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Groundwater and soil water recharge

Datamap on Groundwater Recharge Studies

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Groundwater is the largest freshwater reservoir and a key resource for humanity. Half of the population is dependent on groundwater for drinking water and irrigation. A sustainable use of groundwater requires an understanding of groundwater recharge as it creates a delay between precipitation and discharge and impacts water quality. However, quantifying recharge is challenging due to the complexity and uncertainty of hydrological processes in the soil, such as root water uptake, preferential flow, infiltration, and capillary rise. Tracers, such as stable water isotopes, can provide valuable insights into these complex processes and have already been applied in many studies. However, finding these studies and quickly accessing their key findings can be time-consuming and difficult, which limits their use for practical applications.

To improve the findability and accessibility of groundwater recharge studies in Europe, a datamap was created. Over 50 European studies that used isotopes and/or other tracers to quantify groundwater recharge were identified and reviewed. The studies were categorized and plotted on a map. The map allows users to toggle their search for studies based on the type of study or method used. For instance, users can search by groundwater system (springs, shallow or deep groundwater), tracer (stable water isotopes, tritium, or electrical conductivity), tracer analysis method (laser absorption spectroscopy, isotope ratio mass spectrometry), and data availability. Users can click on specific studies to view further information, including the study objectives, key findings, and a DOI link to the paper. The datamap is published on the WATSON website (hiips://watson-cost.eu/outputs/databases/groundwater_recharge/) and will be updated as new studies become available.

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Combining vadose zone water stable isotope and volumetric water content profiles to estimate groundwater recharge and understand water percolation mechanism through the vadose zone

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Vadose zone water stable isotope profile can be combined with the vadose zone volumetric water content profile to determine the timing and amount of water that has percolated during specific periods. For this purpose, soil samples were collected along two boreholes of 7-m deep and analysed in laboratory to determine their stable isotope ratios ($\delta^{2}H_{H2O}$ and $\delta^{18}O_{H2O}$) and volumetric water content. Here, one borehole was completed at a site sparsely covered by vegetation (S1), while the second borehole was completed at a site covered by a pine forest (S2). Using the stable isotope-based method called the "peak-shift method", high groundwater recharge rates were assessed at both sites during winter–spring period (S1 with 71% and S2 with 75%), whereas the summer–autumn period had lower recharge rates of 63% (S1) and 41% (S2). Using water balance values, an evapotranspiration rate of 0.7 mm/day was estimated for the pine trees covering site S2. This study not only confirms the accuracy of the peak-shift method for assessing groundwater recharge and deriving evapotranspiration, but also demonstrate the ability of combining vadose zone water stable isotope profile with volumetric water content profile to understand the water percolation mechanism through a vadose zone. In fact, the water infiltrating the subsurface was observed to travel from ground surface to the bottom the investigated vadose zone of S1 and S2 within a duration of one year. However, there is specific percolation mechanism through the vadose zone of each investigated site.

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WATSON Soil Tracer Training School and Experiment Data

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We present the outcome of a WATSON training school took place near Florence, Italy, between 12-14 September 2023.We introduce the open access tracer data that were collected during the training school on isotopic tracer and labelling experiments, organized as part of the WATSON COST Action. The data includes tracer data from a multi-tracer experiment carried out on a single soil plot of 3 m^2: Images of brilliant blue dye from 4 soil transects, timeseries of electrical conductivity, temperature and volumetric water content measured through 9 soil moisture probes, and isotope composition of 10 soil cores. The data are free to use by anyone and can be found on:
hiips://github.com/pbenettin/TracerExperiment_WATSON

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Gauging the impact of future climatic conditions on soil water transport and mixing

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Soil water is a critical resource for terrestrial life, yet its fate is uncertain under warmer, more CO_2-rich, and drought prone climatic conditions projected for the 21st century. Increasing isotopic evidence suggests that common assumptions of a well-mixed soil water reservoir may be misguided, though, clear mechanistic validation is lacking. Climate manipulation experiments have the potential to alter soil hydrological properties, making these systems ideal for studying variable mixing processes belowground. We used deuterated water to 1) trace the impacts of elevated atmospheric CO_2 (+ 300 ppm), warming (+ 3 °C), and drought on soil water storage and transport through a temperate grassland, and 2) refine our understanding of disconnected storage in the vadose zone. Elevated CO_2 had a wetter rootzone relative to ambient conditions, whereas warming generally decreased this storage. Soil water remained well-mixed throughout the tracer study for all climate manipulations, except for future drought conditions combining warming and elevated CO_2. Future drought conditions forced the grassland to limit water loss through evapotranspiration (ET), and constrained soil water flow to highly conductive soil pores without mixing with small, slowly draining pores under high tension. Further, a low preference of ET for the high tension, labelled water which initially filled the soil matrix, allowed the tracer to remain in the rootzone for >150 days and created a strong contrast in water ages across the pore space. We provide evidence that drought in a warmer, more CO_2-rich climate can severely alter grassland ecohydrological processes and improve our mechanistic understanding of hydrological disconnections in near-surface waters.

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A simple water samples storage test for water isotope analysis

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Water is pivotal for human societies' sustainability and resilience. Isotope hydrology, ecohydrology and critical-zone research plays an important role in understanding and managing water resources. Reliable scientific results hinge on high-quality data. Preventing water sample evaporation is essential for accurate isotopic analysis. In this study, the impacts on the quality of isotopic data were tested for the storage of water samples and the repetitive opening of a laboratory reference materials (LRM) sub-sample replica during daily operation. Twenty 15 ml water samples were stored in high-density polyethylene (HDPE) bottles at room temperature and humidity to simulate storage conditions. One 60 ml water sample was collected from the same starting batch to simulate the LRM sub-sample. Each 15 ml sample was analysed once over 80 days for the isotopic composition of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$). The 60 ml sample was repeatedly analysed in the same period. The data were tested to identify shifts in the isotopic composition induced by evaporative processes. The main results of the work are the following: i) storage of the 15 ml water samples did not cause detectable evaporation in the testing period; ii) the 60 ml $\delta^{18}O$ values showed evidence of evaporation as proved by the positive shift of the isotopic data; iii) the repetitive opening of the 60 ml sample was the main cause of evaporation; iv) already 5 openings can cause detectable isotopic enrichment. Careful manipulation and frequent replacement of the LRM are thus necessary to prevent deterioration of the quality of the analyses.

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The evaluation of the groundwater recharge patterns using environmental stable isotopes for Moldavian artesian basin

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The proper evaluation of groundwater resources is a very important for the sustainable development of countries with arid climate conditions. This paper presents results of the of the stable isotope and geochemical study of surface and groundwaters for the Moldavian artesian basin for the better understanding of the hydrogeological system and groundwater reserve formation. The seven principal aquifers were studied for stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) and geochemical composition. The stable isotope composition was analysed using Laser Absorption Spectrometry Pikarro L2130i. The geochemical parameters of water were determined in filed conditions by potentiometry methods and Ion Chromatography system. Obtained results showed a different stable isotope composition for deep (confined) and shallow (unconfined) aquifers. The shallow aquifers have a heavier stable isotope composition in the comparison with deep aquifers and demonstrate an evaporation effect to the ration $\delta^{18}O$ and $\delta^{2}H$ in the comparison with LMWL and GMWL, which can be explained by the climate and hydrogeological conditions: lithology, interaction between different aquifers. Deep aquifers have a lighter isotopic composition by the case of the confined hydrogeological conditions and a close regularity of stable isotope composition to GMWL. The stable isotopes demonstrated that principal source for the groundwater recharge for the study area is a precipitation in the cold periods of the year and in past cold periods. The comparison of stable isotopes in surface and groundwaters demonstrate the complex character of the interaction between them in the actual time. From one-part groundwaters are discharged in river system by springs and subsurface interaction. From other part is indicated the groundwater recharge by the karstic system from principal rivers. The area of the groundwater recharge is situated in the north part of the country in the transboundary region between Ukraine and Romania. The general groundwater flow from north to south is illustrated by the increasing of stable isotopes in shallow aquifers in this direction. The conceptual hydrogeological model was confirmed by the obtained results for the modelling purposes of the groundwater flow and reserve formation. The main factors in the formation of groundwater reserves are the recharge by atmospheric precipitation and the interaction between aquifers and with surface waters.

