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Technical note: A Water Analysis Trailer for Environmental Research (WATER)

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Abstract

In complex hydrological systems, flow path dynamics, water storage and mixing, and biogeochemical processing vary in space and may change rapidly during events. Understanding source areas, connectivity and short-term dynamics in stream water quality therefore requires high-temporal-frequency, multi-source observations both within and across catchments. Revolutions in field-deployable analysers and sensors, together with advancement in automation techniques, now make such observations feasible via true “labs-in-the-field”. This paper details the technical realisation and proof-of-concept for the Water Analysis Trailer for Environmental Research (WATER). The WATER is a mobile, trailer-based platform for environmental sensing and automated, high-temporal-frequency sampling and analysis of water from multiple (currently up to 11) sources. It is currently equipped to measure stable water isotopes, nitrate, electrical conductivity, pH and temperature, though its modular design supports the integration of additional measurement devices in the future. A field test in the 1.03 km^2 Schwingbach Environmental Observatory, Germany, demonstrated the ability of the WATER to successfully and autonomously collect and analyse samples from six water sources (2 × stream water, 3 × groundwater, 1 × precipitation) over a period of six months, with collected data offering potential for new understanding of catchment functioning. Insights were also gained into the practical considerations necessary when deploying the WATER for an extended period of time, such as ensuring an adequate self-sufficient power supply and scheduling routine maintenance visits. Simulation of the reduced sampling frequency that would result from extending the WATER to sample at its full capacity of 11 sources also indicated that, over multi-month periods, key distributional characteristics of the collected data would likely be maintained. Overall, the WATER provides a mobile and scalable solution for high-temporal-frequency, multi-source hydrological and hydrochemical monitoring that can be (re-)deployed in different locations or targeted to specific events.

1 Introduction

It has been known for some time that in order to understand the hydrological and hydrochemical functioning of a catchment, measurements pertaining to water quantity and quality must be made at the timescales relevant to the governing processes (Kirchner et al., 2004). As a result, significant advances have been made in the development of field-deployable analysers and sensors that permit *in-situ*, high-temporal-resolution measurements at a reasonable cost and without requiring the transport and analysis of water samples in a laboratory (Rode et al., 2016). For example, laser spectroscopes have been successfully adapted for use in the field (Berman et al., 2009; Pangle et al., 2013), and are capable of making quasi-continuous measurements of stable water isotopes when combined with a diffusive sampler to rapidly transform water from its liquid to vapour phase via diffusion across a porous membrane (Munksgaard et al., 2012). Meanwhile, UV hyperspectral spectrometers capable of measuring parameters such as nitrate (Sandford et al., 2007) and dissolved organic carbon (Sandford et al., 2010) at a very high temporal frequency, have helped increased the array of water quality parameters that can be measured *in-situ* beyond those possible with electrode-based sensors that have been available for decades (e.g., Carritt and Kanwisher, 1959). As reviewed by several recent papers (Benettin et al., 2022; Bieroza et al., 2023; Burns et al., 2019; Rode et al., 2016; Rozemeijer et al., 2025; Van Geer et al., 2016), the revolution in high-temporal-frequency measurement devices has transformed – and will continue to transform – our ability to trace water fluxes through catchment systems, elucidate the sources and flow paths that contribute pollutants to rivers, improve estimation of pollutant loading, assess compliance with regulatory standards, develop and test new conceptual and numerical models, and inform appropriate catchment management strategies.

An emerging approach for combining multiple analytical and sensor technologies for longer-term, high-temporal-frequency measurements is the development of so-called "labs-in-the-field" – powered and fixed installations housing various measurement devices and some form of automated sample acquisition and delivery system. For example, von Freyberg et al. (2017) developed a lab with a dual-channel ion chromatograph (IC) and a diffusive sampler coupled to a cavity ring-down laser spectrometer to automatically measure major anions/cations and stable water isotopes in stream water or precipitation every 30 minutes. Meanwhile, Floury et al. (2017) developed the "River Lab", which houses two ICs and several water quality probes to measure the hydrochemistry (anions/cations, pH, conductivity, dissolved oxygen, dissolved organic carbon, turbidity and temperature) of continuously pumped stream water every 30 to 40 minutes. Following the prototype, further River Labs have been customised and installed to sample rivers draining catchments up to 1500 km^2 in area (Brekenfeld et al., 2025). Both lab variants have successfully captured multi-parameter, high-temporal-frequency data for contrasting events occurring over an extended period of time, permitting new inferences to be made regarding catchment water storage and release (von Freyberg et al., 2017), the role of vertical connectivity in setting solute- and event-specific concentration-discharge relationships (Floury et al., 2024), and the disproportionate contribution of large storms to solute export (Wang et al., 2024).

As high-temporal-frequency analysis has become more common, it is increasingly recognised that continuing to advance our understanding of hydrological and hydrochemical processes requires monitoring to be extended from one or two stream water sources to spatially-distributed sources within multiple catchment compartments (Bieroza et al., 2023). Such measurements can help identify longitudinal patterns of stream water chemistry which can be linked to in-stream processes or local solute sources (Winter et al., 2021), constrain the changing nature of lateral and vertical hydrological connectivity and solute distributions under contrasting hydroclimatic and antecedent conditions (Knapp et al., 2022), and overall reduce issues of process equifinality that can arise when drawing inferences from measurements taken from a limited number of in-stream locations (Knapp and Musolff, 2024). Furthermore, being able to gather similar measurements from a range of different catchments or in rapid response to extreme events (e.g., floods, droughts, accidental spills) can enable hypotheses of catchment functioning to be tested in contrasting environments (Knapp et al., 2025) and provide greater understanding of how catchments may respond to increasing pressure from climatic and anthropogenic change (Li et al., 2021; 2024). Heinz et al. (2014) designed and implemented a lab-in-the-field that permitted flexible and automated sampling of multiple water sources from a centralised location using one set of measurement devices. The system was successfully implemented in a rice paddy environment to measure stable water isotopes and nitrate in precipitation and irrigation water, as well as in 10 groundwater and ponded surface water sources located in fields experiencing contrasting management regimes. Each source could be sampled once every 6 hours (Mahindawansha et al., 2018). However, this setup was again restricted to a fixed location and required a local power supply. Consequently, cross-catchment investigations would still require multiple instances of the lab-in-the-field to be installed at significant expense, whilst rapid response sampling of extreme events would not be possible.

This paper reports on the development and testing of the Water Analysis Trailer for Environmental Research (WATER). The intended purpose of the WATER is to provide a mobile sampling platform capable of measuring the stable water isotope composition and water quality of multiple water sources distributed in space at a high temporal frequency. The next section outlines the design of the WATER, which builds on experiences made by Heinz et al. (2014) and Mahindawansha et al. (2018). A field test is then presented to provide a proof-of-concept for the WATER and highlight practical considerations for its operational use. Finally, the scalability of the WATER is assessed to understand the potential trade-offs between the number of water sources that are sampled, the temporal frequency of sampling, and the resultant distribution of collected data.

2 Design of the WATER

To fulfil its intended purpose, the design of the WATER needed to incorporate the following features:

- A mobile housing to facilitate deployment to a new location within a day.
- A self-sufficient power supply and automated security and fire suppression systems for deployment to remote areas.
- An automated sample acquisition and measurement system with a high throughput rate (maximum 20 minutes per sample) to enable high-temporal-frequency analysis of multiple water sources.
- Modular hardware and software constructions to offer flexibility in the measurement devices that can be installed.
- Remote software access to check system status, alarm messages and the sampling schedule.
- The ability to connect to local and remote sensor networks for the acquisition of complementary hydrometric data or to trigger sampling of specific water sources.

