which requires high standards of quality assurance and confidence.

3.3 Calibration

Different organisations reported different approaches to calibrating sondes. For instance, the Environment Agency swap their sondes (YSI) at a monitoring site every month. The sondes removed from a site are calibrated at a centralised location known as the National Water Quality Instrumentation Service (NWQIS). UKCEH follows a similar approach, with YSI sondes swapped every six weeks and calibrated back at the laboratory. Proteus sondes used by United Utilities were calibrated in the field with standards provided by the manufacturer every six weeks. The benefits of in-the-field calibration include a lower number of sondes to carry out monitoring, resulting in reduced initial capital equipment costs. However, weather conditions or remote locations may decrease the accuracy of in-the-field calibrations. Additionally, if issues arise that require further investigation, this may require further site visits or removal of equipment from the field to be fixed increasing pressure on staff time further.

Stakeholders recognised the importance of accurate and accredited calibration, to ensure reliable and high-quality data. However, they also expressed a keenness to simplify and reduce costs and time associated with this activity, which is recognised to be relatively resource intensive.



3.4 Maintenance

A lot of statutory monitoring is undertaken on dynamic rivers or streams. Flood events or high flows can make it difficult to maintain or access the sensors, as well as causing damage to equipment. Stakeholders also mentioned issues with vandalism and damage from livestock resulting in equipment failure. Further challenges involved instrument failure or power supply issues, which often required specialist skills or replacement parts. As such, most stakeholders acknowledged that frequent maintenance or site visits are typical and are usually always more frequent than initially anticipated or planned for.

Most maintenance was reported to be due to environmental damage. This included blockage or burial of equipment caused by organic material and biofouling which consequently disrupts sensor readings. This results in the need for regular cleaning of sensors and cages and careful thought regarding site selection. Some stakeholders inspect their equipment every two weeks visually and clean where necessary, whereas others wait until sensors are calibrated or until an issue arises. UKCEH, for example, have sensors deployed in upland, flashy streams in the Lake District. This presents a challenge as the sensors need to be firmly secured yet easily removed for maintenance. Often different sites will have unique conditions and sensors will have to withstand different stresses, flow and bedform conditions. Regular checks of sensors are required to remove plant debris in cages or boulders moved in high flows and damage to sensor cages and attachments from the movement of rocks and boulders in high flow events are commonplace. There was a recognition that sensor deployment is a learning curve and that it can take time to appreciate challenges and find the best solutions to address them.

3.5 Ground-truthing data.

Ground-truthing is the validation of sensor data output with actual observations or measurements taken in the field. In terms of nutrients, this often involves taking a water sample followed by accredited laboratory analysis. Ground-truthing ensures accuracy and confidence in the reliability of sensors. Most stakeholders acknowledged the benefits of being able to ground-truth sensor data with spot measurements of water samples using accredited laboratory methods. However, time and financial resources frequently prevent this from occurring, particularly as the sensor or ground-truthing spot sample data is not used for compliance or statutory monitoring. For example, for a pollution event or queries regarding sonde or sensor output, the site is usually attended after the event has occurred with additional measurements taken using handheld sensors and sometimes spot samples. The usefulness of this for interpreting sensor outputs, however, is limited due to the retrospective nature of the investigation particularly following a short-term incident.



One approach to testing if a sensor is recording within the predicted range or values without the need for a site visit, is by comparing sensor outputs to modelled sensor outputs. However, waterbody models are often based on a select series of features and over-simplify the dynamism of freshwaters, therefore the success of ground-truthing this way is very dependent on the robustness and accuracy of the model.

Ground-truthing using spot samples also presents some level of uncertainty and inaccuracy. For example, the sampler must ensure that 1) the sample is taken close to the sensor but does not disturb the sensors measurement. 2) Must occur at the exact timestamp to be able to directly compare to the sensor. 3) The methods need to be comparable and measure the same determinands. Ground-truthing using a second sensor may be the most viable option.