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Water isotope insights into soil water transit from 53 forest plots in Switzerland

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Precipitation percolates through soils for varying amounts of time before it returns to the atmosphere as evapotranspiration, recharges groundwater, or contributes to streamflow. Despite the importance of soil water transit in the water cycle, there have been few systematic analyses of soil water isotopes spanning a wide range of environmental conditions. We analysed the stable water isotope composition ($\delta^{18}O$ and $\delta^{2}H$) of more than 3,600 lysimeter water samples in 127 lysimeters across 53 forest plots in Switzerland. We employed water isotope-based metrics (young and new water fractions, seasonal origin index) to assess the age and seasonal origin of lysimeter waters within the varied forest plots. We utilized Spearman (rank) analysis to understand the relationship between soil water transit and climatological, physical and biological factors. Physical factors (lysimeter depth, soil field capacity, and percentage of stones in soil) displayed the most significant relationships with young and new water fractions in soils. Climatological factors (mean annual precipitation and AET/PET) also displayed significant relationships with young and new water fractions in soils. In addition to exploring relationships between young and new water fractions and climatological, physical and biological factors across the 53 forest plots, we take a closer look at intra-site young and new water fractions to explore how water ages within soil profiles. The results presented here help push forward our understanding of what environmental factors influence how waters percolate through soils.

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Deep Aquifers in Morocco: Integrative Approaches for Sustainable Groundwater Management

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In Morocco, groundwater is an essential resource for drinking, domestic, agriculture and industrial uses due to the scarcity and high vulnerability of surface water to climate change. This reliance is driven by the arid to semi-arid climate conditions that characterize the region, supporting ecosystems dependent on groundwater. Over the past decades, successive droughts, population growth, and economic development, particularly in agriculture, have led to the overexploitation of groundwater, especially in shallow aquifers. Recently, there has been a notable increase in the exploitation of deep aquifers as well. This situation necessitates a thorough investigation of these deep aquifers to manage this essential resource effectively using a multi-faceted approach, including geo-structural analysis, geochemistry, and isotopic studies. The aim of this study is to provide comprehensive insights into Moroccan deep aquifers, focusing on their geometry, hydrodynamics, hydrochemical characteristics, recharge origins, geothermal potential, and residence times. The goal is to identify which aquifers have prolonged recharge periods and should remain unexploited. This research highlights the recharge sources of Morocco's deep aquifers. The Cretaceous deep aquifers, such as Souss, Essaouira, Ouarzazate, Tadla, Haouz, and Errachidia, are primarily recharged from the High Atlas Mountains. In contrast, the deep Jurassic aquifers, including the South Rifain Corridor, High and Middle Moulouya, High Plateau, Horst Chain, Taourirt-Oujda Corridor, Bni-Bouyahi, and Bni-Znassen aquifers, receive recharge from the Middle Atlas or North-Eastern Moroccan Mountains. Most of Moroccan deep aquifers are considered fossil aquifers, with residence times exceeding 20,000 years. The deep Sahara aquifers represent the most significant groundwater reserves due to their lithologic composition and extensive area, approximately 90,000 km^2, but they also have high residence times dating back over 46,500 years. Due to their variable mineralization influenced by differing geological contexts and human activities, these aquifers are highly vulnerable, especially in outcrop areas which are mainly karstic or fissured. The deep aquifers require stringent management and protection due to the arid climate and minimal precipitation across all investigated regions. The study's findings will provide essential indicators regarding the functioning of Moroccan deep aquifers, offering valuable guidelines for decision-makers and policymakers to underscore the need for careful management and conservation of these essential water resources.

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Assessing Groundwater Recharge and Residence Time Using Hydrochemical and Isotopic Tracers: Insights from Errachidia Basin, Central-Eastern Morocco

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The aquifer systems in the Errachidia basin, located to the south of the High Atlas limestone, are constituted by three superimposed and exploitable aquifers (Senonian, Turonian, and Infracenomanian). These aquifers hold economic significance for the central-east region of Morocco. This area experiences an arid to Saharan climate characterized by low precipitation, high temperatures, and very high evaporation. It is one of the most exposed and vulnerable regions to climate change in Morocco. The low local rainfall cannot explain the recharge of the deep aquifers. However, the significant spring discharges from these aquifers indicate the existence of other recharge contributions.

The aim of this study is to elucidate the recharge processes of the Cretaceous aquifers in the investigated basin, clarify hydraulic relationships between them and the Jurassic aquifers of the High Atlas Mountains and estimate the residence time of groundwaters. Water samples from aquifers are collected and analyzed for chemical and isotopic elements. Several statistical methods (SOM, discriminant factorial analysis, CPA) are employed. The results reveal that many samples from different aquifers exhibit clear similarities in chemical characteristics, providing evidence of water transfer between aquifers. Isotopic findings are consistent with chemical characterization and mineralization anomalies.

Recharge of the investigated aquifers originates from the Jurassic limestone of the High Atlas Mountains, facilitated by the karstic nature of the Jurassic in contact with the permeable formations of the Cretaceous basin. Age dating results, using ^{3}H and ^{14}C values, confirm that most of the investigated groundwater results from a mixing of old and recent recharges. This process of groundwater renewability is relevant. All the findings are valuable for decision-makers to enhance their understanding of the aquifer system's functioning and inform sustainable management strategies for future sustainability.

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Analyzing O and H water isotopes in organic enriched solutions

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The arrival of isotope ratio infrared spectroscopy (IRIS) for analysing stable water isotopes based on the different adsorption spectra of water molecules with different isotopic composition allowed much faster sampling processing, in-situ measurements in the field, and lower costs per sample. Currently two IRIS instruments are available on the market with measurement technology based on i) off-axis integrated cavity output spectroscopy (OA-ICOS) and ii) wavelength scanned cavity ring-down spectroscopy (WS-CRDS). However, IRIS measurements of water samples can be seriously compromised by interference of some specific organic compounds in the sample with the absorption spectrum of water isotopologues. The impact of contamination issue by organic compounds on the IRIS measured isotopic composition has led to a range of measures to support usability of IRIS instruments in ecohydrological studies.

Until recently isotope ratio mass spectrometry (IRMS) was the standard in isotope hydrology studies and it is still considered as the reference in ecohydrology to mitigate the effects of organic contamination. However, IRMS analysis of water samples include the oxygen and hydrogen isotopes of organic compounds that are present in the water before entering the furnace of the spectrometer. Those compounds are burned at the same time as the oxygen and hydrogen of the water molecule and can dissipate together with those resulting in joint signal detection in the mass spectrometer analysis. This contribution to the measured oxygen and hydrogen isotopic composition from the organic compounds has the potential to compromise the IRMS results depending on the concentration, species, and the isotopic composition of the organic compounds present in the water sample.

In this study, we assess the type and concentration of organic compounds in extracted xylem water and evaluate their impact on stable water isotope analysis with IRMS and IRIS. Our working hypothesis is that samples that are currently analysed in ecohydrology, such as xylem samples heavily enriched in organic compounds, decrease more the analytical precision of IRMS than that of IRIS. We perform an intercomparison study between IRMS and two IRIS instruments with different configurations (with and without combustion module; old and new catalyst) on water without organic compounds, water spiked using different organic molecules (glucose, ethanol, methanol) and beech sap samples.

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Simple, exact and reliable way to extract soil water for stable isotope analysis

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Water stable isotope analysis in ecohydrological studies often requires soil water extraction. Here, we present a new soil water extraction method based on the principle of complete evaporation and condensation of the soil water in a close circuit. We have developed an apparatus that has four extraction slots and can be used multiple times a day. Thanks to its simple design, there is no need for any chemicals, gases, high pressure or high-temperature regimes. A set of system functionality tests confirmed that the extraction method has high accuracy and high precision and does not cause any isotope fractionation effects leading to erroneous results. When extracting pure water samples, the accuracy is 0.04 ‰ and 0.06 ‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively, with a precision of ±0.06‰ and ±0.35 ‰ respectively. The accuracy for the extraction of oven-dried and rehydrated soils ranged between -0.04 and 0.03‰ for $\delta^{18}O$ and 0.06 and 0.68 ‰ for $\delta^{2}H$ with precision of ±0.06 to 0.13‰ and ±0.34 to 0.58 ‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively in individual tests. These results are more accurate than results achieved by cryogenic vacuum extraction, which is the most widely used extraction method for soils. So far, our method was only tested for soil water extractions.

