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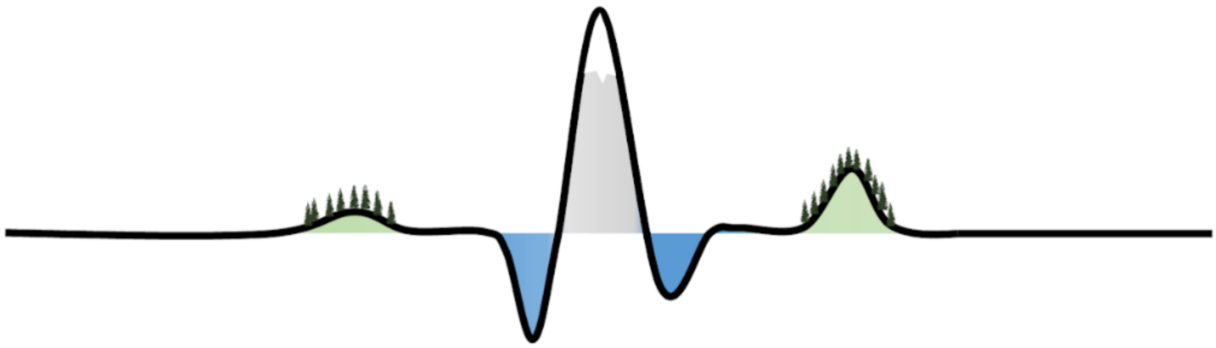

6th International Workshop on High Temporal Resolution Water Quality Monitoring and Analysis

2nd to 4th September 2026

University of Freiburg
Freiburg im Breisgau
Germany

Programme and book of abstracts

Scientific description

The High Temporal Resolution Water Quality Monitoring and Analysis series of international workshops exists to provide a forum for sharing experiences and establishing best practices in the application of high-temporal-frequency sensor technology in water quality studies, facilitate knowledge exchange in relation to hydrochemical processes across a diverse range of catchments, and stimulate new collaborations and research directions within the field. This 6th meeting follows previous workshops held in Aberdeen (2024), Uppsala (2021), Clonakilty (2018), Sandjberg (2016) and Magdeburg (2014). Details of these events, including associated publications, can be found on the workshop series website at this link or by scanning the QR code →→→→→→→→→→→→→→→→→→→→

The present workshop will consider three key topics that broadly consider the question of which measurements and analytics are needed beyond the stream network to improve understanding of water quality. The topics are:

- Emerging High-Frequency Measurements: From the stream channel to the whole catchment.
- Spatio-Temporal Patterns: Increasing data in space and time to detect trends and changes.
- Smart Analytics: Machine learning and beyond for high-frequency water quality data.

These themes will be explored through a combination of keynote talks, oral and poster presentations, and interactive sessions.

Organising committee

From the University of Freiburg:

Dr Carolin Winter, Walter Hettler, Jessica Fröbel and Fabian Nikq

From Justus Liebig University Giessen:

Dr Aaron Neill

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Programme overview

Wed 02 Sept 26		Thurs 03 Sept 26		Fri 04 Sept 26	
0845-0915	Arrival & registration	0900-0930	Julia Knapp (Keynote)	0900	Meet for field excursion
0915-0930	Opening remarks	0930-1030	Smart analytics	0915-1400	Field excursion
0930-1000	Joachim Rozemeijer (Keynote)	1030-1100	Coffee break	1400	Return to Freiburg Hbf (main station) and then University
1000-1045	Increasing high-frequency data in space and time (1)	1100-1215	Emerging high-frequency measurements		
1045-1115	Coffee break	1215-1315	Lunch		
1115-1215	Increasing high-frequency data in space and time (2)	1315-1515	World Café		
1215-1315	Lunch	1515-1545	Coffee break		
1315-1415	Low-cost sensors and routes to commercialisation	1545-1645	World Café feedback and next steps		
1415-1430	1-minute poster introductions	1645-1700	Closing remarks		
1430-1445	Coffee break into next session	1900-open	Workshop dinner		
1445-1615	Poster, interactive & coffee discussions				
1615-1645	Day 1 summary and wrap-up				
1645-1700	Group photo				

Guidelines for presenters

To ensure smooth running of the workshop, we kindly ask our conference speakers to keep to the following times and formats:

- Oral presentations: 12-minute talk in widescreen (16:9) PowerPoint format + 3 minutes Q&A.

- Invited speakers: 20-minute talk in widescreen (16:9) PowerPoint format + 10 minutes Q&A.

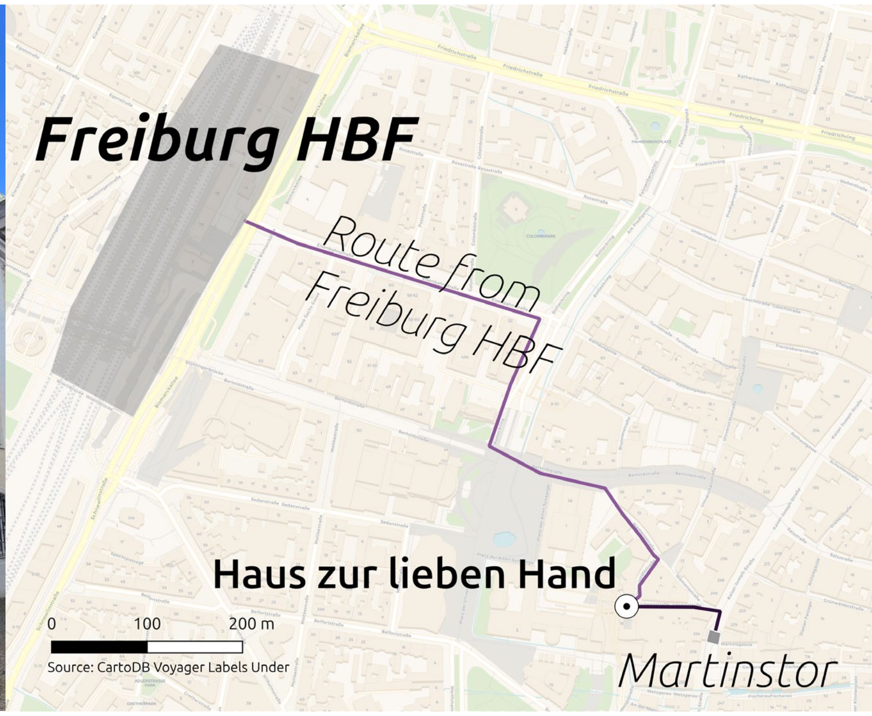
- Poster presentations: A0 poster in landscape format. Please be ready to introduce your poster in a quick, informal one-minute talk.