3.6 Data collection

There were several approaches to data collection reported being employed by stakeholders. Sensor data is either downloaded directly from the equipment, which involves site visits and a USB or Bluetooth connection to a laptop or tablet. Alternatively, and increasingly, there are those which use telemetry of data via mobile phone or other communication networks to transmit data from sensors to physical or virtual servers and via data portals. Both types have pros and cons. The pro of telemetry is that any sensor issues or “events” of interest can be viewed in real-time, allowing for rapid response. Whereas standalone systems require downloads every few weeks or months, resulting in a delayed response to either sensor issues or pollution events for instance. Downloads are much more human resource heavy and time-consuming given the need to visit the sensor in-situ but are perhaps more reliable in remote locations where telemetry networks are not available. This time cost may also not be so large where routine visits are already carried out for maintenance or calibration purposes. The cons of telemetry systems are the greater potential for signal transmission issues, additional energy requirement, cloud availability or storage, application failure or other issues such as errors with updates and risks of security breaches. Notwithstanding, a general stakeholder consensus indicated telemetry systems were more attractive given the reduced demand on time compared to in-situ download coupled with being able to be more responsive.

Stakeholders recognised the issues of integrating different sensor units or types i.e. combining water quality sondes with hydrological or meteorological units, which all usually have their own unique associated software to visualise the data. Users often download the raw data from each unit individually and combine thereafter, increasing staff resource pressure. Alternatively, end-users must develop their own platforms or interfaces which can cope with multiple sensors, requiring technical expertise. Ideally, integration of multiple sensors on one platform would be straightforward meaning interoperability should be a priority of sensor developers.



3.7 Data processing

Datafiles and metadata need to be clear and concise. Monitoring datafiles can sometimes consist of multiple datasets and have too many determinands with the same determinand measured using different methods. This is often not reported in the metadata and neither is it clear which determinand is the most appropriate to use. Stakeholders acknowledged that metadata often does not support the datafile adequately enough. For example, as part of compliance reporting, raw datafiles containing details and dates of calibration or maintenance, as well as power output need to be provided. Often this information is provided separately to the raw data and must be added retrospectively so becomes an extra step the data user must undertake.

Stakeholders noted the difficulty identifying “events” versus “errors” when processing high frequency sensor data and the high level of subjectivity involved. Correcting for drift and removing outliers requires statistical expertise and experience of using coded scripts and statistical software. However, such approaches can also oversimplify or over-clean the data. This is a big challenge of high-frequency data processing as if it is not performed correctly can reduce the accuracy of reporting. Nearly all stakeholders report the desire to reduce the time spent “cleaning” data and the generation of clear, ‘best practice’ cleaning protocols.

3.8 Data visualisation and reporting

A common challenge amongst stakeholders is how to accurately report and display high-frequency output in multiple formats for different audiences. Most stakeholders summarise high-frequency nutrient data using trends, or daily-monthly-seasonal-annual averages. The Environment Agency publish their readings on their Hydrology Data Explorer ([Hydrology Data Explorer - Explore](#)), and noted routine queries from the public regarding data output from atypical sites or sites with unique conditions. This highlights how one-size-fits-all visualisations and metadata are not appropriate for some sites, with these requiring clearer or more creative communication to lay persons. Water companies also acknowledged that they must report not only to regulatory bodies such as the Environment Agency and DEFRA but also their customers and the wider public as part of National Water Industry Standards. Public scrutiny on water company activity has increased in recent years, demanding faster and transparent data disclosure.

Most stakeholders summarise high-frequency nutrient data using trends, rates of change, time above thresholds or daily-monthly-seasonal-annual averages with standard deviations via either smoother linear time-series graphs or boxplots. This not only serves to make the large volume of data more digestible but accounts for the unreliability of the absolute values. The reporting of absolute values is seen as



a key aim for the use of sensor data, as this would enable use of sensor output in statutory reporting.

UKCEH differ from other stakeholders in that they typically focus on process-based research with data visualisation and reporting requirements more technical than those who must report to non-technical or public audiences. UKCEH often work closely with model developers who require cleaned but extensive datasets.