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Morocco's Groundwater: Understanding and Mitigating Nitrate Pollution

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In various regions around the world, groundwater is the primary source of drinking water. However, increased industrial and agricultural activities, along with recurring droughts in areas like Morocco, have led to water scarcity and the introduction of pollutants into both ground and surface waters. Nitrate, due to its high solubility, has become a widespread contaminant, posing a growing threat, especially in arid environments such as Morocco. This research aims to provide an overview of groundwater and surface water quality across Morocco, to identify contaminated aquifers by nitrate, to determine the sources of this contamination, and to evaluate the suitability of the groundwater for drinking and irrigation. Generally, Moroccan rivers exhibit good to moderate water quality, with poorer quality found only in localized areas downstream of domestic and industrial discharge points. Dams generally maintain excellent to moderate water quality, with only 5% exhibiting poor quality due to wastewater discharge. Conversely, groundwater quality has deteriorated, mainly due to high salinity and elevated nitrate levels. Nitrate contamination is widespread in many Moroccan aquifers, with concentrations sometimes exceeding 100 mg/l, indicating very poor quality. This degradation is mainly caused by domestic and industrial wastewater discharge and the excessive use of fertilizers in irrigated areas. Additionally, nitrate contamination from seawater intrusion is noted in several coastal aquifers, such as R'mel, Mnasra, Chaouia, Doukkala, Akermoud, and Souss-Massa, particularly within 2000 meters from the coastline. Furthermore, isotopic analyses of $\delta^{15}N–NO_3$ and $\delta^{18}O–NO_3$ in the Mediterranean aquifers “BouAreg” and Atlantic aquifers “Massa” suggest that the primary sources of nitrate are manure, sewage, and agricultural fertilizers used in irrigated areas. This comprehensive overview could serve as a reference for decision-makers to develop effective water management strategies.

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Isotopic study of groundwater response to rainfall in different Mediteranean geological and geomorphological contexts. Implications for long-term aquifer sustainability in the climate change context.

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Groundwater recharge is a complex Eco-hydrological mechanism controlled by several factors such as the amount and intensity of precipitation, the geology, the topography and the vegetation characteristics. However, this hydrogeological component of the water cycle is highly sensitive to climate change. Based on long-term stable isotopes in rainfall and groundwater, this paper aims to analyse the groundwater response to rainfall and therefore to define the different recharge mechanisms in various geographical and geological contexts of the Mediterranean area. Results show an evidence of modern recharge of groundwater by rainfall excepted for thermo-mineral reservoir which show the characteristics of stored groundwater from previous years. Focused, diffuse and mountain system recharge mechanisms have been identified with a preferential recharge in winter and autumn. Line-conditioned excess and deuterium-excess highlighted that focused recharge is mostly related to evaporation process. However, some groundwater from autumn reveal a mixing between slightly evaporated waters and depleted rainwater. Finally, the calculation of groundwater recharge ratios and the assessment of rainwater signal damping in the aquifer, reveal a control of plants activity through evapotranspiration and meteorological conditions (existence or not of a snowpack and precipitation intensity) on annual recharge rate. Such work provides a clear understanding of groundwater response to rainfall infiltration. It is clear that subsurface water are not just a mean of rainfall events but rather reflect a complex eco-hydro-meteorological system. The paper is beneficial to predict the infiltration rates according to the climate scenarios in the Mediterranean region and to develop sustainable water management practices.

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Inter-aquifer Interaction of Groundwater and its Hydrological Implications in the Northern Gujarat Region

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Northern Gujarat receives nearly 700mm of rainfall and falls under the semi-arid region. In this area, groundwater plays a major role in providing water for irrigation and agriculture purposes. The high dependency on groundwater, lower rainfall, and unavailability of perennial rivers put this region into an overexploited zone in relation to groundwater abstraction due to the deeper groundwater mining going on. According to the Central Ground Water Board (CGWB) report on the quality of shallow aquifers, this area exhibits high levels of fluoride and nitrate in its shallow groundwater. The significant demand for water has led to using multi-aquifer bore wells, which sometimes function as artificial recharge structures for deeper groundwater. This allows pollutants from shallow aquifers to migrate to deeper ones.

In this study, groundwater samples from shallow (62 samples), as well as deep aquifers (20 samples) were collected in 2023 during pre-monsoon season (May June) and analysed for stable isotopes of oxygen and hydrogen as Stable isotopes of oxygen and hydrogen play an important role in understanding the movement and mixing of two different water masses. The shallow groundwater isotopic values range between -0.8‰ to -5.8‰ with an average value of -3.0‰ while deeper groundwater isotopic values range between -2.7% to -4.5‰ with an average of -3.7‰. The regression line for shallow groundwater has a slope (6.1 ± 0.3), while deeper groundwater has a slope (7.3 ± 0.5). The higher slope and more depleted $\delta^{18}O$ of deeper groundwater suggest they are recharged from different water sources. In some locations, the isotopic values of dipper and shallow groundwater have a similar isotopic composition, indicating the areas where shallow and deep groundwater might interact due to multi-aquifer penetrated borewells.

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Isotope-aided modeling of the Krycklan Catchment Study

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Standard hydrologic model calibration and evaluation primarily depend on streamflow observations, which can limit the accurate representation of the physical processes generating streamflow. Recent studies indicate that incorporating tracers, such as stable water isotope data, alongside flow observations in model calibration significantly reduces parameter uncertainty and enhances the understanding of stream water source dynamics, especially the contributions from subsurface water. In this study, we demonstrate the capabilities of an isotope-aided HYPE model applied to the Swedish flagship experimental catchment, the Krycklan Catchment Study (KCS). We integrated the isotope routine from the isoWATFLOOD model (hiips://github.com/h2obabyts/isoWATFLOOD) into the HYPE model and incorporated extensive time series of stable water isotope data collected from various water sources, including precipitation, snow, groundwater, and stream water. Using multi-objective calibration, we aimed to improve the model's internal structure and deepen the understanding of processes in snow-dominated catchments like the KCS, which are experiencing rapid changes due to global warming.

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Groundwater Recharge and Piezometric Depression Dynamics: Investigating Hydrological Processes in the Chari-Baguirmi Region (Lake Chad, Africa)

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The Chari-Baguirmi region, located in the southeastern part of Lake Chad, features a significant naturally occurring piezometric depression with groundwater levels deeper than expected. The prevailing hypotheses attribute this phenomenon to insufficient rainwater infiltration and exfiltration processes. The regional groundwater level is around 40 m below ground surface at Bokoro (boundary) and more than 50 m deep at Amdedoua (central), far below the root zone to enable evapotranspiration.

This study employs the HYDRUS-1D model to simulate hydrological flow processes in the unsaturated zone across two soil profiles—one in the central part and the other at the boundary of the piezometric depression. These profiles are examined under both bare and vegetated soil conditions over the period from 2004 to 2015, with an average annual rainfall of 715 mm.

Results indicate that groundwater recharge constitutes 21% of total precipitation at the boundary and 12% in the central region. The central part is constrained by a thick, silty, low-permeability layer on the surface, limiting infiltration. Despite the climatic conditions simulated, the influence of rainfall is predominantly limited to the upper soil layers, resulting in minimal aquifer recharge. Additionally, the upward water flux, leading to water table evaporation, remains very low. The current piezometric depression may be explained by past climatic conditions that established a drying front reaching the water table over millennia, combined with geological structural constraints.

Further simulations of these sites from the pluvial Pleistocene to the dry Holocene past climate conditions (changes from mesic to xeric vegetation) indicate the importance of the upper water flux reduction to create a drying front (and an upward water flux) that propagates more deeply into the profile and reaches the water table after several kyr of drying.

The results are considered satisfactory and consistent with the low natural recharge and unlikelihood of exfiltration process from the saturated zone that can be expected for this zone. However, as sources of uncertainty from model conceptualization, model parametrization, hydrological components (climate, runoff) and input parameters (hydraulic parameters), exist and besides, external piezometric data are lacking for model calibration and validation, the

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predicted hydrologic values should only be considered as an indication of current hydrologic process taking place in the area.

Isotopes Geochemistry of Pertek (Tunceli, Türkiye) Geothermal Field.

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Pertek geothermal field is located within the Taurus orogenic belt in the Lower Murat region of the Upper Euphrates section of the Eastern Anatolia Region within the borders of Tunceli province. In this study, it was aimed to determine the origin of thermal waters and their circulation time by isotope geochemistry studies. According to $\delta^{18}O$ and $\delta^{2}H$ isotope results, the thermal and cold waters are of meteoric origin since they are located on and near the Mediterranean and Erzurum meteoric water lines. In general, deviation from the meteoric water line may be due to different processes such as evaporation, condensation and water - rock interaction. Accordingly, especially the water of Keban Dam Lake is exposed to evaporation. Generally, thermal waters have higher $\delta^{18}O$ values than meteoric waters. This is due to the enrichment of the waters by taking $\delta^{18}O$ from the rocks rich in heavy isotopes by interacting with the side rocks during circulation time. It is seen that some of the thermal waters analysed are exposed to more water-rock interactions.