The following sub-sections outline and justify how these design criteria were met.

2.1 Trailer and basic infrastructure

The basis of the WATER is a custom-made closed trailer with an insulated shell and integrated furniture. A trailer was chosen over a dedicated vehicle to optimise the balance between mobility and costs. The insulated shell of the trailer helps to buffer daily and seasonal temperature fluctuations. At low temperatures, supplementary heating is available that offers temperature control to within ±5 °C. Meanwhile, in-built ventilation aids cooling during higher temperatures. For measurement devices that are particularly sensitive to temperature, a climate-controlled server enclosure (TS IT 5528.129, Rittal GmbH & Co. KG, Herborn, Germany) with two thermoelectric coolers (SK 3201300, Rittal GmbH & Co. KG, Herborn, Germany) is available, offering heating and cooling to within ±1 °C of a specified temperature.

Power to the trailer can be provided by solar panels with battery storage, a 5.1 kW diesel generator (5000i, Fischer Panda GmbH, Paderborn, Germany), or mains (grid) AC power. Whilst the former is the most sustainable, it requires an open site for installation and is sensitive to sunlight availability. In addition, careful planning is needed to ensure that the power generated by the solar panels can meet the requirements of the measurement devices installed in the WATER. By contrast, the diesel generator offers a rapid, ready-to-use power supply that can provide a consistent high-power output whilst maintaining mobility. Power within the trailer can be supplied at 12V and 24V DC, as well as by converted 230V AC. For security purposes, the trailer is fitted with an alarm system, video surveillance and a GPS. A fire suppression system using heptafluoropropane (HFC227) is also installed.

2.2 Sample acquisition system

A diagram of the sample acquisition system is provided by Fig. 1a. A peristaltic pump (*P1*; M1500, Verder GmbH, Haan, Germany) draws water from a source connected to an open valve within a valve array. The number of possible input sources is determined by the size of the valve array. The current setup provides 12 valves, one of which is used for maintenance. Consequently, 11 valves can be connected to external water sources via a sampling line, permitting analysis of multiple source types distributed in space. The sampling line should be made of an inert material (e.g., PTFE) to be consistent with the internal tubing of the WATER and facilitate the full range of hydrological and hydrochemical analyses. The maximum distance to a source depends on the hydraulic properties of the sampling line, the power of the peristaltic pump, and the hydraulic gradient between the source and the WATER. For water sources with a negative hydraulic gradient, the maximum distance is on the order of several hundred metres for water to a depth of 3 m. This could be extended by using an additional pump to draw water up directly from the source itself (c.f. Heinz et al., 2014). With a positive gradient, the distance is much greater.

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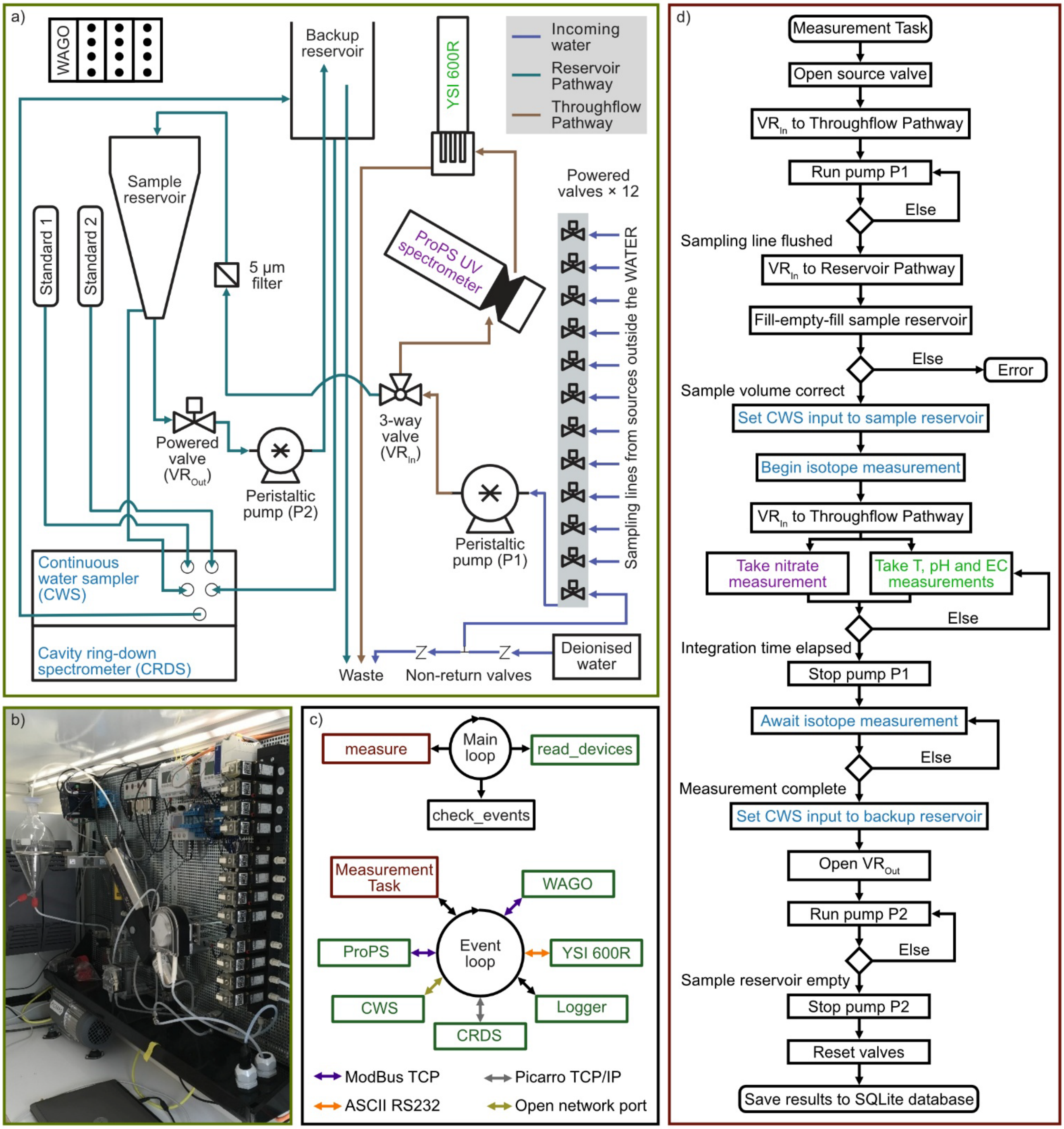


Fig 1: a) Schematic of the automated sample acquisition and measurement system in the WATER; b) photo of the valve and pump system, ProPS, YSI600R and sample reservoir; c) schematic of the main software loop and event loop (coloured arrows in the latter denote the method of interfacing with devices whilst a black arrow indicates a software connection); d) flow chart for a Measurement Task (coloured text denotes the device used in measurement acquisition and corresponds to device labelling in a).