Venue

The main programme of the workshop will take place in the **Großer Saal (1st Floor) of the Haus zur Lieben Hand, Löwenstraße 16, 79098 Freiburg im Breisgau**. Scan or click the links below to plan your journey. You can also use what3words: sourced.removes.gangway.

Google Maps | Apple Maps | Openstreetmap

Below shows the entrance to the Haus zur Lieben Hand and a route map from Freiburg Hbf (main station) and the Martinstor (landmark in Freiburg).



Field excursion

On the final day of the workshop, Friday, September 4th, we will first visit the University of Freiburg's Ecotron and Lysimeter Station. This station is part of the Cluster of Excellence Future Forests, which investigates climate-resilient adaptation and conservation of forest ecosystems through the use of cutting-edge and high-frequency measurement equipment for water flux and environmental monitoring under controlled conditions. We will then head to the Sub-Surface Stormflow (SSF) field site of the University in Au. Here, a range of hydrometric, stable water isotope and water quality measurements are incorporated within a multi-tracer approach to understand sub-surface stormflow generation along a forested hillslope. The field excursion will be led by Prof Dr Markus Weiler.

If you have registered to join the field excursion, please meet us by **09:00** at **Friedrichstraße 39, 79104 Freiburg im Breisgau.** **NOTE!** This is not the main workshop venue. Scan or click the links below to plan your journey. You can also use what3words: shirt.clings.ruffle.

Google Maps	Apple Maps	Openstreetmap

More details will be provided on during the first two days of the workshop, but please bring sturdy shoes, waterproof clothing, hat and sunscreen, and a bottle of water. Lunch will be provided.

Workshop dinner

For those joining, the workshop dinner will be held from 19:00 onwards on Thursday 03 September at the **Schlosscafé, Kapellenweg 1, 79104 Freiburg im Breisgau**. A shuttle bus may be arranged from the main venue to the restaurant depending on demand.

Detailed programme: Day 1 – Wednesday 02 September

Time	Presenter	Title
0845-0915		Arrival and registration
0915-0930	Carolin Winter Aaron Neill	Welcome and opening remarks
Theme: Increasing high-frequency data in space and time (1)		
0930-1000	Joachim Rozemeijer (Invited Speaker)	Best practice in high-frequency water quality monitoring and application to support a spatial targeting approach in two agricultural catchments
1000-1015	Rémi Dupas	The effect of high-intensity rainfall and droughts on nutrient and dissolved organic matter dynamics in an agricultural temperate catchment
1015-1030	Anita Alexandra Sanchez	Hotspots and Hot Moments of Metal Mobilization: Dynamic Connectivity in Subsurface Mine Waters
1030-1045	Erik Nixdorf	Investigation of Spatiotemporal Dynamics of Acid Mine Drainage Loads Based on High-Resolution Electrical Conductivity Measurements in Streams of the Lusatian Mining District
1045-1115		Coffee break
Theme: Increasing high-frequency data in space and time (2)		
1115-1130	Admin Husic	STREAM: a high-frequency, large-sample water quality resource to enable modeling and scientific discovery
1130-1145	Xiaoyun Wang	Influence of Calibration Strategy and Temporal Resolution on Nutrient Hysteresis Characterization in High-Frequency UV Monitoring: A Case Study in the Kielstau Catchment
1145-1200	Jakob Benisch	The Urban Observatory in Dresden – A summary about 10 years online monitoring at urban streams
1200-1215	Suzanne Jacobs	Event-based and seasonal water quality dynamics in tropical montane catchments with contrasting land use
1215-1315		Lunch
1315-1415	Markus Weiler Heinke Paulsen Jasmin Tesch Jonas Pyschik	**Low-cost sensors and routes to commercialisation**
1415-1430	Poster presenters	1-minute poster introductions
1430-1445		Coffee break continuing into the next session
1445-1615		**Poster presentations and interactive sessions**
1615-1645	Carolin Winter Aaron Neill Walter Hettler	Summary of discussions from Day 1 Information: World Café (Day 2) and field excursion (Day 3)
1645-1700	All	Group photo

Detailed programme: Day 2 – Thursday 03 September

Time	Presenter	Title
Theme: Smart analytics		
0900-0930	Julia Knapp (Invited Speaker)	From Signals to Inference: Making the Most of High Frequency Water Quality Data for Event Scale Analysis
0930-0945	Gunnar Lischeid	Exploring stream biogeochemical processes with multivariate and multi-site high frequency data using Principal Component Analysis (PCA) and Cumulative Periodogram Convexity (CPC)
0945-1000	Walter Hettler	Predicting Shifts in High-Frequency Water Quality Across Germany During the 2018 Drought
1000-1015	Shulamit Nussboim	KCCA – a ML method for revealing flowpath-structured spatial distributions of pesticides and pharmaceuticals in agricultural fields
1015-1030	Felipe Saavedra	Leveraging machine learning and large-scale datasets to elucidate the spatial and temporal dynamics of C, N and P
1030-1100	Coffee break	
Theme: Emerging high-frequency measurements		
1100-1115	Maria Grundmann	Spatio-temporal water temperature variability: the effect of air temperature and discharge in an alpine catchment
1115-1130	Immanuel Frenzel	From Leaf Litter to Stormflow: High-Frequency Tracking of Trifluoroacetate (TFA) in Forest Soils
1130-1145	Lars Duester	New insights into element dynamics in rivers by timely high resolution ICP analyses
1145-1200	Magdalena Bieroza	High-frequency water quality measurements from a drain to the catchment outlet
1200-1215	Michael Rode	How to quantify nitrate and phosphorus in-stream uptake using dial concentration pattern
1215-1315	Lunch	
1315-1515	**World Café**	
1515-1545	Coffee break	
1545-1645	Carolin Winter Aaron Neill Walter Hettler	World Café feedback Next steps including publication discussion
1645-1700	Carolin Winter Aaron Neill	Closing remarks
1900-open	**Workshop dinner: Schlosscafé, Kapellenweg 1, 79104 Freiburg im Breisgau**	