3.9 Summary of current sensor experiences

Key themes which emerged from the stakeholder discussion session on contemporary experiences of water quality sensors included sensitivity and range, reliability, calibration, maintenance, ground-truthing and the collection, processing, visualisation and reporting of sensor data. A common thread throughout was the demand on time and consequently financial resourcing for many of the activities, and the desire to automate as much of this activity to reduce this pressure. In addition, calibration is required to improve the reliability of sensor operation but damage from environmental conditions can reduce the reliability of sensor output and demand for maintenance. There was also a desire to provide and improve best practice models for reporting sensor monitoring which can often be subjective.



4. Future Directions

This section details a “blue skies” discussion around future challenges and opportunities for nutrient monitoring as determined by the stakeholders. This section is of particular importance to the ADAPT-NP project as it helps to identify user needs and foster innovative thinking.

4.1 Statutory and compliance monitoring

Currently, regulatory monitoring in Wales and England excludes the use of sensor data due to a lack of established quality assurance of methods and limited confidence in absolute concentration values returned by sensor-based methods. Therefore, having accreditation and quality assurance, alongside improvements to the sensitivity and robustness of concentration measurements was determined to be a key future need of stakeholders involved in statutory and compliance reporting.

The Environment Act 2021 is new legal framework following Brexit, aimed to better protect and restore the natural environment. The Act sets out several targets associated with improved monitoring of the water environment for both governmental organisations and the water utilities. For example, non-departmental government bodies such as Natural England have a target of carrying out site condition assessments on all SSSI's by 2028. For upland freshwaters, this presents a challenge in terms of accessing SSSI's in remote locations. Reducing costs through streamlining monitoring is seen as imperative. From the perspective of sensor-based approaches, this presents both a challenge considering the issues detailed in section 3 as well as an opportunity if novel sensors can be made reliable and robust.

Government agencies such as Natural England and Environment Agency who are involved in the statutory monitoring and reporting of freshwater ecosystems must report Total Nitrogen and Total Phosphorus. This is seen as a holistic approach to nutrient assessment, as it encompasses the different fractions including particulate and dissolved. The Environment Agency does measure different forms of Nitrogen such as Nitrate-N, Ammonium, as well as different Phosphorus fractions including Orthophosphate in lake and fluvial environments. One such government initiative which requires Total Nitrogen and Total Phosphorus is Nutrient Neutrality, which demands that any developments do not add additional nutrients to surface waters or Habitat Sites. Natural England is involved in this assessment and guidance for these Habitat Sites. Nutrient mitigation measures such as constructed wetlands or riparian and buffer zones may also help reduce the nutrient burden. Real-time monitoring which is well-validated and commercially available for these determinands is currently not available, making assessments of Nutrient Neutrality



difficult. In addition, nutrient load calculations are required so monitoring flows is important, as changes in concentration alone can be due to either dilution or concentration from low flows. Therefore, sensors and other monitoring must consider how best they can meet these requirements.

Section 82 of the Environment Act requires that water companies must monitor at high frequency (15 mins to 1 hour) upstream and downstream of combined sewer overflows and wastewater treatment works where they discharge into a watercourse. Water companies expressed an ambition to expand their monitoring across catchments. In other words, monitoring includes being able to detect “events” or issues with their assets and continual diffuse sources, such as leaky or poorly maintained wastewater assets, or from agricultural sources. A catchment perspective could present opportunities for investment in not only point sources but upland restoration or natural flood management schemes too. The requirements for sensor technologies and sensing systems must therefore be adaptable to a large and variable range of freshwater conditions. For instance, water companies will have scenarios where they are dealing with routine wastewater release to incidences from damaged infrastructure which result in a big increase in nutrient concentrations. As such, sensors need to be interoperable with their other assets and monitoring (e.g. with Event Duration Monitors) and data output needs to withstand the highest level of scrutiny to be able to use it in enforcement. These sensors must be competitively priced if they are to be widely deployed, though this market demand may drive prices down for consumers.