A water sample is pumped either along the "Throughflow Pathway" or "Reservoir Pathway". The pathway is determined by a 3-way valve (VR_{In}). The two pathways allow integration of measurement devices that require a continuous throughflow of unfiltered water or filtered water drawn from a reservoir, respectively. Water directed along the Reservoir Pathway is passed through a 5 µm filter before being received by a 1000 mL sample reservoir connected to a 5 kg load cell (SP4M-series, Hottinger Brüel & Kjaer GmbH, Darmstadt, Germany) used to measure sample volume. A powered valve (VR_{Out}) and second peristaltic pump (*P2*; CP83, Gemke Technik GmbH, Ennepetal, Germany) are used to empty the sample reservoir into a backup reservoir, which in turn drains under gravity to the waste outlet of the WATER once it reaches a certain fill level. A 10 L container of deionised water is also connected to the system for rinsing purposes. The valves, pumps and load cell are controlled by a WAGO programmable logic controller (PLC) with 32 digital outputs, 16 digital inputs and 4 analogue inputs (WAGO I/O system 750, WAGO Kontakttechnik GmbH, Minden, Germany). A central controller PC with a GNU-Linux operating system communicates commands to the PLC using self-developed software (see Sect. 2.4).

2.3 Measurement devices

The WATER is able to support measurement devices via the PLC or the Linux control computer. The latter supports multiple communication protocols (e.g., Modbus TCP/RTU, SDI-12, TCP/IP) and physical or wireless standards (e.g., RS232/485, ethernet, radio telemetry). Devices may be used directly in the analysis of a water sample, to trigger event-based sampling, or to collect ancillary environmental data. The latter, along with non-measurement devices related to the security of the trailer, are handled via a virtual logger device.

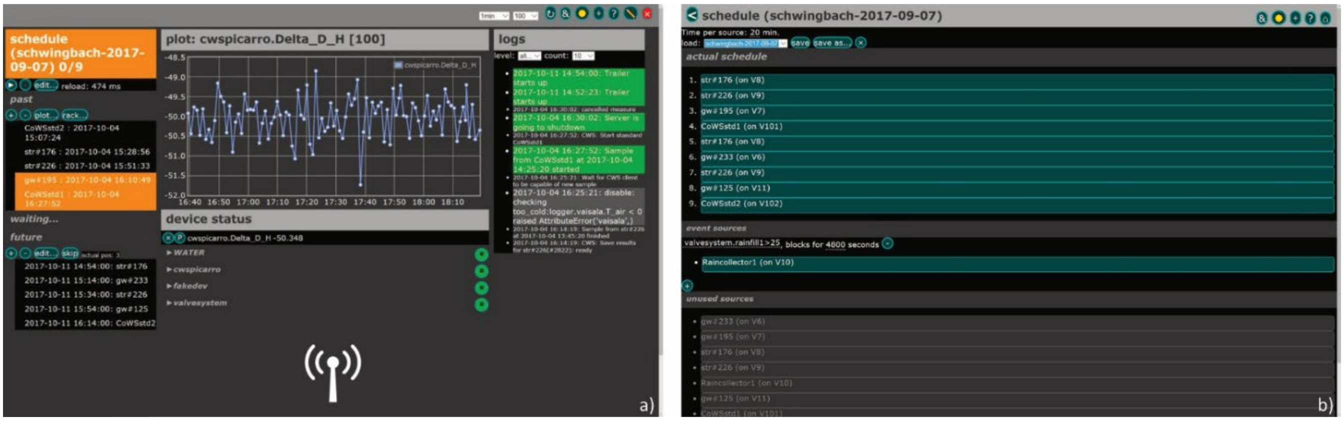
Figure 1a-b shows the configuration of the sample acquisition system and measurement devices in the current setup of the WATER. A YSI 600R multi-parameter probe (YSI Inc., Yellow Springs, USA) and a ProPS UV spectrometer connected to a TriBox2 measurement and control system (TriOS GmbH, Rastede, Germany) are available to make water quality measurements. The YSI 600R can measure electrical conductivity (EC), pH and water temperature, whilst the ProPS currently measures nitrate (NO_3-N); measurement of nitrite (NO_2) and organic content (CSBeq, BSBeq, DOCeq, TOCeq) would also be possible. Both devices are configured with a flow cell and incorporated into the Throughflow Pathway. A Continuous Water Sampler (CWS; A0217, Picarro Inc., Santa Clara, USA), connected to a wavelength-scanned Cavity Ring-Down Spectrometer (CRDS; L2130-i, Picarro Inc., Santa Clara, USA), is available to measure the stable water isotope (deuterium and oxygen-18) composition of a sample. Measurements are reported in δ notation (δ^2H and δ^{18}O) relative to Vienna Standard Mean Ocean Water (VSMOW). The CWS is based on the diffusion sampling system of Munksgaard et al. (2011) and permits quasi-continuous measurement of stable water isotopes from liquid water. Standards with a known isotopic composition are required to correct for drift caused by the CWS (e.g., due to biofilm accumulation in the membrane) and CRDS. The CWS is part of the Reservoir Pathway, with one of its four inlets connected to the sample reservoir. Water is drawn into the CWS via a built-in solenoid diaphragm pump at a rate of 1 mL per minute. Additional reservoirs containing isotopically heavy (+3.13‰ for δ^{18}O and −1.52‰ for δ^2H) and light (−22.43‰ for δ^{18}O and −164.60‰ for δ^2H) standard water are installed at the same height as the sample reservoir, and each is connected to an inlet of the CWS. Ensuring a consistent height of all reservoirs is necessary as the height of a reservoir above the waste outlet of a CWS has been shown to affect measured isotope values (von Freyberg et al., 2017). The waste outlet is connected to the backup reservoir. The final inlet of the CWS is also connected to the backup reservoir so that a source of water should always be available to prevent the sampler from running dry.

2.4 Software

The WATER is largely controlled via high-level software written in Python running on the Linux control PC, though a separate program running on the WAGO PLC interacts with the valves, pumps and other hardware of the sample acquisition system. Both pieces of software are self-developed.

2.4.1 High-level software

The high-level software (Kraft et al., 2026) interfaces with all installed measurement devices, manages sample scheduling, acquisition and measurement, handles local data storage, facilitates remote access, and monitors the overall status (e.g., security alerts, fuel warnings, etc.) of the WATER. The code aligns with FAIR principles (Barker et al., 2022) and is designed to be free, extendable (e.g., to incorporate additional measurement devices), accessible and useful. Configuration files specifying the attached measurement devices, functions specific to the operation of each device, and the sampling schedule, are read by the software to define the operational setup of the WATER. The schedule includes the sequence in which sources should be routinely sampled and any events that should trigger sampling of a specific source. The schedule can be edited after deployment of the WATER via the web app provided by the software, which also displays information about measurement and device statuses (Fig. 2).



CoWSstd2 : 2017-10-04 15:07:24
str#176 : 2017-10-04 15:28:56
str#226 : 2017-10-04 15:51:33
gw#195 : 2017-10-04 16:10:49
CoWSstd1 : 2017-10-04 16:27:52

2017-10-11 14:54:00: str#176
2017-10-11 15:14:00: gw#233
2017-10-11 15:34:00: str#226
2017-10-11 15:54:00: gw#125
2017-10-11 16:14:00: CoWSstd2

```
• 2017-10-11 14:54:00: Trailer starts up
• 2017-10-11 14:52:23: Trailer starts up
• 2017-10-04 16:30:02: cancelled measure
• 2017-10-04 16:30:02: Server is going to shutdown
• 2017-10-04 16:27:52: CWS: Start standard CoWSstd1
• 2017-10-04 16:27:52: Sample from CoWSstd1 at 2017-10-04 14:25:20 started
• 2017-10-04 16:25:21: Wait for CWS client to be capable of new sample
• 2017-10-04 16:25:21: disable: checking too_cold:logger.vaisala.T_air < 0 raised AttributeError('vaisala',)
• 2017-10-04 16:14:19: Sample from str#226 at 2017-10-04 13:45:20 finished
• 2017-10-04 16:14:19: CWS: Save results for str#226(#2822): ready
```

Time per source: 20 min.