According to ^{3}H-EC relationship of the waters in the study area, it is seen that the thermal waters have low tritium and high EC and are deeper circulating waters compared to cold waters. It is observed that some thermal waters in the area differ from others due to mixing with cold groundwater. The electrical tritium and oxygen-18 (Tritium-$\delta^{18}O$) relationship of the waters shows that thermal waters with low tritium (<2 TU) content in the study area have a longer residence time and are fed from higher elevations.

When the study is evaluated as a whole, thermal waters are formed by meteoric waters filtering deep under the control of faults, heating and resurfacing along fault lines. Thermal waters mix with cold groundwater at certain depths during their circulation. The dominant processes that control the major ion composition and trace element content in thermal and cold waters within the geothermal system are water-rock interaction, dissolution-precipitation reactions, and dissolution of clay and/or alteration minerals present in fractures and cracks.

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Recharge estimation using different methods in a mountainous aquifer of Greece

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The estimation of natural recharge is an important tool for the rational and sustainable management of groundwater systems. Various methods have been used to quantify recharge to an aquifer (empirical methods, tracer techniques, direct measurements, groundwater level methods, chloride mass balance, mathematical models, etc.). As aquifers are depleted in many countries, recharge estimates have become increasingly important for calculating the safe yield of aquifers and for determining appropriate levels of groundwater abstraction.

Kastoria Basin is located in the NW part of Greece at an altitude ranging between 600 m and 1680 m. It is drained by Xiropotamos torrent, which discharges in Kastoria Lake during the wet period. The basin is underlain by alluvial deposits in the lowlands and by metamorphic (gneiss) rocks in the mountains. The alluvial sediments contain an aquifer of unconfined-semi-confined conditions. The aquifer is recharged by direct infiltration of rainfall, return flow of irrigation water, percolation from riverbeds and lateral subsurface inflow from outside areas. The mean annual rainfall is 695 mm and the mean temperature is 12.7^{o}C. The coefficient of real evapotranspiration is 64% of the yearly rainfall (Thornthwaite method).

In this work, different methods were applied to estimate the natural (wet period) recharge of the aquifer: chloride mass balance, hydrological balance, and groundwater level fluctuation between dry and wet periods. For this reason, hydrometeorological, hydrochemical, and hydrogeological data were used. The methods use different parameters and produce relatively different results. The advantages and limitations of each method are presented. Finally, some recommendations are proposed for the sustainable management of the aquifer.

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Ecohydrology, plant water uptake

The WATSON Pan European Sampling Campaign to Investigate Large-Scale Variation in Plant Water Uptake

Marco Lehmann[1], Katrin Meusburger[1], Josie Geris[2], Youri Rothfuss[3], Daniele Penna[4,5], Ilja van Meerveld[6], and the full sampling team

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The COST Action WATer isotopeS in the critical zONe initiated a synchronized, participatory sampling campaign in late spring and summer of 2023. Soil and vegetation samples were taken from 40 forest sites in 17 European countries. The samples were analyzed for the stable isotopes of oxygen and hydrogen at the WSL laboratory in Switzerland. The data enable us to investigate the spatial and temporal (spring vs summer) variability of root water uptake of the shallower-rooted spruce (Picea abies) and deeper-rooted beech (Fagus sylvatica) trees. This presentation will describe the sampling campaign, the resulting dataset that can be used by anyone, and some preliminary results on root water uptake for both species across Europe.

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Towards a common methodological framework for the sampling, extraction, and isotopic analysis of water in the Critical Zone to study vegetation water-use

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The analysis of the stable isotopic composition of hydrogen and oxygen in water samples from soils and plants can help to identify sources of vegetation water uptake. This approach requires that the heterogeneous nature of plant and soil matrices is carefully accounted for during experimental design, sample collection, water extraction and analyses. The comparability and shortcomings of the different methods for extracting water and analyzing isotopic composition have been discussed in specialized literature. Yet, despite insightful comparisons of extraction methods and benchmarking methodologies of laboratories worldwide, the community still lacks a roadmap to guide sample collection, extraction, and isotopic analyses, and many practical issues for potential users remain unresolved: for example, which (soil or plant) water. pool(s) does the extracted water represent? These constitute a hurdle for the implementation of the approach by newcomers. Here, we summarize discussions led in the framework of the COST Action WATSON ("WATer isotopeS in the critical zONe: from groundwater recharge to plant transpiration" CA19120). We provide guidelines for (1) sampling soil and plant material for isotopic analysis, (2) methods for laboratory or in situ water extraction, and (3) measurements of isotopic composition. We highlight the importance of considering the process chain as a whole, from experimental design to isotopic analysis to minimize biased estimates of the relative contribution of different water sources to plant water uptake. We conclude by acknowledging some of the limitations of this methodology and advice on the collection of key environmental parameters prior to sample collection for isotopic analyses.

How the incorporation of stable water isotopologues into process based SPAC models can help to decrease uncertainties and deepen our process understanding

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If we want to make predictions about plant water relations in a changing environment, we need mechanistic models which are based on parameters that can be related to plant physiological traits. While there are several mechanistic SPAC (Soil-Plant-Atmosphere-Continuum) models in use, soil moisture usually is the main observation they are validated against. Stable water isotopic signatures can add additional information for the validation of such models and thereby help to identify parameters which are critical to plant water uptake. Until recently, the main obstacle for this promising approach has been the lack of ready-to-use stable water isotope enabled SPAC models, but with recent developments there are promising candidates for this task. In this talk I want to give a short overview over water isotope enabled SPAC models, their potentials, current limitations, and future perspectives.

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Promoting the practical application of stable isotopes in water management

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This work focuses on the importance and versatility of isotopic analysis in water management, and aims at raising the interest of a wide audience of potential stakeholders. We loosely define a stakeholder as anyone who can directly or indirectly benefit from a detailed knowledge of water storage and fluxes, that is farmers and foresters, but also urban water and garden managers, risk managers, land reclamation authorities, and policy makers. The techniques based on the analysis of stable isotopes have been used for decades in research and have helped to answer many scientific questions, but they are generally underused to solve stakeholders' issues. In this work, we provide several examples of practical applications taken from the literature, but we also report four case studies taken from our own experience with different categories of stakeholders. Finally, we propose a workflow that guides users through a sequence of decisions required to apply stable isotope methods to examples of water management issues. With this work we aim at promoting the dialogue between water management stakeholders and water stable isotope practitioners to identify the most pressing issues and develop best-practice guidelines to apply stable-isotope-based techniques.

The effect of rain pulses on the water source partitioning of woody species in a semi-arid coastal dune system

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Rain and groundwater are important water sources in water-limited regions such as semi-arid coastal dune systems. The availability of these resources is expected to change due to both climate change and anthropogenic pressures. Thus, it is crucial to understand how plants cope with changes in water resources availability, and especially how much they rely on rain pulses in dry periods. Therefore, this study aims to understand the effects of rain pulses on the water-sources-use of co-occurring woody species from different functional types. We tested whether water-sources-use, and its dependency on rain pulses, was (i) different between contrasting groundwater availability conditions (shallow vs deep water-table); (ii) dependent on growth form or plant size; and (iii) influenced by vegetation density or composition. For that purpose, lignified woody stems from a total of 20 individuals of 6 different species, and samples of soil water (from 3 depths), groundwater, and rainwater were collected on Tróia Peninsula, Portugal, on two plots with contrasting hydrological conditions (i.e. shallow and deep water table) before a rain pulse, after a first rain pulse, and after a second rain pulse. The oxygen stable isotope ratios ($\delta^{18}O$) of these water samples were analysed and the contribution of the different water sources to the xylem water was examined with Bayesian mixing models. Our results will reveal water source partitioning patterns among woody dune species under contrasting water availability conditions. This study will show dynamic shifts in the water-use strategies among functional types and uncovers the effects of vegetation abundance and of water table depth and soil moisture on these water-sources-use patterns.

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Does high resolution in situ xylem and atmospheric vapor isotope data help improve modelled estimates of ecohydrological partitioning?