The requirements of future environmental legislation remain unknown presenting uncertainty in terms of the sensitivity requirements and demands on nutrient monitoring. Phosphorus is deemed the determinant of most interest, given its key role in nutrient enrichment and degradation of water quality in freshwater environments. High frequency monitoring of bioavailable forms of Phosphorus may help identify locations and timings of algal bloom risk, improving the predictive capacity of models and facilitating short-term water quality forecasting. It has also been identified as a key nutrient of interest to policy, government designations and future iterations of directives (i.e. the Habitats Directive) which will demand stricter and lower nutrient thresholds in freshwaters. Improving the accuracy of Ammonium monitoring using sensors is also attractive in terms of point source asset monitoring and compliance reporting. Further, there is also a recognition that organisations may need to be prepared to measure other organic or synthetic contaminants should changes to legislation require monitoring at high frequency, necessitating the development of novel sensors.

4.2 Ecological monitoring

Beyond nutrient sensing, there was a recognition among stakeholders of a need for better understanding ecological impacts of nutrient inputs over different timescales.



For example, there was interest in developing approaches such as environmental DNA (eDNA) or in-situ flow cytometry or imagery for the quantification of species of interest such as algae, particularly harmful algal bloom species. These approaches used alongside nutrient monitoring would potentially enable the improved management of algal blooms and a better understanding of nutrient impacts on freshwater organisms. However, whilst these approaches are of growing interest to the freshwater monitoring community, these novel methods have their limitations, and further development is needed to improve their utility. For example, eDNA is currently largely used as a measure of species' presence or absence and methods to provide information on species' abundance are still in development. Flow imagery requires taxonomical expertise to train datasets, as artificial intelligence classifications are still in their infancy and taxonomic resolution limited by image quality. Notwithstanding these challenges for ecological monitoring, the interest in developments in this area raised by stakeholders highlights the need to combine and integrate different environmental datasets to get a more comprehensive overview of freshwater ecosystems.

4.3 Challenging Environments

Climate change is already modifying the seasonality and unpredictability of rainfall and air temperature, with attendant impacts on freshwaters and their ecology. Stakeholders were interested in the performance of nutrient microfluidic sensors under changing temperature, given that laboratory-based colorimetric assessments of nutrients require controlled temperatures for accurate measurements. Extreme flow events on both scales will likely need to be considered when deploying and fixing in the sensors. Low and high flows may impact the throughput of sample and reagent and therefore, the accuracy of the measurement. As well as cause damage to monitoring infrastructure.

Being able to deploy microfluidic nutrient sensors from fresh to saline surface waters would be attractive to those monitoring in estuarine systems. This is tricky given the need to matrix match and calibrate samples of different salinities when undertaking colorimetric analyses in saline conditions. The SouthWestSensors will be tested in the laboratory across a range of salinities to assess their capacity and accuracy in saline waters. One option to overcome this maybe to do some post-measurement correction using data from salinity monitoring.

4.4 Summary of future directions

Discussions with sensor users on their future needs is important to understand the key characteristics that are being sought in commercially available water quality nutrient sensors and where innovation should focus. The biggest driving force appears to be legislation (1) which is favouring increasing data-driven management under ever-constrained resources and was identified in the ADAPT-NP stakeholder workshop discussions. In addition, stakeholders discussed interest in innovating



nutrient monitoring with high-frequency ecological monitoring to track ecological consequences of nutrient pollution and forecast algal bloom development. Finally, climate change was noted as being important not only as a pressure to monitor but when considering the impacts of temperature and rainfall to sensor accuracy. For instance, temperature can interfere with the reliability of the colorimetric reactions in nutrient sensors and extreme and variable conditions may damage kit or interfere with data quality and transmission.

- 4.4.1 Whelan, M. J., Linstead, C., Worrall, F., Ormerod, S. J., Durance, I., Johnson, A. C., ... & Tickner, D. (2022). Is water quality in British rivers "better than at any time since the end of the Industrial Revolution"? *Science of the Total Environment*, 843, 157014.