1. str#176 (on V8)
2. str#226 (on V9)
3. gw#195 (on V7)
4. CoWSstd1 (on V101)
5. str#176 (on V8)
6. gw#233 (on V6)
7. str#226 (on V9)
8. gw#125 (on V11)
9. CoWSstd2 (on V102)

valvesystem.rainfill1>25, blocks for 4800 seconds

- Raincollector1 (on V10)

- gw#233 (on V6)
- gw#195 (on V7)
- str#176 (on V8)
- str#226 (on V9)
- Raincollector1 (on V10)
- gw#125 (on V11)
- CoWSstd1 (on V101)

Fig 2: a) The dashboard of the web user interface for the WATER, showing the past and future sampling schedule, measured data and the system log; b) the sample schedule, consisting of routine and event-triggered samples.

After setup, the main software loop runs continuously whilst the WATER is active and repeatedly calls three functions: read_devices, check_events and measure (Fig. 1c). The first function updates the status of all connected devices, logs any errors, and deactivates any device that is consistently unresponsive. The second checks whether any of the specified conditions for event-triggered sampling have been met and, if so, inserts the relevant source as the next source in the sampling schedule. The third begins a new "Measurement Task" if the previous task has finished and the next source is due in the sampling schedule. The main loop relies heavily on the built-in Python package *asyncio* to facilitate asynchronous execution of functions (i.e., new functions can start whilst running functions are waiting for something to happen) submitted to an Event Loop (Fig. 1c). Measurement data, along with a log of measurement processes and any errors, are stored in an SQLite database. The SQLite engine is integrated directly into the software.

2.4.2 PLC software

The software for the WAGO PLC covers the basic functions of water flow through the sample acquisition system: flush sample line, fill sample reservoir, empty sample reservoir, and clean filter. Each function has a pre-programmed timeout and other error conditions to prevent damages by continuous running water if the connection between the high-level software and the PLC is lost due to either hardware or software failures. The high-level software activates the PLC functions over a ModBus TCP interface. The PLC software also provides additional functionality like reading and filtering analogue signals from the load cell of the sample reservoir and monitoring the temperature in/outside of the WATER. The system is programmed in CODESYS 2.3.9, partly by using the graphical programming language Functional Block Design (FBD) and partly by Structured Text (ST). The CODESYS 2.3.9 project is published as a CODESYS-XML file (Kraft, 2026).

2.5 Measurement Task

With the current hardware and measurement device setup, a Measurement Task initiated by the high-level control software proceeds as shown in Fig. 1d. After the required source valve is opened and VR_{In} is set to the Throughflow Pathway, $P1$ starts running and flushes the external sampling line. The flush time is set for each source separately based on an assigned flow rate and the volume of water in the line (dependent on length and diameter). VR_{In} is then set to the Reservoir Pathway so that the sample reservoir can be filled. To minimise carry-over effects between samples, the reservoir is rinsed with 60 mL of sample water, emptied, and then refilled with a further 60 mL of water. If the load cell does not detect any water in the reservoir (e.g., due to clogging of a sample line), an error is raised and the Measurement Task ends. Otherwise, stable water isotope analysis with the CWS/CRDS begins. The CWS samples water from the reservoir for 20 minutes. This allows ample time for measurements to stabilise between samples (~10 minutes), with the final isotopic composition of a sample recorded as the average measurement over the last 3 minutes of analysis.

Whilst the stable water isotope analysis is in progress, VR_{In} switches to the Throughflow Pathway and water is passed through the YSI 600R and ProPS for water quality analysis. For parameters measured by the YSI 600R, values are averaged over an integration period of 20 seconds. Meanwhile, to conserve the deuterium lamp of the ProPS, a single absorption measurement is made as water passes through the flow cell. Once the water quality measurements have been made, *P1* stops, and the system waits for the stable water isotope measurements to finish. On completion, VR_{Out} opens and *P2* empties the sample reservoir into the backup reservoir. The input of the CWS is also set to the backup reservoir so that it does not run dry whilst the next sample is acquired. All valves are then reset, and the measurement data saved to the SQLite database.

The total time for the analysis of one water sample is 20 minutes, set by the time required for the stable water isotope measurements to complete. With this sampling resolution, the WATER can analyse 72 samples per day. At least once every 6 hours, material accumulated on the face of the 5 µm filter is dislodged by filling the sample reservoir with deionised water from the 10 L container and then reversing the direction of *P1* to draw water back through the filter and to the waste outlet of the WATER.

3 Field testing of the WATER

To provide a proof-of-concept and elucidate the practical considerations necessary for successful operation, a six-month (12.04.19 to 11.10.19) field deployment of the WATER to the headwater catchment of the Schwingbach Environmental Observatory (SEO) in Hesse, Germany (Fig. 3) was undertaken.

3.1 Catchment characteristics and setup of the WATER

The major land covers (Fig 3b-c) of the 1.03 km^2 catchment area are forest (76%), arable land (15%) and grassland meadows (7%). The latter mainly border arable land and the perennial Schwingbach stream. Cambisols and Stagnsols are the main soil types under forested and arable land, respectively. Elevation ranges from 310 m.a.s.l. at the outlet to 415 m.a.s.l. in the south-west of the catchment. The climate is temperate oceanic (Köppen climate classification). An automatic climate station (AQ5, Campbell Scientific Inc., Shepshed, UK) is located just outside the catchment boundary (Fig. 3c) and records climatic variables at 5-minute intervals. Stream discharge at the outlet is derived at 10-minute intervals using an RBC flume (Eijkelkamp Agrisearch Equipment, Giesbeek, Netherlands) equipped with a micro-diver pressure transducer (Eigenbrodt Inc., Königsmoor, Germany), and a calibrated stage-discharge rating curve for the flume provided by the manufacturer.

The WATER was positioned close to the outlet of the catchment (Fig. 3a, c). Two solar panels with a combined peak output of 1.7 kW and connected to a battery pack were installed to provide the continuous load of 400 W required by the measurement devices, with supplementary power available from the diesel generator when necessary. Six external water sources were connected to the WATER for sampling: two stream water sources (SW1-2), three shallow groundwater sources (GW1-3), and a precipitation source (Fig. 3c). SW1 was located at the catchment outlet, whilst SW2 was approximately 145 m upstream at the edge of the arable land. Each groundwater source was sampled from a piezometer made from a perforated PVC tube sealed with bentonite clay to prevent ingress of surface water. GW1 and GW2 were located either side of the stream under arable land and grassland meadow, respectively. GW3 was positioned further upslope at the edge of the forest. Precipitation was collected via a 3.3 m^2 funnel-type tarp connected to a 5 L bucket. A tank electrode (Votronic GmbH, Lauterbach, Germany) installed in the bucket and connected to the WAGO PLC triggered event-based sampling of precipitation based on accumulated depth.