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Ecohydrological partitioning of rainfall into different sources of evaporated and transpired water is crucial to quantify water balance changes in the context of land cover change. However, resolving ecohydrological water partitioning into component fluxes can be ambiguous and highly uncertain, even where detailed, small-scale measurements are available. To constrain ecohydrological water fluxes at the scale of an individual tree in an urban setting, we combined hydrometeorological, sap flow, soil water and novel high-resolution *in situ* plant xylem and atmospheric vapor stable isotope measurements over a complete growing season from April to October 2022. These data were integrated with parsimonious tracer-aided conceptual modelling. The unique data set helped isolate temporal patterns of shifting preferential fractionation in xylem and atmospheric vapor from $\delta^{18}O$ to $\delta^{2}H$ depending on environmental variables such as air temperature and relative humidity. High-resolution *in situ* isotope modelling revealed the dominant local influence of interception, soil evaporation and transpired water sources on atmospheric vapor particularly during dry periods, whereas wet periods were driven by more variable non-local moisture sources. Additional model tree water storage did not explain the highly variable and more depleted xylem isotope data compared to enriched and fractionated soil water. Despite a volumetrically constrained (within transpiration measurement uncertainty bounds) ecohydrological water partitioning, the atmospheric vapor isotope data showed that fine-scale variations of interception and soil evaporation vapor sources can have nuanced impacts on the atmospheric vapor mixture. The comparison of a more complex conceptualization of modelled soil storages (three soil storages) with a minimal two-storage model indicated the notoriously difficult isotopic discrimination of root water uptake depths. Nonetheless, the combination of volumetric and high-resolution in situ isotope measurements with modelling helped enhance our understanding of plot-scale vegetation-mediated hydrological processes.

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Comparing cavitron flow-rotor centrifuge and cryogenic vacuum distillation for the extraction of plant water

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In the last two decades, various techniques have been developed to extract water samples from soil and plants to perform isotopic analysis for such samples and investigate ecohydrological processes. Among these techniques, there is cryogenic vacuum distillation, which is the most widely used method and is able to extract total plant water. Furthermore, cryogenic vacuum distillation is easily applicable and less expensive than other techniques, but recent studies have shown that it may be responsible for isotopic bias. An alternative method to cryogenic vacuum distillation is cavitron, which is a specialized rotor attached to a centrifuge to extract water from tree species. With this study, we aimed to compare cryogenic vacuum distillation and cavitron techniques for various tree species. Specific objectives were i) analyzing differences in δ^2H and $\delta^{18}O$ between the two extraction methods, and ii) determining whether these differences are influenced by the species or technical aspects related to the technique.

Sampling campaigns were conducted in Spain in July and October 2023, and in Italy in late September. The cavitron extractions were carried out at the Department of "Biologia Evolutiva, Ecologia y Ciències Ambientales" at the University of Barcelona, and the cryogenic vacuum distillation extraction was performed at the Faculty of Science and Technology at the Free University of -Bozen-Bolzano.

First results indicate that there was a marked difference between the two extraction techniques, indeed water samples extracted by cryogenic vacuum distillation had a more depleted isotopic composition compared to the cavitron method. These differences were more marked for $\delta^{18}O$ than δ^2H. Cavitron-extracted samples plotted close to the local meteoric water lines, suggesting that they had an isotopic signature more similar to rain water, and likely to non-evaporated soil water readily available for plant uptake. In addition, plant species did not have a significant effect on isotopic differences.

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Tracing water sources in a Mediterranean vineyard – an SNSF COST project based on WATSON

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Viticulture is an essential sector in agriculture as wine production plays a vital role in the socio-economic life of many countries, especially in the Mediterranean area. Grapevines are a valuable, long-lived species able to grow in hot and dry regions. We currently do not know whether rain-fed grapevines entirely rely on deep soil water or make substantial use of shallow water from summer precipitation events. Without knowing this, we poorly understand what fraction of summer precipitation inputs contributes to grapevine transpiration. This has implications for how we quantify grapevine-relevant precipitation budgets and for predicting the impacts of climate change on grape and wine production. With support from the Swiss NSF COST project “TRACET: Tracing the origins of transpired waters: theoretical developments and application to a vineyard in the Chianti region”, we monitored two vineyards in central Italy, and we collected over 1000 samples of rainfall, soil, and plants for water isotope analysis. Since the traditional xylem sampling is problematic for grapevines, we also collected alternative plant samples (from shoots, leaves, and condensed leaf transpiration after sealed plastic bags were wrapped around a shoot) to test whether they could help reconstruct the plant's seasonal water origin. While the field campaign is still ongoing, we could already observe that, throughout the growing season, soil water and plant water were disproportionately contributed by rain that had fallen in the winter, even when compensating for the Mediterranean climate of the area. This work featured the contribution of many WATSON members, and the resulting research contributes to a better understanding of ecohydrological interactions and water uptake dynamics in valuable socio-economic agroecosystems such as vineyards.

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Scots pines water use dynamics under different wetness conditions: ecohydrological and isotopic insight

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Mountain regions in the Mediterranean face heightened vulnerability to climate change, anticipating decreased rainfall and increased drought frequency. Effective hydrological management is crucial to mitigate these impacts on local ecosystems. Despite its significance for sustaining ecosystem services, understanding the critical zone remains challenging due to its complex water partitioning mechanisms that are influenced by various heterogeneities. Integrating insights from various approaches to unravel intricate soil-plant-water interactions is therefore essential.

This study investigates water use dynamics of montane Scots pines (Pinus sylvestris L.) under varying wetness conditions, employing ecohydrological datasets together with stable water isotopes (^{2}H and ^{18}O). We designed a field monitoring set up in a Scots pine trees plot within the Vallcebre research catchments (NE Spain). The monitoring was carried out from May to October 2022. It included measurement of throughfall, sap flow, and dial stem diameter variation, as well as of soil water potential and soil water content (in vertical profiles down to 70cm) at high temporal (5min) resolution. Furthermore, we sampled weekly water from the different water pools (throughfall, soil water (bulk and mobile), groundwater, and xylem water (twigs) for isotopic analysis.

We identified three distinct consecutive periods within the growing season of 2022: “Dry” (20 days), “Transition” (3 days), and “Wet” (10 days) periods. We observed distinct patterns in sap flow (SF) and tree water deficit (TWD) responses to fluctuating atmospheric and soil conditions throughout these periods. SF demonstrated a stronger correlation with atmospheric demand, whereas TWD exhibited a more significant correlation with SWP. However, during the brief 3-day transition period, the atmospheric conditions changed rapidly and this was met with an instantaneous decrease in TWD despite SWP remaining low. Additionally, our isotopic analysis showed a complex and dynamic behavior of tree water uptake. These high-resolution interactions highlight the complex and coupled nature of hydrological and physiological processes governing tree water uptake and stress the need for considering both atmospheric and soil factors in ecohydrological models.

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Evaluating possible variations of isotopic signatures in Scots pine for a better understanding of soil-root-tree water uptakes

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Water stable isotopes are helpful proxies to trace water fluxes in the critical zone (the Earth's layer that runs from top vegetation to deep aquifers) allowing to generate conceptual models that seek to explain water distribution at different scales. However, the understanding of how water is distributed and stored across trees' compartments is still not well understood. In this study, the main aim was to evaluate the potential variability of the isotopic signature in different parts of the tree to enhance our understanding of soil-root-tree water uptake. To do so, we sampled for isotopic analysis a representative individual tree (*Pinus sylvestris L.*) in an ecohydrological monitored forest plot located in the Vallcebre research catchments (NE Spain). Soil samples at different depths (0-100 cm), woody tissue of twigs and branches (3 heights along the canopy), stem (increment cores at 3 different heights) and roots (in the four cardinal directions) were collected on two dates (July and September 2023). Bulk soil and xylem (wood) water was extracted using cryogenic vacuum distillation and sap xylem water was extracted using the cavitron technique (i.e. via centrifugation). All extracted water samples were analyzed to obtain stable isotopes ratios. In addition, long-term meteorological data, throughfall volume and isotopic signature, soil water content, and sapflow rates (in adjacent trees) were available. Preliminary results revealed consistent patterns for both dates. Twigs and branches isotopic values grouped closely with soil and throughfall signatures. However, roots and stems displayed more depleted values, clearly differentiated from soil, twigs and branches. We are currently investigating whether the differences observed in the water isotopic composition of different parts of the tree are related to methodological issues (differences between cavitron and cryogenic extraction), mixing of waters from different functional parts of the tree or differences in xylem anatomy.