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Detailed programme: Day 3 – Friday 04 September

Time	Activity
0900	Meet for field excursion at: **Friedrichstraße 39, 79104 Freiburg im Breisgau**
Stop 1	Arrive at Ecotron site
	Lunch
Stop 2	Arrive at SSF-Station Au
1400	Drop-off at Freiburg Hbf (main station) and arrival back at the University

Poster and interactive session: Day 1 – Tuesday 02 September

Presenter	Format	Title
Alessandro Cattapan	Poster	Filtering and Analysing Distributed Temperature Sensing Data: lessons learnt from the Wüstebach headwater stream, Germany
Anastasija Isidorova	Poster	Accessing nutrient retention in two Norwegian constructed wetlands using turbidity and nitrate sensors
Devikrishna Radhakrishnan	Poster	System Memory Enhances Prediction of High-Frequency Water Quality Dynamics
Felina Schwalm	Poster	Hydrological transport of dissolved inorganic nitrogen through a forest ecosystem: Retention and enrichment along the way from precipitation to stream and groundwater
Jean-Paul Brede	Poster	Coupled Water Quality and Quantity Modelling
Maximilian Mäder	Poster	Prediction of high-temporal-frequency nitrate concentrations in sub-Saharan Africa with long short-term memory models
Tom König	Poster	Concentration-discharge relationships for multi-pollutants in diverse catchments and varying climatic conditions
Heinke Paulsen	Interactive (practical demo)	Low-Cost Integrated Monitoring of Ground-Water Recharge, Nitrate and DOC Fluxes
Aaron Neill	Interactive (360 tour and VR)	A Water Analysis Trailer for Environmental Research (WATER)

Abstracts: Increasing high-frequency data in space and time (1)

Best practice in high-frequency water quality monitoring and application to support a spatial targeting approach in two agricultural catchments (Invited Speaker)

Rozemeijer, J.*, Jordan, P., Hooijboer, A., Kronvang, B., Glendell, M., Hensley, R., Rinke, K., Stutter, M., Bieroza, M., Turner, R., Mellander, P., Thorburn, P., Cassidy, R., Appels, J., Ouwerkerk, K., Gommans, K., Rode, M.

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Nutrient emissions from agricultural fields contribute to eutrophication and loss of biodiversity in water resources worldwide. After decades of improvement in The Netherlands, the most recent assessments show deterioration both in nutrient concentration levels and in compliance with the goals of the Water Framework Directive. The national government of The Netherlands currently makes a case for a spatial targeting approach for nutrients in problematic catchments. This requires insight into within catchment hot spots and hot moments, which conventional low frequency monitoring often fails to capture. High frequency sensors and in situ auto-analysers offer a way forward, especially as event-driven nutrient losses become more pronounced under a changing climate.

To support a broad adoption of high frequency monitoring in statutory programmes, we reviewed international best practices and developed a decision workflow covering sensor selection, field maintenance, calibration, and data processing. Our objectives were (1) to summarize the added value of high-frequency water quality monitoring, (2) to describe sensor and analyser field practices, and (3) to evaluate experiences with high-frequency data cleaning.

In two agricultural catchments, we showcased how detailed monitoring can support targeted nutrient mitigation. We combined high-frequency monitoring (Ptot, TRP, NO_3, NH_4, EC, pH, and O_2) for detecting hot moments of nutrient losses with spatial routings to detect specific within-catchment sources and transport routes (hot spots). The collected monitoring information is considered a good starting point for selecting the right mitigation options at the right locations in discussion with farmers, the water boards, and other stakeholders.

The effect of high-intensity rainfall and droughts on nutrient and dissolved organic matter dynamics in an agricultural temperate catchment

Rémi Dupas[1*], Damaris Rios Guzman[1], Ophélie Fovet[1]

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The profound influence of climate change on the hydrological cycle raises concerns about its impacts on water quality, particularly for nitrate, TP and DOC. In western France, hydroclimatic projections indicate an increasing frequency and intensity of both high-rainfall events and droughts. Anticipating future water quality trajectories therefore requires a mechanistic understanding of catchment responses to such hydroclimatic extremes. Here, we present a retrospective analysis of water-quality responses to high-rainfall and drought events in Kervidy-Naizin (5 km^2), an intensively monitored agricultural temperate catchment. The study combines sub-hourly data (2016–2026) with long-term daily records (2000–2026). Extreme Value Theory applied to the high-frequency data revealed that concentration changes during high-rainfall events followed the same direction as during average storm events—namely, nitrate dilution and TP and DOC accretion—but with amplified magnitudes. The Kervidy-Naizin stream is intermittent, with a seasonal drying phase lasting between 0 and 164 days. Analysis of the seasonal rewetting period using long-term daily data showed that nitrate, TP, and DOC concentrations increased with increasing duration of antecedent dry periods, indicating enhanced flushing after intensive droughts. Overall, increasing hydroclimatic extremes are likely to substantially amplify nutrient and carbon export pulses in temperate agricultural catchments.

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Hotspots and Hot Moments of Metal Mobilization: Dynamic Connectivity in Subsurface Mine Waters

Anita A. Sanchez[1*], Conrad Jackisch[2], Sean Adam[2], Sabrina Hedrich[3], Maximilian P. Lau[1]

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[2]Institute of Drilling Technology and Fluid Mining, Interdisciplinary Environmental Research Centre, TU Bergakademie Freiberg

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Monitoring and remediation of contaminated mine water conventionally focuses on end-of-pipe treatment at mine outlets after closure, while the pollutant release and transport pathways within abandoned mines remain largely overlooked. This study examines flowing waters in subsurface mining structures. We study the dynamic hydrogeochemical behaviour and transport pathways within them, revealing how variable subsurface flow activation impacts harmful metal(loid) mobilization. Using in-situ sensors, hydrogeochemical monitoring, and stable water isotopes at the Reiche Zeche mine (Ore Mountains, Germany), we reveal a hydrodynamic regime in which episodic shifts in connectivity govern solute release from localized storage zones. Event-scale concentration–discharge (C–Q) relationships and the Pollution Load Index (PLI) reveal site- and element-specific shifts in flow path connectivity. Contrary to common assumptions, low flow periods can represent high pollution risk, as poorly connected zones accumulate solutes that are subsequently mobilized once connectivity thresholds are crossed, consistent with fill-and-spill and lotic-lentic cycle concepts. Notably, Zn loads periods before flush peaks but still considered low in flow reached up to six times median values. These findings indicate that a substantial fraction of metal export originates from internally stored contaminant stocks mobilized prior to peak flow, highlighting the potential of source-oriented water treatment strategies.