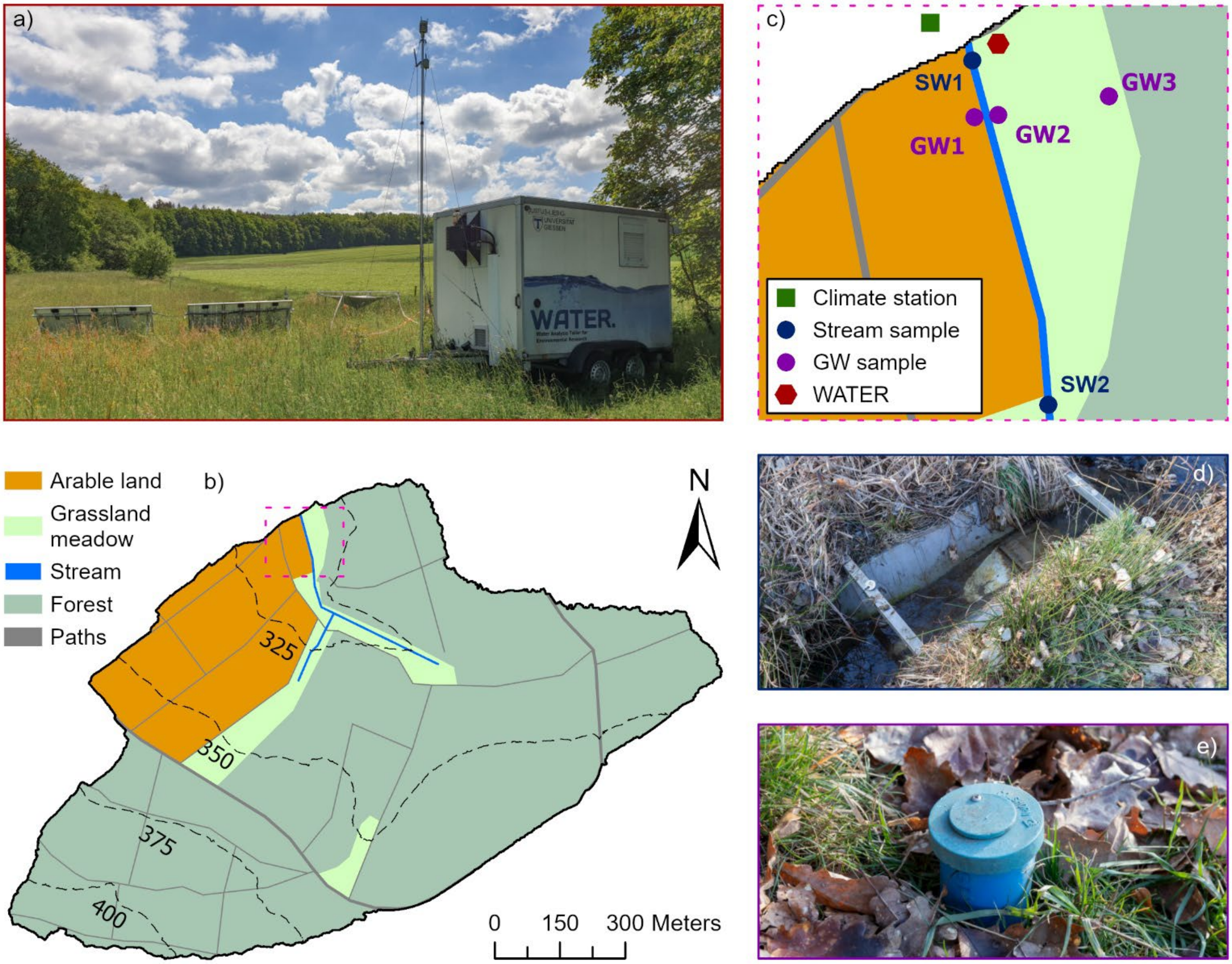


Fig 3: a) The WATER positioned at the outlet of the Schwingbach catchment together with the precipitation collector and solar panels; b) a map of the Schwingbach catchment showing the main land covers and elevation contours; c) a map showing the location of the WATER (and precipitation collector) and sampled sources around the catchment outlet (extent is given by the dashed pink box in b); d) an example of a sampled stream water (SW) source; e) an example of a sampled groundwater (GW) source.

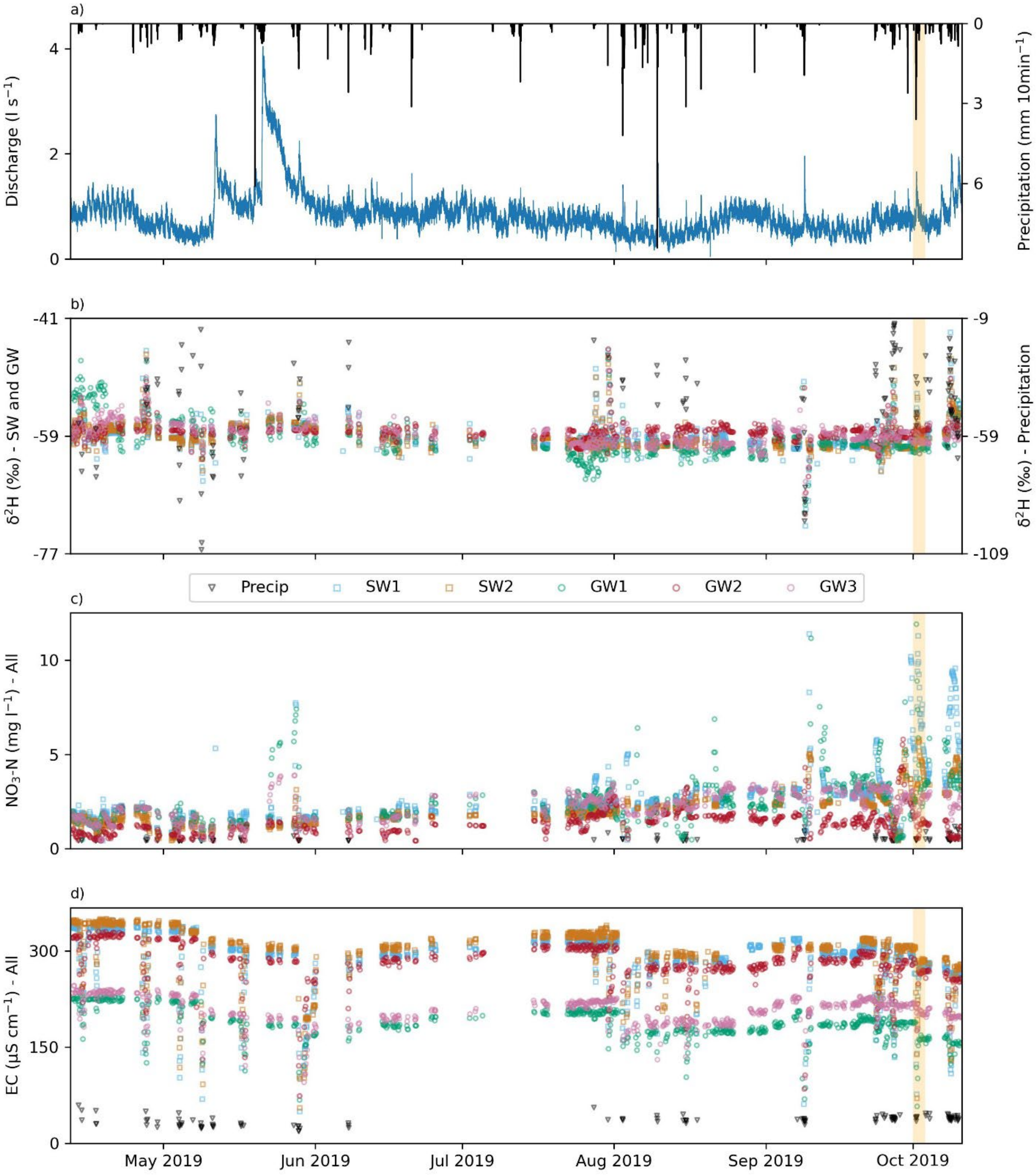
The 72 daily samples that can be analysed by the WATER were distributed as follows. In the case of no precipitation, 16 samples would be analysed from each stream water source (n=32), eight from each groundwater source (n=24), and eight from each stable water isotope standard (n=16). If precipitation did occur, then an event sample would be taken whenever the accumulated depth in the collection bucket exceeded 0.3 mm. To avoid carry-over effects, the bucket was emptied after sampling had taken place, and the precipitation source blocked from the sampling schedule for 60 minutes to allow other sources to be sampled in the event of continuous precipitation.