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A novel sampling system of in-canopy precipitation for isotopic analysis

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In hydrology, water stable isotopes ($\delta^{18}O$, $\delta^{2}H$) of precipitation play a central role as essential input data to study catchments. By tracking the different isotope signatures in water bodies, a deeper understanding of hydrological processes and watershed dynamics can be gained. In forested catchments, the isotope ratio of precipitation passing through canopy is altered by different processes, e.g., evaporative fractionation. However, the exact impact of these processes is poorly understood mostly due to lack of detailed measurements of isotopic changes within the canopy. To improve the understanding of how rainwater isotope ratios are changed within the canopy, a sampling system has been developed that collects and stores water passing the canopy, while also allowing for collection of samples for isotope ratio measurement. The reliability of the developed system was tested in the laboratory, and rainfall simulator and outdoor experiments with real and artificial trees were conducted to test the operation of the system under more natural conditions. Having evaluated multiple collection system variations, we chose the system that demonstrated the highest reliability in preventing evaporation and the greatest ease of handling. In the selected system the collection took place with a funnel, which transports the water into a sphere attached at the bottom of the funnel. In the rainfall simulator and outdoor tests, five positions inside the tree canopy were tested for differences in weight and isotope ratios of the collected water. Laboratory results showed that the collection system was reliable for up to 72 hours after a rain event, with deviations smaller than 0.5‰ to the initial $\delta^{18}O$. The results of the rainfall simulator and outdoor tests showed the general applicability of the system under real conditions but were inconclusive regarding in-canopy processes due to the small number of repetitions. Nonetheless, suggestions for improving the sampling system were formulated. This approach could potentially improve hydrological models on the plot- and watershed-scale by providing insights into the processes responsible for altering rainwater isotope ratios in canopy.

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Hydrogen and oxygen isotopes in tree-ring cellulose as indicators of source water variations

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Although the hydrogen (δ^2H) and oxygen ($\delta^{18}O$) isotopic signature of tree rings is dependent on the environmental water, such as precipitation and soil water that trees have taken up (i.e. “source water”), estimating the spatio-temporal origin of water sources through analysis of δ^2H and $\delta^{18}O$ of tree rings is still limited. This is because in situ measurements that consider the variability of the isotopic composition of both source water and tree-ring cellulose are rare.

Within the framework of the EU Cost Action WATSON (#CA19120), we analysed (1) δ^2H and $\delta^{18}O$ of tree-ring cellulose, (2) δ^2H and $\delta^{18}O$ of soil water at shallower (15 cm) and deeper (80 cm) depths in up to bi-weekly resolution and (3) modelled δ^2H and $\delta^{18}O$ of precipitation at three long-term forest monitoring sites (Beatenberg, Bettlachstock and Vordemwald) in Switzerland over 17 years (2006-2022). We used this data to explain inter-annual δ^2H and $\delta^{18}O$ variations in tree-ring cellulose of spruce (*Picea abies*).

We found a pronounced isotopic enrichment in the second half of the growing season and marked temporal variations in the isotopic compositions of soil water at 15 cm depth compared with that at 80 cm depth. Time-window correlation analyses show that the isotopic compositions of soil water at 15 cm depth were positively correlated with that of precipitation spanning from the current month to the previous four months. The $\delta^{18}O$ of tree-ring cellulose was positively correlated with that of soil water at 15 cm depth in the current year's growing season. This positive correlation was also found for soil water at 80 cm depth, but only at Bettlachstock. For δ^2H, correlations between tree-ring cellulose and soil water or precipitation were weak, likely influenced by post-photosynthetic biochemical processes.

In further analyses, we will investigate how well δ^2H and $\delta^{18}O$ of tree rings can function as indicators of source water by including modelled soil water and xylem water isotope data. In addition, more detailed tree water-use patterns will be illustrated by accounting for the seasonal water origin derived from mechanistic and process-based models. Our study will enhance the combined use of δ^2H and $\delta^{18}O$ of tree rings as innovative ecohydrological proxies for reconstructing environmental water sources.

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One decade exploring the use of gypsum crystallization water by plants: methodological challenges and new avenues

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Among the minerals commonly known for containing water in their crystalline structure, gypsum ($CaSO_4$ $2H_2O$) is notable for requiring relatively low energy to release water. Gypsum in soil can undergo hydration and dehydration cycles depending on environmental conditions, being released from soils at temperatures above 40ºC. At the turn of the millennium, Herrero and co-workers suggested that the water molecules associated with gypsum could contribute to soil moisture availability, making this water available to plants during dry periods. This hypothesis would explain observations of shallow-rooted plants that remain active during intense droughts, a period when traditional water sources are typically unavailable. Due to fractionation during rehydration, the isotopic composition of gypsum water differs strongly from any alternative water source. Applying a two-step distillation to extract separately free and crystallization water, Palacio et al. (2014 *Nature comm*) presented the first isotopic evidence that plants can utilize water stored in gypsum crystals. However, there is still a lack of knowledge on the physiological and biochemical mechanisms through which plants access crystallization water. Furthermore, field studies performed so far display contrasting results, suggesting that the process might depend on soil and environmental conditions, and replication under laboratory remains elusive. Here we will present the different approaches followed during the last decade in order to 1) elucidate the thermodynamic mechanisms and the eventual plant-soil-microbial interactions involved and 2) provide unequivocal evidence of the use of gypsum water under controlled conditions, using D_2O-labelled gypsum soil. We will discuss the methodological challenges found and give insight into the approaches we can follow in the future to overcome them.

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Xylem water in Fagus sylvatica L.: a multi-isotopes study

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Stable isotopes of water have been largely used as tracers in ecohydrology, contributing enormously to the development of various hypotheses and interpretations on tree water uptake dynamics and evapo-transpiration fluxes. However, many issues remain when using O-H stable isotopes to trace the origin of the tree water uptake. The lack of standard protocols for tree water sampling and analysis, alongside the little attention given to the effect that tree physiology and biochemistry may have on the isotopic composition of xylem water, is a limitation to the use of these tracers in the regolith-tree continuum.

In this work, we present tree sap O and H isotopic data collected during three years with two different techniques: (i) an in-situ vacuum extraction of the sap flowing in the xylem vessel and (ii) the well-known cryogenic vacuum distillation applied on wood cores. Nine beech trees were sampled at different heights in the root-twigs continuum along a hillslope in the Weierbach Experimental Catchment in Luxembourg. The O-H isotopic signatures of the samples were then compared for observing differences proper to the techniques and/or to potential effects of internal tree processes controlled by either (1) the retention and mixing of water of different ages and/or (2) water exchange in xylem tissues. We also introduce the use of radiogenic Pd isotopes as a complementary tool to assess tree water source.

We observed a significant difference between the OH isotopic signatures in water collected with the two different techniques. The water sampling protocol from the root with the in-situ vacuum extraction appears to be more appropriate for the identification of the potentially absorbed water source. Our results also show a progressive ^{18}O and ^{2}H enrichment in the xylem water along the root-twig flow path for all studied trees. The range of the water isotopic signature obtained via cryogenic vacuum distillation is closely related to the tree compartment from which the water was collected from – questioning the contribution to internal tree process understanding from data obtained via this technique. $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ ratios indicated that the Pb present in the sap samples originated from groundwater.

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Evapotranspiration partitioning across US ecoregions: a multi-site study using field stable-isotope observations

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Evapotranspiration (ET) is the largest output flux in the terrestrial water balance. Therefore, predicting changes in ET magnitudes and trends due to climate change requires an understanding of the factors that control the constituent components of this flux: soil evaporation (E) and plant transpiration (T). To better uncover the factors controlling ET, we partition the ET flux by leveraging the distinct oxygen and hydrogen isotopic signatures that arise through the isotopic fractionation processes inherent in soil evaporation and plant transpiration.

In this study we bring together three complementary datasets: the National Ecological Observatory Network (NEON) terrestrial field site data products, the NEON Daily Isotopic Composition of Environmental Exchanges (DICEE) dataset, and field-collected soil and plant isotope ratios sampled at 13 NEON sites across the contiguous United States. These 13 sites encompassed a wide range of climates with mean elevations ranging from 46-m to 3490 m, mean annual temperatures from 0.3 to 20.9°C, and mean annual precipitation from 344 mm to 2224 mm. An isotope-based method was employed to partition ET, and the daily relative fractions of soil evaporation and plant transpiration in ET were estimated for 3 to 10 sample dates at each of the 13 sites.