Investigation of Spatiotemporal Dynamics of Acid Mine Drainage Loads Based on High-Resolution Electrical Conductivity Measurements in Streams of the Lusatian Mining District

Erik Nixdorf[1*], Maik Boehmeke[1], Marcus Fahle[1]

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The presence of substantial lignite and other mineral reserves in the German region of Lusatia has led to intensive mining activities over the past centuries. These operations exposed significant amounts of pyrite to weathering, causing the formation of strong acid mine drainage (AMD) loads polluting receiving waters. Storm events can increase these pollutant loads, temporarily, by orders of magnitude. We investigate the temporal dynamics of AMD loads by deploying data loggers at the streambed of the Spree River and its tributaries near gauging stations. Electrical conductivity (EC) was monitored at 10 minutes intervals over more than two years, complemented by bimonthly surface water sampling. These data was used to set up river-reach-scale mass balance models by interpreting the product of measured flow rate provided by gauging stations and EC as a proxy for AMD loads. The results show that exchange fluxes vary in both space and time, leading to a net loss of stream water to the groundwater while simultaneously increasing AMD loads. Storm events are associated with a substantial rise in AMD inputs compared to pre-event conditions, likely driven by the mobilization of stored pore water in the sediments. As events progress, AMD loads drop below pre-event levels due to dilution by increasing stormwater inflow. Our findings highlight the need for high-resolution measurements to accurately assess AMD loads and may contribute to enhanced management of AMD in receiving waters.

Abstracts: Increasing high-frequency data in space and time (2)

STREAM: a high-frequency, large-sample water quality resource to enable modeling and scientific discovery

Admin Husic[1*], Shannon Speir[2]

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[2]Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR, USA

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Understanding water quality dynamics across freshwater systems is essential for assessing ecosystem health, managing resources, and responding to the accelerating impacts of land use and climate change. However, progress in these areas is often limited by fragmented, low-resolution, or short-duration datasets that constrain the ability to detect trends, identify drivers, and build predictive models at broad spatial and temporal scales. We present STREAM (Sensor-based Time-series Repository for Environmental Assessment and Modeling), a robust high-frequency water quality dataset for the US compiled from multiple sources, including federal agencies, regional monitoring organizations, and academic labs. STREAM features continuous sensor measurements of critical biogeochemical and physical parameters: water temperature, dissolved oxygen, pH, conductivity, turbidity, nitrate, fluorescent dissolved organic matter, orthophosphate, chlorophyll-a, and phycocyanin, as well as flow discharge. In addition to sensor measurements, hourly meteorological forcings for historic and future periods are aggregated at the basin scale, as our historical-to-future land use change. The STREAM dataset is designed to foster interdisciplinary collaboration and drive data-driven research across hydrology and aquatic science.

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Influence of Calibration Strategy and Temporal Resolution on Nutrient Hysteresis Characterization in High-Frequency UV Monitoring: A Case Study in the Kielstau Catchment

Xiaoyun Wang[1*], Kirsten Rücker[2], Nicola Fohrer[3]

[1]Institute for Natural Resource Conservation, Department of Hydrology and Water Resources Management, Kiel University, Christian-Albrechts-Platz 4, 24118 Kiel, Germany

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This study investigates the impact of calibration approach and data aggregation scale on nutrient hysteresis analysis in the agricultural lowland catchment of Kielstau which is recognized as UNESCO demo site for ecohydrology since 2010.

A UV/Vis spectrometer recorded water-quality parameters at 10-minute intervals and was complemented by three daily laboratory samples. Spectral data were matched to laboratory measurements using a defined time-window median approach to establish calibration datasets. Comparative analysis of spectral pre-processing techniques showed that temporal window aggregation of cleaned absorbance spectra provided the highest and most robust predictive performance for nitrogen species, outperforming first-derivative preprocessing under the conditions of this study. Device-based calibration (MLR) was compared with post-processing calibration using partial least squares regression (PLSR).

Based on calibrated time series, concentration–discharge hysteresis loops were constructed at multiple temporal resolutions (10-minute, 8-hour, and daily). Differences in hysteresis direction, loop shape, and peak timing were evaluated to assess how calibration strategy and temporal aggregation level influence the interpretation of nutrient transport dynamics.

The Urban Observatory in Dresden – A summary about 10 years online monitoring at urban streams

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The aim of research in urban water management is to identify the relevant compound fluxes and the interaction between drainage network and ecosystem. To gain information on a high temporal resolution, the working group on Urban Hydrology of the Institute for Urban Water Management established an integrated monitoring network in the city area of Dresden. Compound fluxes in the sewers as well as the receiving waters are monitored with state-of-the-art technologies to provide detailed insights in complex runoff and discharge processes as well as on (stress) conditions in the urban stream.

The observatory consists of six measurement stations in the catchment of Lockwitzbach and Geberbach, both are small streams flowing through the city of Dresden. In the Lockwitzbach catchment there are two stations directly located in the creek and one more in a storm sewer network discharging in the creek during (heavy) rain events. The concentration of oxygen, chloride, nitrate as well as bulk organic pollutants, pH, conductivity and discharge are being recorded every minute.

Our research focuses on detecting the effects of the Urban Stream Syndrome. We found evidence for elevated nutrient and pollutant concentrations, hydraulic stress by quick flow coming from urban sub-catchments, decreased baseflow during dry weather summer periods. Furthermore, we found excessive metabolic regimes, high primary production and respiration together with increasing water temperatures.