3.2 Performance of the WATER

Over the six-month field test, the WATER automatically collected and analysed over 4000 surface water, groundwater and precipitation samples. Figure 4 presents precipitation and stream discharge during the field deployment, together with deuterium (δ^2H), nitrate (NO_3-N) and electrical conductivity (EC) data for each source connected to the WATER. To better illustrate the high-temporal-resolution characteristics of the data, Fig. 5 presents the same data series but focused on a dynamic phase of catchment re-wetting, from 01.10.19 00:00 to 03.10.19 12:00 (“focused period”). During this period, 12.8 mm of precipitation falling over a period of approximately three hours caused a clear peak in discharge of 1.7 $l\ s^{-1}$ (Fig. 5a).

Sampling and analysis of precipitation by the WATER could generally be successfully triggered based on the depth of water in the precipitation collector, though temporary issues with the tank electrode and funnel tarp did lead to some precipitation events being missed. Whilst the magnitude and variability of NO_3-N and EC in precipitation were minimal, the data collected by the WATER characterised substantial event-scale variability in δ^2H. For instance, δ^2H measurements from the main 3-hour precipitation event in the focused period varied between -54.7‰ and -34.0‰ (Fig. 5b). The flexibility of the control software allowed precipitation sampling to be triggered at a sufficient frequency to capture such variability, despite the WATER also being connected to multiple surface and groundwater sources. Indeed, the sampling frequency of precipitation was comparable to the lab-in-the-field of von Freyberg et al. (2017), which sampled only a single stream water source in addition to precipitation. It would also be possible to prioritise other sources over precipitation (or other event-triggered sources) in applications where variability in the parameters of interest is expected to be low.

The WATER was also able to successfully sample multiple, spatially-distributed stream and groundwater sources at a high-temporal-frequency for an extended period (Figs. 4b-d). Source-specific data gaps usually reflected unavailability of a source (e.g., due to groundwater levels falling below the depth of the sampling line), or temporary obstructions in the sampling line. The data collected by the WATER revealed both common and unique characteristics of the sampled sources, from which insights into the hydrological and hydrochemical functioning of the catchment can be gained. For instance, whilst the δ^2H signal at all SW and GW sites was damped relative to measured precipitation (Fig. 4b), all sites could show deviations in the



295 **Fig 4: a) Stream discharge at the catchment outlet and precipitation measured at the nearby climate station; b) deuterium (δ^2H) measurements in stream water (SW) and groundwater (GW) sources (left axis) and precipitation (right axis – both axes are centred on the mean SW and GW value but span different ranges); c) nitrate (NO_3-N) measurements for all sources; d) electrical conductivity (EC) measurements for all sources. Data are presented for the full field test.**

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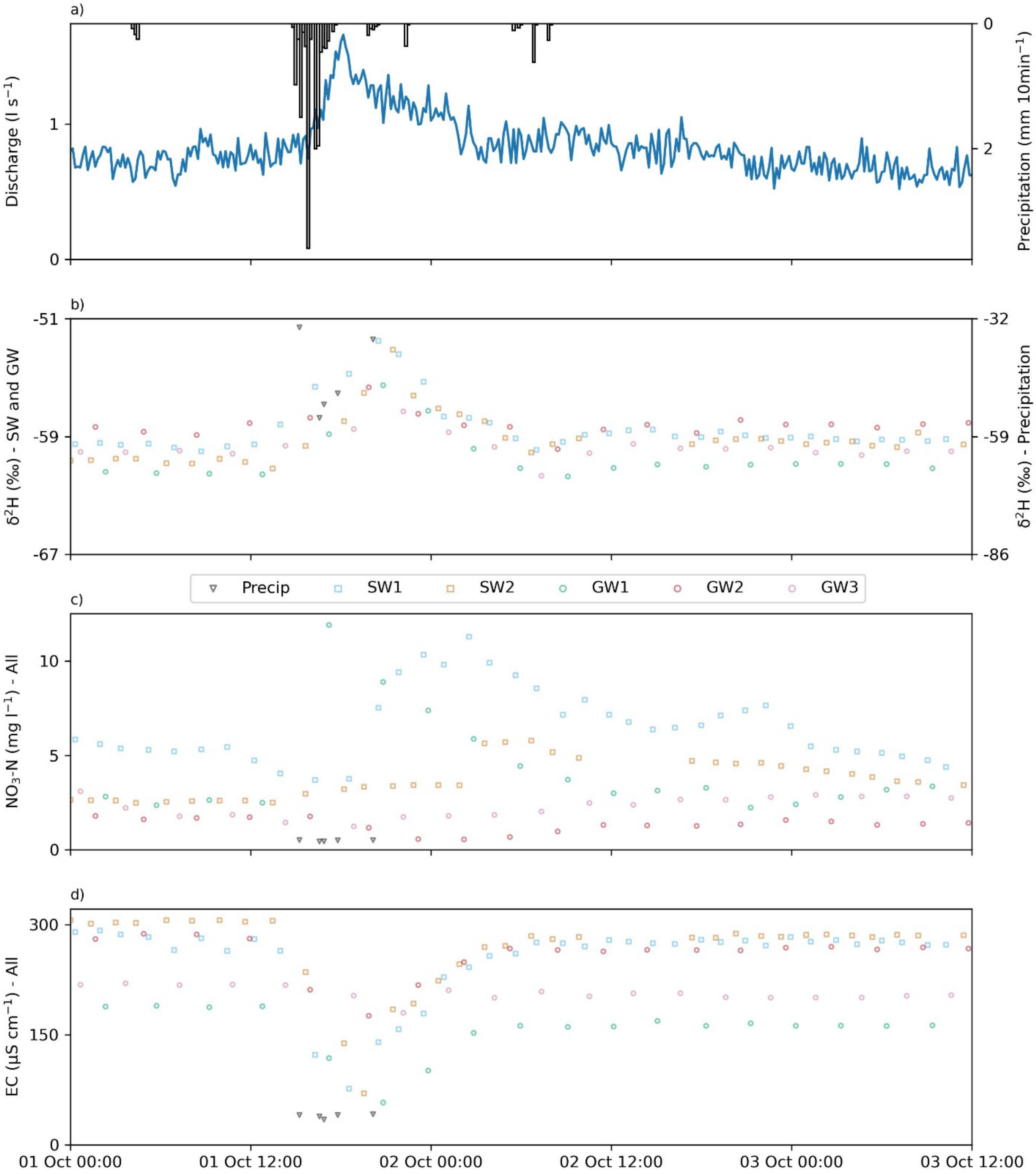