Preliminary results suggest that transpiration dominates the evapotranspiration flux with mean T/ET fractions of 0.79±0.14, as inferred from $\delta^{18}O$ values, and 0.72±0.29 as inferred from $\delta^{2}H$ values. Among the five ecosystem types examined, forests tended to have the highest T/ET values with an average of 0.90±0.10, and shrublands had the lowest average T/ET, 0.68±0.15, with grasslands, woodlands and tundra falling somewhere in between. Key differences in mean T/ET fractions may be controlled by canopy closure and above ground biomass. This cross-site analysis is an important step forward in understanding ecosystem-specific controls in the terrestrial water balance.

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Estimating the temporal origin of root water uptake and drainage in Hydrus-1D

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The temporal origin of root water uptake (RWU) and drainage provides insights into the impact of natural and anthropogenic disturbances on plant resilience and aquifer vulnerability. Virtual tracer experiments help track water pathways across the soil-plant-atmosphere continuum (SPAC) originating from labelled irrigation/rainfall events and are used to assess the temporal origin of RWU and drainage and rainfall partitioning. Yet the implementation of virtual tracer experiments is not straightforward, and clear guidelines are still missing. A virtual tracer experiment was carried out in a potted olive tree and in a 150-cm-thick soil lysimeter by using an isotope-enabled module of Hydrus-1D. This isotope-enabled module assumes that the advection-dispersion equation governs the tracer transport in soils and allows tracers to leave the soil profile with evaporation (contrary to other types of solutes). Still, the tracer transport simulation is influenced by the hydrodynamic dispersion (either measured, calibrated, or commonly assumed as 1/10th of soil profile depth), and the transit time is not given directly as a model output. Indeed, the model simulations provide the tracer mass breakthrough curve at the target point and the user must fix a prescribed percentage of the tracer output flux to assess the arrival time. The estimated RWU and drainage transit times were compared to those derived from a particle tracking algorithm that simulates the particle trajectories subject to convective transport. The results from each daily event can be aggregated at any desired temporal resolution to investigate the effects of climate seasonality on water balance and timing. The temporal origin of water can be explored in other plots using the standard guidelines proposed in this study.

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Ecohydrological investigation of an alluvial plain vineyard in Precenicco (Italy)

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In recent summers, there has been an increase in torrid periods and droughts in the Mediterranean area due to climate changes, leading to a more common use of emergency irrigation in viticulture and reinforcing the need to achieve a more sustainable use of the water resources. In this context, by tracking water in the soil-plant-atmosphere continuum using $\delta^{18}O$ and $\delta^{2}H$ isotopic values and monitoring water potential in the soil and vines during the growing season, it is possible to understand the water dynamics in the soil, the depth of root water uptake, the water status of the vines, and in the end evaluate the water requirements of the vineyard to achieve a more rational irrigation.

In the Interreg Ita-Slo Acquavitis project, this ecohydrological method was applied on six vineyards between Italy and Slovenia. Here we present the results for a vineyard (*Vitis vinifera* L. cv. Glera) in Precenicco (Friuli-Venezia Giulia, NE Italy). The vineyard is located on the silty-clay alluvial deposits of the Low Tagliamento plain, an area characterized by the presence of multi-layered confined and artesian aquifer systems. Precipitations are abundant in autumn while summers are usually hot and dry (average annual precipitation: 900 ÷ 1000 mm/year).

Monthly precipitations were sampled from April 2020 to December 2021. The sampling campaigns for soil (down to 120 cm), xylem sap and water potentials were conducted in the summers of 2020 and 2021. Surface waters and groundwaters samples were collected from a ditch and some wells in the area. During the summer 2021 the vineyard was irrigated three times, and the irrigation water was sampled. The isotopic composition of the water samples was analyzed using an IRMS and a CRDS. The CRDS was also coupled with an induction module to extract and analyze soil water and to analyze xylem sap samples extracted in the field with a vacuum system.

The isotopic and water potential data suggest that during the summer of 2020 the vines root water uptake occurred mainly at the most superficial soil layers as in June they were almost saturated by the heavy rainfall. In August and September 2020, the topsoil appeared to have greater water availability than the deeper soil, due to the frequent, albeit scarcer, precipitation occurred in those months. In 2021, we observed a progressive negativization of soil water and xylem sap isotopic values due to the growing contribution of irrigation as a water source.

Leaf economics and plant water use are tightly coupled across Mediterranean woody species

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The leaf economics spectrum (LES) describes covariation in traits relevant to C and nutrient economics across plant species globally, but less is known about the relationship between the LES and water use in drylands where both water and nutrients constrain plant growth and survival. We characterized the LES in 62 woody plant species across 6 sites along a steep aridity gradient encompassing most of the climatic variation across the Mediterranean region. We measured 5 morphological and chemical traits (SLA, LDMC, leaf N, P, K), leaf $\delta^{13}C$ (time-integrated proxy of intrinsic water-use efficiency, WUEi) and leaf $\Delta^{18}O$ (proxy of stomatal conductance) in 501 individuals from 62 species. We also characterized soil water uptake depth using xylem and soil water stable isotopic composition (δ^2H, $\delta^{18}O$). In line with the LES, traits aligned along a first PCA axis explaining 54.2 % of the total variation across species and sites, with acquisitive species exhibiting high SLA and nutrient concentrations combined with low WUEi (profligate water use). Conversely, resource conservative species showed opposite traits (high LDMC and WUEi, low nutrient concentrations). We found strong associations between soil water uptake depth, leaf-level water use and the LES; species extracting water from shallower soil showed an acquisitive carbon and nutrient use strategy combined with profligate water use, and species extracting water from deeper soil layers exhibited more conservative traits and water use. Our data reveal a tight coordination between leaf-level carbon, water and nutrient-use strategies and soil water uptake depth across woody plant species in the Mediterranean.

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Hydrological Variability in Indian Forest Ecosystems: Investigating Drought Resilience, Recovery, and Water Use Efficiency in Moist and Dry Deciduous Forests

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This study investigates precipitation trends and drought dynamics in Moist Deciduous Forests (MDF) and Dry Deciduous Forests (DDF) over twenty years (2001-2020), with a focus on water use efficiency (WUE). Utilizing the Mann-Kendall test (MK-test), seasonal precipitation trends were analyzed, revealing nuanced patterns across forest types and seasons. The standardized precipitation index (SPI) approach was adopted to identify drought and non-drought/normal conditions. Additionally, MODIS-derived WUE dynamics were scrutinized during drought and non-drought periods to understand ecosystem responses to hydrological challenges. CHIRPS precipitation data was employed for seasonal Mann-Kendall (MK) tests, uncovering distinct trends and identification of drought and non-drought periods in MDF and DDF. The results indicate a decreasing trend in precipitation from January to May in MDF, while DDF shows no significant trend over the twenty years. The drought period (July-December of 2002) and (June-December of 2008) and the non-drought period (July-December of 2012) and (June-December of 2012) were identified for MDF and DDF, respectively. Analysis of WUE during these periods revealed resilient and resistant forest types. This study highlights the importance of understanding ecosystem responses to hydrological variability for informed forest management and conservation. The findings underline that MDF and DDF exhibit different responses to drought periods, reflecting their unique ecological attributes and environmental contexts. MDF demonstrates resilience to drought, with decreasing precipitation trends and sustained WUE during dry periods, while DDF displays resistance, characterized by reduced evapotranspiration rates and increased WUE. These empirical insights emphasize the need to comprehend diverse responses and adaptations within forest ecosystems to develop effective management and conservation strategies in the face of evolving climatic dynamics.

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Catchment hydrology, catchment-scale water residence time and travel times

Outcomes of four years of WATSON's Working Group 3 activities

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In this contribution, we will give an overview of the results of four years of exchanges and discussions between the members of WATSON's Working Group 3 on using isotopes of the water molecule to estimate transit time in catchments. The main outcomes are:

1. A technical guide on modelling approaches to estimate water residence time and travel time comprising a theoretical summary, recommendations, and best practices for using tracer-aided models in water resources management and case studies.
2. A brand new, specifically developed R-based script for input-output isotope modelling.
3. A beginner's guide to the R script.
4. A database of catchment scale (water) residence and travel times in Europe.
5. A review paper on the use of isotopes of the nitrate molecule in catchment hydrology.

The technical report aims to compare various approaches for calculating storage and transit times of tracers and water using tritium, deuterium and oxygen-18. It begins with (i) a short review of the theory behind isotope input-output modelling, then dives into (ii) model complexity including modelling double porous medium, multiple reservoirs as well as (iii) dealing with data availability and quality (for instance going from one or two tracers or how to model long time series), before finally (iv) presenting case studies of relevant hydrological environments to illustrate and clarify how estimation of storage or waiting times can be obtained, highlighting the similarities, differences, advantages, and limitations of each approach.