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Decadal and Seasonal N:P Regime Shifts Across 680 European Catchments – Providing a Baseline

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Understanding nutrient concentrations together with their ratios is essential for assessing eutrophication patterns and risk. While most studies focus on concentrations, ecological responses often depend on the stoichiometric balance between nitrogen (N) and phosphorus (P). Because concentrations and their ratios vary space and time, characterizing nutrient dynamics requires both high-frequency measurements that resolve short-term variability and hot moments and long-term monitoring that identifies trends and baselines. We analyze >30 years (<1990 up to 2023) of low-frequency data from 680 catchments in France, Germany, and Denmark to assess decadal trajectories of riverine N:P ratios for annual and summer conditions. N:P ratios were classified into ecologically relevant regimes: N-depletion N:P<20, P-depletion N:P>50 & co-depletion. We observed a widespread increase in N:P until 2010 (~80% of stations), followed by stabilization or partial reversal. Over the study period, 40% of catchments shifted at least once between depletion classes, mostly from N- or co-depletion toward P depletion. Summer N:P were consistently lower than annual medians, highlighting seasonal differences in potential nutrient limitation. Long-term monitoring reveals coherent spatial patterns and regime shifts, providing a baseline to interpret emerging high-frequency water-quality data. Integrating both perspectives offers a more comprehensive understanding of nutrient and eutrophication dynamics.

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Event-based and seasonal water quality dynamics in tropical montane catchments with contrasting land use

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Land use plays a key role in the regulation of water quality through differences in the use of (agro)chemicals, as well as the transport and fate of pollutants. Here we use six years of data recorded at 10-minute intervals in three sub-catchments characterised by either natural forest, smallholder agriculture or commercial tea plantations in the Sondu river basin in western Kenya to investigate short-term and seasonal dynamics of nitrate, dissolved organic carbon, electrical conductivity and total suspended solids.

The agricultural catchments had higher nitrate and total suspended sediment concentrations, especially during the wet seasons. Wavelet analysis revealed diel patterns in nitrate concentrations, particularly during low flow in the natural forest. Discharge showed a stronger correlation with water quality parameters in both agricultural catchments than in the forest, suggesting stronger hydrological connectivity. Solute responses to rainfall events, investigated with hysteresis analysis, were diverse across land use types and seasons.

The results highlight the strong effect that both land use and climate exert on water quality dynamics in tropical montane landscapes. Therefore, understanding processes that affect water quality can help to identify management strategies to reduce the pressure on the aquatic environment in landscapes where natural ecosystems have been replaced by agriculture.

Filtering and Analysing Distributed Temperature Sensing Data: lessons learnt from the Wüstebach headwater stream, Germany

Alessandro Cattapan[1,2], Jochen Wenninger[1], Gijs Vis[2], Raymond Venneker[1], Roland Bol[3,4], Konstantina Katsanou[1*]

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Heat has long been used as a tracer in hydrology, and fibre-optic distributed temperature sensing (DTS) enables high-resolution temperature measurements along stream reaches. DTS interpretation commonly assumes that the fibre is surrounded by a single medium, but this assumption is often violated in natural environments. Variable water levels, sediment scour, and installation constraints can expose sections of the cable to air or sediments, imposing different boundary conditions and heat-transfer processes. These conditions produce temperature signals that differ from those of fully submerged segments and must be identified to correctly interpret hydrologic fluxes. This study presents a statistical method to detect fibre-optic cable sections exposed to the atmosphere using DTS data from the Wüstebach headwater stream (Eifel National Park, Germany), part of the TERENO Observatory. Since October 2023, surface water temperature has been monitored along a 293 m reach (extended to 440 m in April 2024) using a DTS system connected to a DTS unit with 25 cm spatial resolution and 15-minute sampling. Segments affected by different exposure states are treated as distinct statistical populations and identified through changes in the temperature signal. The median daily temperature range is used to detect atmospheric exposure, while spectral analysis helps identify groundwater-driven fluctuations. The workflow provides an objective preprocessing approach for filtering DTS datasets.

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Accessing nutrient retention in two Norwegian constructed wetlands using turbidity and nitrate sensors

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[1]Norwegian Institute of Bioeconomy Research (NIBIO), Division of Environment and Natural Resources, Ås, Norway

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Constructed wetlands (CWs) are effective environmental measures for reducing nutrient and sediment losses from agricultural streams to downstream water bodies. We installed high frequency turbidity and nitrate sensors at the inlet and outlet of a 275 m long CW in an agricultural creek in South-Eastern Norway, with a surface area of 2500 m^2 and a catchment area of 4.5 km^2. In addition, nitrate sensors were deployed at the inlet and outlet of a CW in South-Western Norway, with a surface area of 700 m^2 and a catchment area of 1.4 km^2. The two regions differ in climate and land use, with higher precipitation and pasture dominated agriculture in the South-West, and lower precipitation with cereal dominated agriculture in the South-East. Using sensor data, we quantified nutrient retention and losses in the CWs and evaluated seasonal variations in nutrient loads. A major advantage of high frequency sensors is their ability to capture short duration extreme events that are often missed by traditional grab sampling. These events can contribute disproportionately to annual nutrient export. We therefore assessed the contribution of extreme events to total nutrient loads and their significance for overall CW performance and downstream water quality. The findings offer insights into nutrient dynamics and constructed wetland performance under variable hydrological conditions.

System Memory Enhances Prediction of High-Frequency Water Quality Dynamics

E. Fallah-Mehdipour[1], D. Radhakrishnan[1*], J. Dieckhoff[1], J. Dietrich[1]

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High-frequency water quality data provide valuable opportunities to understand short-term environmental dynamics; however, their strong seasonality, noise, and autocorrelation pose significant analytical challenges. This study investigates the prediction of short-term variability in the spectral absorption coefficient at 254 nm (SAK254), a proxy for humic substances, at the inlet of Ecker Dam in the Upper Harz, Germany, using statistical decomposition and machine learning methods. To consider the high variability of SAK254, daily observations from 2017 to 2024 were decomposed using a LOESS-based seasonal trend method, enabling a focused analysis of event-driven dynamics. A decision tree (DT) model was applied as an interpretable machine learning method to predict daily SAK254. Two modelling strategies were trained on data from 2017 to 2021: (1) using hydrological and water quality variables from the current and previous days as model inputs, and (2) extending this input set by including the residual of the previous day as an additional representation of system memory. Both approaches were evaluated on an independent test period from 2022 to 2024. Results show that incorporating system memory improves model performance, and the RMSE of SAK254 estimation decreases from 10.21 to 7.39 (m^{-1}), while the R^2 increases from 0.68 to 0.83. These findings indicate that the interpretable DT model, along with the system memory, can reproduce the observed dynamics with reasonable accuracy.