300 **Fig 5: a) Stream discharge at the catchment outlet and precipitation measured at the nearby climate station; b) deuterium (δ^{2}H) measurements in stream water (SW) and groundwater (GW) sources (left axis) and precipitation (right axis – both axes are centred on the mean SW and GW value but span different ranges); c) nitrate (NO$_3$-N) measurements for all sources; d) electrical conductivity (EC) measurements for all sources. Data are presented for the focused period (01.10.19 00:00 to 03.10.19 12:00).**

direction of the precipitation signal during events (Fig. 5b). A similar responsiveness was also observed in EC measurements (Fig. 5d). This implies a rapid vertical movement of incoming precipitation into shallow groundwater and the importance of shallow sub-surface flow paths in delivering water to the stream (Sahraei et al., 2020), catchment processes previously unresolved by previous studies utilising weekly stable water isotope data (Orlowski et al., 2016).

Additionally, despite a separation distance of only 145 m (Fig. 3c), NO_3-N dynamics at SW2 and SW1 were markedly different. Instead, the latter showed greater synchronicity in terms of magnitude and response timing with GW1 (Fig 4c; 5c), likely indicating the vertical leaching and subsequent lateral transfer of nitrate in fertiliser applied to the arable land between SW1 and SW2 (Fig. 3b). Data collection over several events also revealed that the relative timing of the response at SW1 and GW1 was not consistent (Fig. 4c), potentially reflecting changes in the spatio-temporal distribution of solute sources and their connectivity to the stream under various hydroclimatic and antecedent conditions (Floury et al., 2024; Knapp et al., 2022; Li et al., 2024). Such observations demonstrate the value of the spatially distributed data collected by the WATER in unravelling the confounding influences of upstream versus localised controls on stream water quality, and how these change over time (Bieroza et al., 2023).

Overall, the results from the field test provide a successful proof-of-concept for the WATER, both with respect to the ability of the system to automatically collect and analyse samples from multiple water sources at a high temporal frequency, and the potential value of the collected data in advancing understanding of hydrological and hydrochemical processes.

3.3 Considerations when operating the WATER

Despite being mobile, the WATER is still a laboratory utilising complex measurement devices whilst operating in the natural environment. Consequently, there is a need for routine maintenance tasks to be carried out. These include cleaning and calibrating the sensors of the YSI 600R and ProPS UV spectrometer, refilling the standard water reservoirs (ca. 5 L month^{-1}) and replacing the Drierite air column for the CWS, ensuring the sampling lines are clean and free of obstruction, and replacing the 5 µm filter on the Reservoir Pathway. Experience from the field test showed that at least weekly maintenance was required, with shorter intervals being necessary if the quality of the sampled water was especially poor. This frequency of maintenance is comparable to other lab-in-the-field setups (Brekenfeld et al., 2025; von Freyberg et al., 2017).

The biggest consideration for the WATER is ensuring there is a sufficient, consistent power supply for the measurement devices. Despite the power rating of the solar panels installed for the field test substantially exceeding the requirements of the measurement devices, it was often necessary for supplementary power to be provided from the diesel generator. In addition, the two larger data gaps during the field test in June and July (Fig. 4) reflect more significant issues with the power supply system that required repair at a workshop, including a deep-discharge of the battery pack due to a manufacturing error and a

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complete failure of the diesel generator. Whilst these failures are unlikely to be a recurrent issue, they do highlight the vulnerability of the WATER to power supply issues. Therefore, whilst it is reasonable to expect that the WATER can be sustained by a combination of solar and diesel power over a period of a few months, longer deployments would likely benefit from the availability of a mains power supply.

4 Scalability of the WATER

A major advantage of the WATER is that the sample acquisition system and self-developed software provide significant flexibility in terms of how many water sources are sampled and at what frequency. However, since samples are processed sequentially, a trade-off exists between the number of connected sources and the maximum possible sampling frequency of each source. To gain insight into how this affects the scalability of the WATER, data from the field test (hereafter the Baseline scenario) were sub-sampled to simulate the reduced sampling frequency that would result if the number of connected SW and GW sources was doubled. In this scenario (hereafter S1), all 11 inputs to the WATER would be in use (SW × 4, GW × 6, Precipitation × 1). It was assumed that the relative sampling frequency of SW and GW sources would remain consistent with the Baseline (i.e., 2:1). Precipitation was still considered to be an event-triggered source, with sampling occurring at the same frequency as in the Baseline. It was also required that the two isotope standards each still be sampled eight times per day. Under these conditions, sub-sampling simply involved retaining every other Baseline sample for each source. Datasets for δ^2H, NO_3-N and EC were then generated using the measurements associated with the retained samples. To compare how the two different sampling configurations of the WATER compared to more traditional approaches, the Baseline data were also sub-sampled to simulate a Daily sampling strategy, with one sample collected per day per source between the hours of 1200 and 1500. This timeframe is representative of an automatic sampler being triggered in the early afternoon to minimise malfunctions due to freezing conditions that may occur in winter. Sub-sampling was achieved by generally retaining the first available sample for each day and source that was collected after 1200 but before 1500. However, if the first sample was missing a δ^2H, NO_3-N or EC measurement but a later sample within the specified timeframe had no missing data, the latter was retained instead. To evaluate how the two alternative sampling scenarios would affect the distribution of the collected data over the duration of the field test, probability density functions (PDFs) of the Baseline datasets at each site were estimated by fitting histograms. Using the same histogram bins, PDFs were then estimated for the sub-sampled datasets and compared with the Baseline.

Figure 6 shows the histograms for the Baseline and alternative sampling scenarios. For all measured parameters and water sources, the PDFs estimated for the Daily sampling scenario deviated most strongly from those of the Baseline. For NO_3-N, daily sampling captured fewer peaks in the data, resulting in a loss of probability density in the right tails of the PDFs. The exception was for GW3 (Fig. 6e), where NO_3-N concentrations in the Baseline were more evenly distributed and the effect of