5. Opportunities for the ADAPT-NP project.

The following section details the discussion which followed a demonstration of SouthWestSensors existing single nutrient sensor and introduction to adaptive monitoring. The multi-nutrient (Nitrate, Nitrite, Ammonium and Phosphate) sensor will mainly utilise the same microfluidic technology as the single Phosphate sensor but with additional innovations. The stakeholders got to ask questions on the development of the new multi-nutrient sensors to the engineering team at the University of Southampton and the data science team at UKCEH who will be developing the adaptive monitoring tools. This section details the answers provided to the stakeholder questions by essentially outlining the future development of the multi-nutrient sensors and adaptive sampling tools.

5.1 Sensor operation

The micro-fluidic nutrient sensor developed by Prof Niu and subsequently commercialised via SouthWestSensors works by testing a droplet of water with standard chemical reagents and measuring the concentration of the determinand following a reaction. The sensor can measure the volume of sample analysed which will enable the scaling up of standard reported nutrient volumes. In addition, the droplet system employed limits dispersion effects of other fluidic systems (often typical in chromatography too) and therefore, increases the accuracy of the measurement.

Stakeholders noted some concern with how such a small volume of water could represent large systems such as lakes, but this is an inherent issue with contemporary monitoring of lakes, large rivers and indeed catchments, often requiring a network of monitoring locations and samples. The sensor, however, can sample from a continuous flow which is pumped into the chamber thus enabling larger volumes of water to be analysed compared to typical laboratory samples.

As the sensor uses a droplet of water mixed with a chemical reagent which must then undergo a chemical reaction before a measurement is made, a delay between sampling to output is apparent. The time this will take is yet to be determined but will have to consider reaction kinetics. Stakeholders were concerned this would limit the rapid response needed for “event” monitoring if timescales were over an hour.

The multi-nutrient sensors being developed by University of Southampton in this project will be a step forward of the single parameter nutrient sensors developed by SouthWestSensors. The new system will target simultaneous monitoring of multiple nutrient analytes, and with much reduced response time (sample to signal time) from previously an hour to a few minutes. The multi-nutrient sensors will utilise a



cartridge system, containing refills of reagents and calibration standards. The system would alert the user as to when the cartridge needs replacing. The specifics of calibration and its automation will require some trial and development, but the sensor is designed so that the user can select when calibration occurs and for it to be automated. Whilst a site visit will still be necessary to replace cartridges, simplifying in-field calibration in this way was deemed an attractive prospect particularly by those stakeholders who currently undertake sensor calibration ex-situ. The waste chemicals following the reactions will be kept in the cartridge and will not be released into the environment.

Stakeholders reported the attractiveness of self-diagnostics and alarms to alert users to errors or issues. The SouthWestSensor has already an element of self-diagnostics in that it can identify drift and correct itself. Tracking sensor issues or alerts would be easier if these were automatically logged in the datafile too, aiding quality control of the data. On a similar note, being able to track different sensor components from manufacture through to deployment and calibration would also be useful for water companies for example, who must supply this information as part of compliance monitoring.

5.2 Sensor components

As the sensor is not submersed in the water column, it requires an external pump and pipe in which to deliver the sample to be tested, with the sensor being housed in a dry box. Trialling this equipment in dynamic freshwater systems such as upland streams will help test the robustness of the environmentally exposed equipment.

The sensor is housed in a dry box that can connect via USB cable or Bluetooth to a tablet or laptop. The data will be sent to a database via a 4G and cloud service.

The power source to the sensors can be obtained from solar panels and/or rechargeable batteries allowing for improved sustainability and adaptability to suit different environments. The sensor takes 3 watts to run so has a very low energy consumption. The low energy consumption and flexibility of power sources was attractive to stakeholders with regards to reducing the need for site visits and environmental sustainability.

The environmental impact of deployment needs to be acknowledged, and attempts made to reduce as much as possible damage to sensitive habitats. Whilst the sensors are relatively small compared to other infrastructure, deploying several in a catchment and in sensitive riparian habitats may overall have a notable impact. One way to reduce this, is to deploy sensors where current monitoring infrastructure already exists as will be undertaken in the field tests on the UKCEH lake monitoring buoys. However, most lakes do not have monitoring buoys, again, presenting potential impacts from disturbance as infrastructure is installed and



damage to sensitive habitats from the shoreline to the buoy from those who will maintain this network.