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Hydrological transport of dissolved inorganic nitrogen through a forest ecosystem: Retention and enrichment along the way from precipitation to stream and groundwater

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This study evaluates the relationships between the hydrological cycle and the dissolved ions nitrate, nitrite, and ammonium of a temperate mixed forest, i.e., the WaldLab Forest Experimental Site in Zurich, Switzerland. Using data from 2020 to 2025, precipitation (P), throughfall (TF), stemflow (SF), soilwater, groundwater and discharge are systematically compared regarding their water quantity, nitrogen (N) concentrations and -loads. Differences between the species Norway spruce (Picea abies) and European beech (Fagus sylvatica) and between seasons are analyzed. The aim of the study is to identify and quantify the enrichment or retention of N between the different pools along the forest water cycle. Between P and TF we found enrichment of nitrate in the canopy while ammonium and nitrite are retained depending on the tree species. A strong enrichment is observed from P to SF. The soil water holds the most nitrogen in terms of loads, the highest concentrations are found in SF. The analyzed forest ecosystem retains 88% of nitrate, 91% of ammonium, and 98% on nitrite when comparing N-input via TF and SF to N-output via discharge. There is a clear effect of species, as both N loads and concentrations are higher under spruce compared to beech. An understanding of the hydrological transport of dissolved inorganic nitrogen through a forest ecosystem could help determine fluxes and water transport at the catchment scale with regard to the complex interactions in forested catchments.

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Coupled Water Quality and Quantity Modelling

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Deep learning models, and in particular Long Short-Term Memory (LSTM) networks, have become an established tool in hydrology, most notably for rainfall–runoff simulation at daily scales. In contrast, their application to joint modeling of water quantity and water quality remains comparatively limited, despite the strong process coupling between discharge dynamics and in-stream chemistry. A key challenge lies in the sparse, irregular, and catchment-specific nature of water quality observations, which complicates the training of data-driven sequence models. In this study, we explore a self-supervised learning framework based on an LSTM autoencoder for the simultaneous modeling of streamflow and multiple water chemistry variables. The proposed autoencoder architecture is trained on meteorological forcings and discharge data from CAMELS-DE together with water quality observations from Quadica, including nitrate, dissolved oxygen, water temperature, phosphate, and related constituents. Initial results indicate that the joint model attains streamflow performance comparable to standard rainfall–runoff LSTM baselines, while producing physically plausible reconstructions of multiple water quality variables across space and time. While the focus of this contribution is methodological, the results suggest that self-supervised sequence models provide a promising pathway toward integrated water quantity–quality modeling in large-sample hydrology.

Prediction of high-temporal-frequency nitrate concentrations in sub-Saharan Africa with long short-term memory models

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Elevated nitrate concentrations in sub-Saharan Africa are a risk to human and environmental health. However, routine monitoring of nitrate is not usually economically viable. Here, we make use of an unprecedented long-term, high-frequency dataset collected in the Mao Forest region of Kenya to assess the potential for using long short-term memory (LSTM) models to predict nitrate concentrations in data-scarce environments. The dataset contains 19 variables measured at 10-minute intervals, including precipitation at six rain gauges, meteorological and soil-state data at two climate stations, and water quality parameters measured with a s::can spectro::lyser at the outlets of three sub-catchments draining different land use types (natural forest, small holder agriculture, tea and tree plantation). A benchmark model incorporating all data was implemented to index the likely best performance of LSTMs in predicting the observed nitrate concentrations (RMSE=0.250; NSE=0.618; MBE=-0.089; KGE=0.791). A systematic data reductionist approach was then adopted to determine the minimum number of input variables necessary to still capture the key characteristics of the observed data. Initial results indicate that LSTMs excluding water quality training data can still preform comparably to the benchmark (RMSE=0.258; NSE=0.592; MBE=-0.019; KGE=0.740). Further results from this ongoing work, together with insights for futureproofing the LSTM code, will be presented in this contribution.

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Concentration-discharge relationships for multi-pollutants in diverse catchments and varying climatic conditions

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The use of high-frequency (HF) water quality sensors in rivers and streams has become more prevalent in past decades. These instruments allow a sub-hourly monitoring of water quality determinants, providing valuable insights into catchment responses that otherwise may remain undetected relying solely on low-frequency (LF) data. Agricultural headwater catchments are of special interest when it comes to their environmental impact. Excessive use of fertilizers causes a vast range of environmental issues, most notably eutrophication and erosion, leading to a degradation of aquatic ecosystems. Long-term concentration-discharge (CQ) relationships provide important information on the average release of pollutants from catchments at varying discharge levels. However, water quality catchment responses at an event scale often exhibit a deviation from the LF prediction, indicating limits in their interpretability. This study aims to set up a random forest model using properties of seven diverse European catchments equipped with HF monitoring of water quality. We focus on nutrients (nitrate-nitrogen, phosphorus) as indicators of eutrophication, turbidity as an indicator of erosion, specific conductivity and dissolved organic carbon as indicators of hydrological and biogeochemical functioning. To understand their behavior at an event scale, we evaluate the metrics of CQ relationships including slope, hysteresis index, flushing index and ratio of coefficient of variation and discharge.

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Low-Cost Integrated Monitoring of Ground-Water Recharge, Nitrate and DOC Fluxes

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Agriculture threatens drinking-water supplies through nitrate leaching. Conventional monitoring is costly and provides sparse data. We present two low-cost systems that deliver continuous, high-resolution water-flux and solute data.

WICKIE (WICK-sampler In-situ Estimations) uses eight fiberglass wicks in a collector operating at field-capacity suction. A 3D-printed tipping bucket records each drainage event as an absolute volume, giving direct percolation measurements without external power. A six-month trial at a cropping-grassland interface captured the lag between rainfall and infiltration and consistently showed higher recharge on grassland. The system caused minimal soil disturbance and supplied volumetric flux data for water-balance calculations.

An optical sensor allows for in-situ nitrate and dissolved organic carbon monitoring. Three LED-photodiode modules (UVA, UVC, red) measure absorbance and fluorescence at characteristic wavelengths. Laboratory calibration with nitrate standards gave a linear response (R^2=0.99); tests with natural waters retained strong performance. Remaining issues are spectral interference, turbidity and site- and application-specific calibrations.

Together, WICKIE and the optical sensor form a modular, affordable platform for simultaneous measurement of recharge and nitrate loads, linking infiltration events to contaminant transport and supporting sustainable agricultural and aquifer management.