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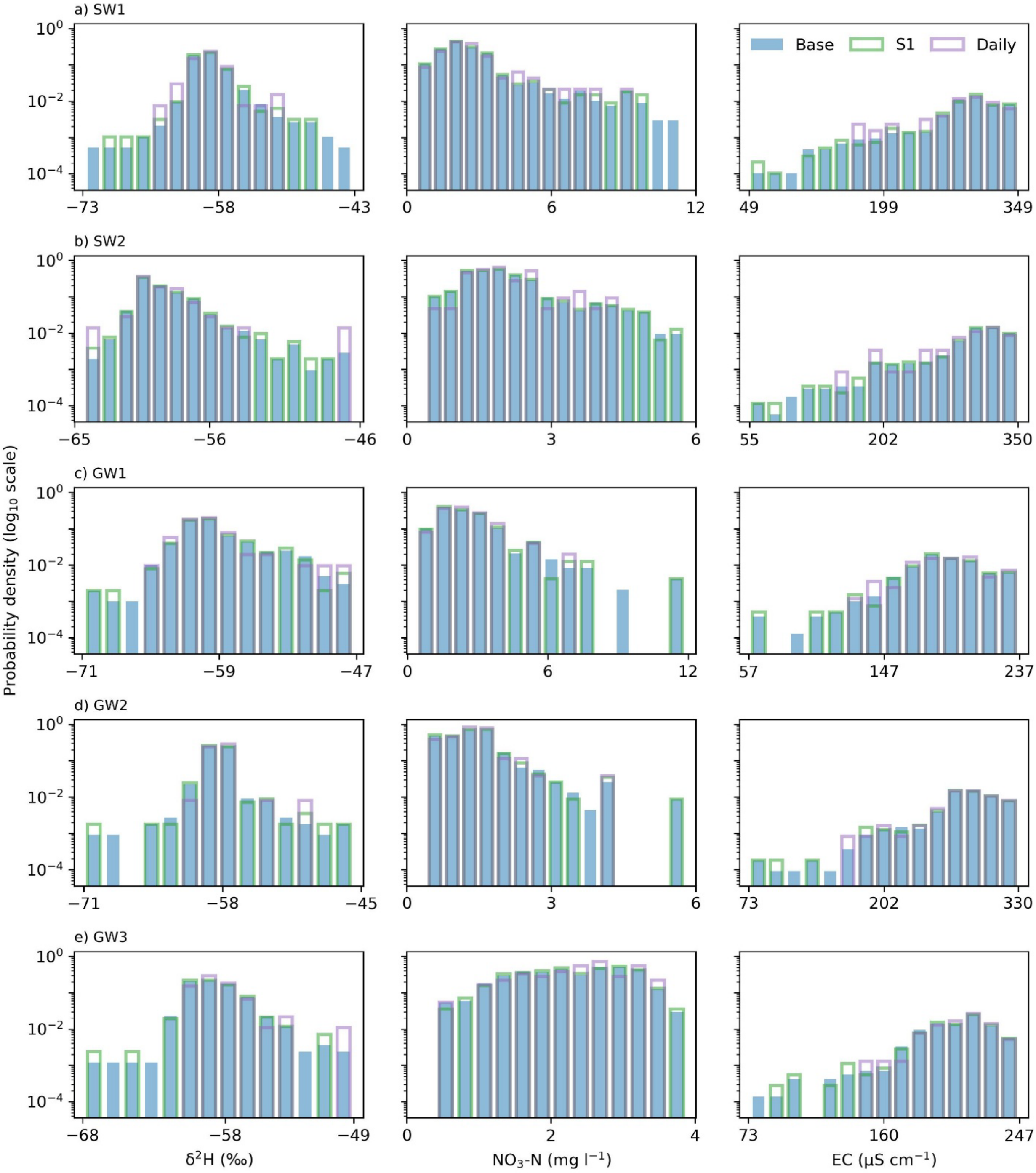

370 **Fig 6: For each water source (a-e), probability density functions estimated via histograms for the deuterium (δ^2H), nitrate (NO_3-N), and electrical conductivity (EC) data collected under the Baseline and two alternative sampling scenarios. Note that probability density is on a log$_{10}$ scale to aid visualisation and x-axes are unique to each site and parameter.**

moving to daily sampling was less pronounced. The EC data displayed the opposite behaviour to NO_3-N, with daily sampling capturing fewer of the minimum values measured during precipitation events in the Baseline and reducing weight in the left tails of the PDFs. The effect of daily sampling on δ^2H was more varied. Probability density was completely lost in the left tails of the PDFs for SW1 and GW1-3, likely due to under-sampling during the relatively rarer precipitation events with depleted δ^2H measurements (Fig. 4b). Losses of probability density from the right tails were more fragmented, with daily sampling still able to capture some extreme values for SW2, GW1 and GW3. Probability density around the mean δ^2H for each source was largely unchanged. In contrast to the Daily PDFs, those estimated for S1 largely reflected the characteristics of the PDFs estimated for the Baseline, including, for most sources and parameters, the length of the tails (although there could be some redistribution of probability density). Preservation of the tails was sometimes only possible due to the 24/7 automated sampling by the WATER; for example, the outlying peaks in NO_3-N for GW1 and GW2 were both measured at night and would, therefore, never have been captured by usual daily sampling strategies.

Overall, the analysis of alternative sampling scenarios suggests that if deployed for a period of several months, the WATER could likely still capture the extremes of the measured parameters and certainly improve the characterisation of underlying data distributions relative to daily sampling, even if all 11 source inputs were in use. More caution would likely be required in the selection of which water sources to sample and at what frequency if individual event dynamics were of greater interest. However, sampling with the WATER in any configuration would likely provide greater insight than daily sampling alone.

5 Concluding remarks

This paper presented the Water Analysis Trailer for Environmental Research (WATER), the first example of an automated, mobile sampling platform capable of measuring the stable water isotope composition and water quality of multiple spatially distributed water sources at a high temporal frequency. Deployment of the WATER to the Schwingbach Environmental Observatory (SEO) provided proof-of-concept, demonstrating that the system could automatically acquire and measure samples from six water sources over a period of several months. Sub-sampling of the data to simulate sampling 11 water sources with the WATER suggested that the resultant reduced temporal sampling frequency would still capture much of the distribution of the measured parameters over longer time scales. Beyond the need for routine maintenance that would be necessary for any “lab-in-the-field”, the greatest challenge in operating the WATER for an extended period was ensuring the availability of sufficient power for continuous operation of the measurement devices. Therefore, when designing an experimental setup with the WATER, the potential trade-offs associated with prioritising a guaranteed power supply (i.e., mains power), mobility (i.e., self-sufficient power), or sustainability (i.e., solar over diesel power) should be carefully considered.

The type of data collection that is possible with the WATER was shown to have strong potential for improving process understanding in the SEO beyond previous studies based on coarser data. Significant scope exists for more formal hypothesis testing in relation to catchment functioning by integrating the data into data-driven and process-based models (Li et al., 2021), including those using isotopes to better constrain the flow paths responsible for connecting different solute sources in space and time (Wu et al., 2025). In addition, the mobile nature of the system means that, over time, data can be gathered from multiple catchments using the same analytical setup to test the wider applicability of such hypotheses beyond a single catchment (Knapp et al., 2025). The flexibility offered by its design also means that an even greater range of water sources and parameters could be analysed beyond those considered in the SEO, further underscoring the potential of the WATER for advancing our understanding of catchment hydrological and hydrochemical functioning.

Code availability

The high-level software for the WATER is in the following Zenodo repository: https://doi.org/10.5281/zenodo.18432103
The program for the WAGO PLC is in the following Zenodo repository: https://doi.org/10.5281/zenodo.18386419

Data availability

Data and analysis scripts are in the following Zenodo repository: https://doi.org/10.5281/zenodo.18160631.

Author contributions

The general idea of the WATER was conceptualised by LB, DW and PK. The hardware was implemented by DW whilst PK developed the software. AS undertook the field investigation with the WATER supported by LB, DW and PK. AJN visualised and undertook formal analysis of the data from the WATER for this manuscript. AJN prepared the original draft of the manuscript with all co-authors contributing to review and editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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