5.3 Adaptive monitoring and trigger levels

Adaptive monitoring aims to increase monitoring at certain locations and to different frequencies according to a pre-determined set of environmental conditions or trigger levels. It has several benefits which include reducing the following: consumption of energy, volume of low-quality data and maintenance or site visits. The compatibility with existing telemetry systems is a key aim of the ADAPT-NP project. This is important to enable the comparison of data output with other determinands being monitored in the environment, particularly those which will or could trigger the higher frequency resolution of sampling i.e. from the adaptive monitoring. Indeed, field trials will include integration of the multi-nutrient sensors with existing sensor systems to test the integration and adaptive monitoring capacity. Stakeholders also noted an interest in the development of a coordinated network of sensors across a catchment, which could all be monitored using the same interface.

In terms of process-based science, adaptive sampling presents some exciting developments. Pulses of nutrients often enter freshwaters in events occurring at shorter timescales than the time intervals of current sensors. Being able to track these rapid events will improve models which often are limited by the timescales of the driving data. Using rainfall and soil moisture records and models already utilised by UKCEH for example, may mean that nutrient mobilisation could be incorporated and enable predictions or forecasts as to whether certain rainfall and soil conditions will increase the delivery of nutrients to freshwaters within a catchment.

An R package will be developed which can be adapted by the user to set and run the trigger levels thereby interacting with the sensor. Stakeholders noted an interest in adapting monitoring at extreme flows, particularly high flows given the potential of increased nutrient influx from catchment surface runoff and outfall inputs during and following rainfall events. Similarly, developing trigger levels to increase the frequency of monitoring when Combined Sewer Overflows or other point inputs start flowing would aid compliance assessment. Low flow events would also be of interest, with determinands such as Temperature or Dissolved Oxygen (DO) suggested to define trigger levels to instigate higher frequency nutrient monitoring during droughts. Algal blooms were also mentioned with the use of a combined set of determinands such as Temperature, Chlorophyll and DO helping to trigger an increase in monitoring. Algal blooms could result in lower nutrients so sensitivity to lower or reducing concentrations is again, key here. Finally, often for lake sampling, wind is the biggest restriction to undertaking field sampling particularly when boat work is required, yet wind mixing may be an important component of nutrient biochemical cycling and transport. Therefore, being able to sample nutrients in turbulent conditions would be novel.



There are already developments in the use of Raspberry Pi kits and code to alert sensor users when specified thresholds have been breached. The Campbell logger was suggested as a useful sensor for this work given its ability to output rates of change. For example, it could be useful to provide thresholds in rainfalls using mm per hour. Therefore, if high flows or heavy rainfall events were requested as trigger levels it could be set when XX mm are recorded over an hour or another time period.

5.4 Streamlining the collection, processing and visualisation of data

The collection, processing and visualisation of data presents the biggest time-lag in the reporting of data due to the requirement for human resourcing. If this step was removed, this would present a lot more opportunities in terms of response to events and informing further monitoring or management or response to queries. This would require data to be cleaned or processed in real-time. It may also be applicable for users to select which method is used to address outliers. This “digital twin” model is something UKCEH and researchers elsewhere are striving to achieve from monitoring networks, with the aim of generating faster feedback between the environment to those who can respond. The ADAPT-NP project is an important step towards realising this for nutrient data, due to the provision of near-real time data as opposed to the lags from laboratory analyses.

One important challenge may arise from the reporting of adaptive sampling determinands. Typically averages over selected timestamps are reported but this is done using routinely collected data i.e. standard intervals between samplings. Under adaptive sampling, this may not be appropriate as sampling will be focussed on periods according to specified conditions rather than routine time intervals. Therefore, it might be more applicable to report averages across flow rates rather than averages over time.