A Water Analysis Trailer for Environmental Research (WATER)

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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". Here we present 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 offers two analytical pathways – a Throughflow Pathway for measurement devices using a flow cell and a 5 µm-filtered Reservoir Pathway for devices requiring filtered water – and is currently equipped to measure stable water isotopes, nitrate, electrical conductivity, pH and temperature. Integration of additional measurement devices in the future is supported by the modular design of the WATER. In this interactive presentation, a 360-photo tour of data collected by the WATER during a six-month field test in the 1.03 km^2 Schwingbach Environmental Observatory, Germany can be explored, whilst a 3D internal model of the WATER will be viewable using virtual reality.

Abstracts: Smart analytics

From Signals to Inference: Making the Most of High Frequency Water Quality Data for Event Scale Analysis

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High frequency water quality monitoring enables the observation of concentration–discharge (cQ) dynamics at event timescales, revealing levels of variability that remain obscured in long term, low frequency datasets. However, many of the analytical approaches applied to event scale cQ relationships have been inherited from methods originally developed for long term data. As a result, event scale analyses often rely on per event regressions that are sensitive to sparse sampling, provide inconsistent uncertainty estimates, and require separate post hoc steps to relate slope metrics to environmental drivers. This highlights the need to reconsider whether analytical frameworks designed for long term patterns are appropriate for short term, process rich dynamics. Using high frequency multi solute datasets, hierarchical approaches may be able to improve slope estimation, incorporate event characteristics directly, and provide more coherent uncertainty quantification by leveraging information across events. Re-evaluating event scale c–Q analysis in this way can support a transition from inherited practices toward methods better aligned with the processes revealed by modern high frequency monitoring. In this talk, these challenges and opportunities will be explored by contrasting traditional regression-based approaches with hierarchical alternatives, highlighting how methodological choices influence the interpretation of event-scale cQ behaviour and how more suitable analytical frameworks can strengthen inference from high-frequency water-quality data.

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Exploring stream biogeochemical processes with multivariate and multi-site high frequency data using Principal Component Analysis (PCA) and Cumulative Periodogram Convexity (CPC)

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To exploit the potential of continuous long-term high-frequency monitoring we compared and tested two approaches applied to a comprehensive data set from the Bode catchment. At five stations along the Selke and the Bode stream, six variables were measured at 15-minute intervals over a period of seven years (2013-2020). Firstly, Principal Component Analysis was applied to the total set of 30 time series. The first component captured the typical behaviour during discharge peaks, exerting major effects on electric conductivity, pH values and nitrate concentration. The second component reflected the effect of upwelling saline groundwater along the downstream reaches of the river. The third component was related to within-stream metabolism with clear seasonal patterns but differing between years. Other principal components captured local anthropogenic effects at single sites. Secondly, the CPC (Cumulative Periodogram Convexity) index was applied to the same data set. The index quantifies the degree of low-pass filtering in time series. As a consequence of the second law of thermodynamics the CPC has to decrease along the direction of signal propagation in environmental systems. Thus, any deviation from monotonic decrease would be indicative of additional effects or input fluxes which add high-frequency dynamics to the time series. In fact, the CPC results confirmed the findings from the Principal Component Analysis.

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Predicting Shifts in High-Frequency Water Quality Across Germany During the 2018 Drought

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Persistent drought can radically alter water quality in rivers. In particular, drought as well as post-drought effects profoundly shift biogeochemical regimes. However, most methods have either provided analytical empirical insight or provided black-box models. Consequently, predicting water quality during out-of-distribution climate extremes escapes rigorous validation. We hypothesise that high-frequency water quality data will enable us to better address the equifinality problem by better distinguishing between flood conditions, drought, and rapid post-drought context switches and therefore enable better extrapolation to never-before-seen circumstances in river water quality. What remains unresolved is whether integrating machine learning with physical frameworks can prevent extrapolation collapse. To address this, we test whether several water quality models can extrapolate to never-before-seen drought conditions. We in particular test three distinct models, including a pure LSTM, a hybrid PINN, and a Bayesian DBM state-space process-based model. Because recent years have yielded unprecedented droughts across Germany, we split our multi-year, hourly conductivity dataset from 72 catchments into a period with no major drought for calibration (2005-2015) and a period with major unprecedented drought for validation (2016-2020). Initial results on conductivity indicate that while LSTMs enable a better fit during the calibration period, they struggle to adapt to the never-before-seen drought conditions. Conversely, both models that are limited by water and mass fluxes show improved extrapolation into the never-before-seen drought period. We therefore conclude that pure black-box models have to be viewed cautiously.

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KCCA – a ML method for revealing flowpath-structured spatial distributions of pesticides and pharmaceuticals in agricultural fields

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Pesticides and pharmaceuticals comprise hundreds of compounds used in agricultural fields or enter via irrigation with treated wastewater, posing risks to aquatic ecosystems. Modern methods enable the simultaneous detection of dozens of micropollutants per sample, yielding extensive datasets that limit the identification of systematic relationships.

We investigated two agricultural fields along the Kishon Stream, sampling main flowpaths: overland flow, field drainage channels, subsurface flow, and groundwater. While qualitative pollutant distribution was evident, quantitative attribution was hindered by the complex relationships among compounds.

To address this, we applied Kernel Canonical Correlation Analysis (KCCA), a machine-learning method that captures nonlinear associations via kernel mapping that enables interpretation in a latent canonical space. Results showed high significance of the flowpaths, indicating distinct characteristics of the compounds in each flowpaths. Mobility and degradability properties exerted an additional influence. This result suggests flowpaths as an analysis framework for pollutant distribution. We further defined the dominant flowpath measure for individual compounds, providing a concise descriptor for distribution. This investigation demonstrates the complexity that controls pollutants distribution and applying the KCCA enabled quantification of distribution, revealing hydrological structure and occurrence in agricultural fields.

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Leveraging machine learning and large-scale datasets to elucidate the spatial and temporal dynamics of C, N and P

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Carbon (C), nitrogen (N), and phosphorus (P) are key macronutrients regulating aquatic ecosystem functioning, yet human activities have altered their concentrations, threatening ecosystem health. Large-scale assessments of their temporal dynamics remain challenging because water-quality observations are spatially sparse and discontinuous.