5.5 Summary of opportunities for the ADAPT-NP project.

The multi-nutrient sensor in development as part of the ADAPT-NP project builds on SouthWestSensor’s single Phosphate micro-fluidic system technology. The key design innovations of the micro-fluidic multi-nutrient sensor includes 1) the reduction in time from sample to reaction to measurement from one hour to minutes. 2) Automating calibration and alerts to when reagents need recharging. There will also be design features integrated from the single sensor including 1) the self-diagnostics and correction of drift. 2) The use of a cartridge system containing reagents and calibration standards to remove the risk of waste entering the environment. The multi-fluidic sensor will have two different designs from a bankside analyser to submersible probe. Environmental impact will be reduced from the low energy requirements and optional power sources, coupled with 4G



and cloud service data transmission to reduce the need for site visits, and by increasing the ease of integrating the sensors into existing monitoring networks to reduce infrastructure demands. The interoperability of the micro-fluidic sensor with existing high-frequency monitoring systems will be conducted in field tests as part of the ADAPT-NP project.

Adaptable monitoring involves the user selecting a series of criteria which triggers an increase in the frequency of nutrient measurements. The benefits of adaptive monitoring were discussed such as 1) increasing data quality and 2) reducing time-spent “cleaning” large volumes of data. This will be developed in the ADAPT-NP project using a coded R script. The trigger levels of interest included 1) high and low flows to understand catchment nutrient delivery, 2) when Event Duration Monitors are active for compliance monitoring of combined sewer overflows and 3) increasing Temperature and decreasing Dissolved Oxygen to investigate the risk of algal blooms.

6. Next steps

The next steps for the ADAPT-NP project are the continued development of the sensor technology and associated data packages and interfaces. The stakeholder workshop has identified key challenges by stakeholders in nutrient monitoring, which will be used to drive and inform these developments. Of note, was the need to improve the sensitivity of nutrient sensors in low but ecologically relevant nutrient conditions and be able to reliably report absolute values. To reduce the time and human resource required for site visits whether through the automation of calibration or reduced need to maintain sensor equipment. In addition, designing compatible and intuitive data output and interfaces which are easy to use and interpret.

The next stakeholder workshop will be held later in the project (to be determined) following the three field trials of the multi-nutrient sensors, detailed in Box 1. This will enable the opportunity to report on the outcomes of the field trial and provide an iterative opportunity for stakeholder input into development of the sensor and associated data packages and management.

A quarterly newsletter will be distributed to stakeholders to provide progress updates on the development of the sensor and data packages, and the outcomes of the field trials.



Box 1. Adapt-NP field trials.

Multi-nutrient sensors will be deployed in three distinct freshwater sites, across a range of environmental conditions and sensor networks.

1. Deployment on existing UKCEH Cumbrian Lake monitoring buoys on Windermere's south basin, Esthwaite Water and Blelham Tarn. The solar-powered buoys have a range of sensors sampling at 4-min intervals and form part of UKCEH's long-term lake monitoring programme. This programme also includes spot sample monitoring at fortnightly frequency collecting integrated water samples tested for nutrients via laboratory accredited methods. This will be supplemented by additional measurements to enable the ground-truthing of the sensors. These lakes show distinct seasonal patterns in nutrient concentration and are often low in nutrients during the summer, but current knowledge on short-term variation in nutrient levels is lacking. Relatively small changes in nutrient concentrations have ecological consequences, thus, provide an opportunity to test the sensitivity of the multi-nutrient sensor.
2. Improved "event" detection. Sensors will be deployed in upstream mountainous tributaries as part of a collective UKCEH, Environment Agency and United Utilities monitoring campaign. The aim here is to test the adaptive sampling capabilities and performance of the sensors as part of "event" monitoring.
3. Compliance monitoring under high nutrient conditions. A dual sensor unit will be deployed at the inlet and outlet of the aquaculture site owned by Test Valley Trout Farming Ltd to inform nutrient management and fish health.
4. We will also investigate sensor applications in wastewater treatment in collaboration with Southern Water. Additionally, we will explore small-footprint, portable multi-nutrient sensors suitable for deployment on unmanned surface vehicles. These agile sensors can cover a wider range than fixed units, offering enhanced flexibility for monitoring efforts.

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