Here we leverage the low-frequency (biweekly to monthly) German water-quality dataset QUADICA v2 to train regional deep learning models that predict daily concentrations of dissolved organic carbon (DOC), nitrate (NO_3), and phosphate (PO_4) across 155 catchments. Despite relying on sparse observations, the models successfully reconstruct daily dynamics, achieving median Kling–Gupta efficiencies of 0.55, 0.62, and 0.45 for DOC, NO_3, and PO_4, respectively.

Using explainable AI (SHAP values), we analyze the spatial and temporal drivers of predicted concentrations. Spatial variability indicates that DOC is mainly controlled by topography and climate, NO_3 by diffuse sources and climate, and PO_4 by point sources and hydroclimatic conditions. To investigate temporal dynamics, catchments are clustered based on SHAP differences between high and low concentration conditions. Three clusters emerge, revealing distinct regimes of nutrient dynamics across catchments, where high concentrations arise from different combinations of hydroclimatic forcing and seasonal controls.

Abstracts: Emerging High-Frequency Measurements

Spatio-temporal water temperature variability: the effect of air temperature and discharge in an alpine catchment

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River water temperature is one of the main drivers of water quality in rivers, yet its small-scale variability in mountain catchments is poorly understood. Research on the effect of snowmelt, lakes and groundwater on both discharge and water temperature variability is lacking, even though these processes are essential to mitigate extreme water temperature. To address this research gap, we installed 15 water temperature, pressure and electrical conductivity as well as 6 air temperature sensors in and along a small alpine headwater catchment (Dischmá, Switzerland), to analyse the spatio-temporal variability from 2590 to 1620 m a.s.l at 10 min resolution. We calculated discharge using the water pressure and by conducting salt-dilution experiments to derive rating curves. Additionally, we used daily stable water isotopes samples at 3 locations to determine streamflow composition. First results show that lakes can significantly warm streams, but only dependent on the incoming radiation. Melt water contributions to streamflow cool the stream and vary greatly seasonally and spatially, while groundwater inflow reduces both warm and cold-water temperature extremes. Our results show that water temperature varies significantly over small spatial scales, variability that is often overlooked in large scale studies. Studying the changes in water temperature along such strong elevational gradients will inform adaptation measures to protect these alpine ecosystems in the future.

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From Leaf Litter to Stormflow: High-Frequency Tracking of Trifluoroacetate (TFA) in Forest Soils

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Trifluoroacetate (TFA) is a highly persistent and mobile micropollutant that is ubiquitously present in the hydrological cycle. It forms in the atmosphere through the degradation of precursor compounds, such as fluorinated refrigerant gases, and is deposited via precipitation. Consequently, TFA is consistently detected in rainwater. Because its atmospheric production is driven by photochemical processes, TFA inputs exhibit a pronounced seasonal pattern.

Recent findings indicate that TFA accumulates in vegetation during the growing season and is subsequently released during leaf litter decomposition. This release from the forest floor litter layer generates a distinct TFA signal in percolating water, enabling the tracing of litter-derived contributions within subsurface flow.

In this study, we conducted high-frequency sampling to quantify TFA concentrations in subsurface stormflow (SSF) at the plot scale. By tracking the TFA signal in the litter layer, we analyze its transport dynamics during storm events and evaluate its suitability as a chemical tracer.

To our knowledge, this is the first study to explicitly examine TFA transport processes at the plot scale in forested systems and to assess its implications for its application as a hydrological tracer. Our results provide new insights into TFA cycling in terrestrial ecosystems and highlight its potential for improving the mechanistic understanding of runoff generation.

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New insights into element dynamics in rivers by timely high-resolution ICP analyses

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The presentation introduces a fully automated at-line ICP-QQQ-MS method to monitor 56 elements in river water at hourly resolution. Developed and tested on the Rhine River in Germany, the system combines a self-cleaning Collector/AuTosampler (CAT) with ICP-QQQ-MS, enabling 24/7 operation without human intervention. Key advantages of the high-temporal-resolution multi-element monitoring are so far: (i) It captures rapid changes: Detects short-term events like pollution spikes, heavy rain impacts, or diurnal variations, which are missed by low-frequency sampling. (ii) It improves mass balance accuracy; timely high-resolution data reduces errors in annual element budgets. (iii) It enhances our process understanding. (vi) Supports early warning and management, real-time data enables faster response to contamination and better training datasets for machine learning models. (v) Comprehensive elemental fingerprinting: Simultaneous analysis of many elements provides a holistic view of biogeochemical processes and anthropogenic impacts. The method's validation with certified reference materials and cross-comparison with ICP-QQQ-MS confirms its reliability. By integrating high-resolution elemental data with physico-chemical parameters, this approach offers a powerful tool for water quality management, pollution source tracking, and adaptive river basin governance—especially under climate change and increasing anthropogenic pressures.

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High-frequency water quality measurements from a drain to the catchment outlet

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In this presentation we will present high-frequency water quality measurements from two nested agricultural catchments. Th measurements include concentrations of nutrients determined with the wet-chemistry analysers at the catchments' outlets and a range of physicochemical parameters, such as turbidity, specific conductivity, dissolved oxygen, fDOM, obtained with in situ sensors. Our unique experimental setup allowed us testing specific hypotheses on the hydrological propagation and biogeochemical transformation along the stream networks in the respective catchments and these preliminary results will be presented here.

How to quantify nitrate and phosphorus in-stream uptake using dial concentration pattern

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Transformations of nitrogen and phosphorus in river networks play an important role for modulating their fluvial exports from river catchments. Most important, in-stream nutrient retention is caused by the uptake by primary production, and losses are generated by denitrification processes.

Findings from the Bode River network suggest that our unique retention estimates revealed very similar characteristic diurnal variation of retention pattern. Three very similar clusters of diel uptake patterns were identified in both 1st and 6th order streams, potentially representing changes in dominant autotrophic and heterotrophic retention. These dominating uptake pattern seem to be subject of change during drought conditions. Not only assimilatory uptake of nitrate showed a distinct dial variation but also dissimilatory nitrate removal. These dial uptake patterns were also observed for the uptake of assimilatory phosphorus (SRP). SRP uptake was coupled to N and C assimilation, even though P uptake was not synchronous with the timing of N and C assimilation. Both assimilatory SRP and nitrate uptake strongly control nutrient fluxes in the stream network during the growing season, but assimilatory SRP uptake may be more important for SRP fluxes at the network scale than assimilatory nitrate uptake is for N fluxes. Important methodological constrains to uptake measurements are discussed, like the use of the one and two station uptake methods.