All analysis steps can be replicated by the readers using the accompanying R script and the exemplary datasets. A beginner's guide will serve as a quick introduction to help newcomers becoming familiar with input-output modelling with the R script. The R script integrates different computational methods in a single open-source environment and allows users to calibrate the models in a modular and flexible way. It includes different pre-and post-processing steps designed to make modelling as intuitive and straightforward as possible. All options are summarized in the appendix of the technical report.

A European-wide database has been compiled, listing out scientific publications and data sets on catchment scale transit times using isotopes from the last forty years. This database can serve as a valuable reference for future work and will be presented briefly.

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Finally, the review paper on the isotopes of the nitrate molecule will broaden the scope of the activities of WG3 to include water quality issues that can be approached with isotope hydrology tools.

In search for old water stores

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The old water stores in catchments keep our rivers flowing through prolonged droughts. We need to understand these old water stores, particularly during times of climate change, with unseen drought events predicted, to forecast when rivers will cease flow. Using tritium, we showed previously that catchments in volcanic formations release their water with mean transit times (MTTs) of decades, and up to >100 years (Morgenstern et al., 2015). Further, MTTs change throughout the seasons, with younger water in streams during the wet season (e.g., Morgenstern et al., 2010).

Tritium data from the Wairau River, Marlborough, New Zealand, with a basement rock dominated catchment, indicate 50% of baseflow has a MTT of 8 years (Taylor et al., 1992). The other 50% is younger water. The groundwater storage to provide such long transit times was attributed to large deposits of scree and alluvium infilling U-shaped glacial valleys in the headwater areas of the Upper Wairau catchment.

We have now collected samples during low baseflow conditions from these scree discharges in the Upper Wairau and Rainbow valleys. However, we did not find dominance of old water with MTT = 8 years. The old water storage must therefore be attributed to either, the deep groundwater flow system in the entire Wairau River catchment, or to specific geologic formations.

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Snowmelt stable water isotopes comparison and analysis: testing different meltwater samplers in high latitude.

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The role of snow meltwater in a given hydrological system is currently not well understood. Using stable water isotopes (SWI) in hydrology have revolutionized the way we think about water processes and systems, so one way to approach this issue is to use SWI to identify different water sources and to follow their movement in landscape. However, assigning the correct SWI signal for snowmelt is challenging due to a lack of data and difficulties in sampling. We have been sampling snow from two research sites in boreal and subarctic Finland through three stages (snowfall-snowpack-snowmelt). The snowfall (precipitation) and snowpack (accumulated snow) samples have all been sampled via simple setups and processes. However, the meltwater is much more challenging to sample, with no established best procedures existing. Since 2018 University of Oulu have been sampling snowmelt via snow lysimeters for method comparison we established the Passive Capillary Sampler (PCS) and a simple funnel setup (bulk sampling). The method comparison will be based on the 2023-2024 season data. Meltwaters were sampled daily or weekly depending on the general weather conditions and access to sites. All samples were analysed for their isotopic signature which results were used to look at signal spatial variation in snow melt, but also explore changes between different environmental conditions (forest, mire, hilly, flat) and the type of snow samples (snowfall, snowpack, snowmelt). Out of the three types of setups, the lysimeters seemed to work the best when looking at consistency of providing samples and the general volumes of water caught by the setup. The PCS setup was not a success, at least not in terms of daily-to-subdaily sampling. It is possible that the setup would work in a different environment.

The SWI samples are currently being analysed and compared between the different sampler types and stages of the snow season. The analysis of this data will tell us more about what to expect from different meltwater sampler setups and ideally how to optimize the instrument for best results. Next step is to: i) test the setups in different snow regimes (different snow and terrain conditions), ii) to analyse the SWI and iii) compare data between different snow regimes.

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Water to grow and water to flow:
Isotopic tracers of plant and stream water sources in the tropical Andes Mountains and Amazon Rainforest

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Tropical forests play outsized roles in global water and carbon cycles and house astounding biodiversity that is threatened by climate and land use change. Understanding the storage and flow of water through tropical forests will be critical to the sustainability of these global treasures. Yet these environments remain less well studied than temperate counterparts. Here, we report results of a multi-year study applying water isotopes to assess the sources of water used by trees and delivering flow to streams across seven small catchments in southern Peru that span the the transition from the Andes mountains (characterized by tropical montane cloud forest) to the Amazon floodplain (home to tropical rainforest). Across these catchments, isotope-derived young water fractions (Fyw) in streams, which range from 5-52%, appear to be controlled by a combination of hydroclimate (precipitation regime) and bedrock permeability. Mid-elevation sites have the highest Fyw, likely due to more frequent and intense rainfall, together with less permeable bedrock and poorly developed soils. Lowland soils have low Fyw due to very low flow path gradients despite low permeability. In the Andean mountain sites, Fyw values were found to be low and most streamflow was comprised of wet-season precipitation even during the dry season. In contrast, branch xylem waters changed seasonally, being comprised of wet-season precipitation during the wet season and dry-season precipitation during the dry season. Thus we see a divergence of ecosystem and catchment-scale hydrology : plant roots in this setting appear to use recent precipitation, while that same rainfall mixes and resides in soils, taking longer to transit into the stream. These results have important implications for the response of Andean cloud forest to changes in seasonality of precipitation. A natural next step in this research would be similar study of seasonal plant water uptake in the lowland Amazon rainforest, as we are still only just beginning to build the isotopic datasets needed to understand the connections between ecohydrology and catchment hydrology in this setting.

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Identifying soil water storage and water mobilization processes using stable water isotopes

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Subsurface stormflow (SSF) is an important runoff generation process in hillslope catchments. However, since the process occurs below ground and is invisible, it is difficult to observe and measure. A previous study conducted in winter of 2024 on the same plots as this research showed that 80% of the water that runs off through soils during SSF events is "pre-event water". Therefore, the water which was already stored in the slope before the rainfall event was remobilized by precipitation.

In order to better understand the different processes of water storage and mobilization in the subsurface, we installed an SSF trench in a first-order catchment in the Black Forest, Germany. We then conducted a large sprinkling experiment with deuterated water on the hillslope and monitored the SSF outflow for flow and isotopes. After the sprinkling experiment we tracked the deuterated water in the soil by taking soil water isotope profiles in consecutive time intervals.

During the experiment, SSF increased, but only 1/3 of the sprinkling volume was retrieved in the trench, suggesting storage of the water in the soil or deep percolation. Storage of water in the soil was confirmed by the soil water isotope profiles directly after irrigation, where deuterated water was detected in the top 20 cm. However, the trench outflow showed traces of deuterated water 2 hours after irrigation started, indicating that besides storage, preferential flow, bypassing the matrix, co-occurred. Ultimately, our goal is to compare these findings with sprinkling experiments carried out in three additional trenched research catchments, aiming for a broader understanding of the fundamental mechanisms generating subsurface stormflow.

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Tracing groundwater-surface water interactions in a volcanic maar lake using stable isotopes and radon-222

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Groundwater-surface water interactions are important in controlling lake water residence time, biogeochemistry, and water availability for downstream communities in tropical volcanic catchments. To better understand these complex seasonal interactions, a multi-tracer approach including water and inorganic carbon stable isotopes (δ^2H, $\delta^{18}O$, $\delta^{13}C_{DIC}$), hydrochemistry, and ^{222}Rn was applied in Lake Hule, northern Costa Rica. Seasonal isotope mass balance calculations using lake, stream, precipitation, and groundwater isotope compositions were supplemented with local hydrometeorological information. Evaporation to inflow ratios (*E/I*) revealed a small variability between the dry (December-April) and wet seasons (May-November), with relatively low evaporation losses, 2.9±1.0% and 3.2±1.8%, respectively. Bayesian end-member analysis indicated that annual inputs from groundwater, precipitation, and runoff represented 61.3±8.1%, 24.4±8.4%, and 14.3±5.9% of total inflow, respectively. Temporal variations of $\delta^{13}C_{DIC}$ also confirmed the key role carbonate buffering plays in this lake and indicated greater CO_2 degassing from groundwater sources in the wet season. This first tracer-aided assessment in a volcanic lake maar of northern Costa Rica provides evidence of previously unknown groundwater-surface water interactions and poses a promising tool for estimating seasonal variability of groundwater discharge into natural lakes across the volcanic front of Central America.

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CryoSCOPE: Investigating hydrologic partitioning in snowy regions

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CryoSCOPE, an EU-Horizon project set to commence in February 2025, will explore the interactions between atmospheric, cryospheric, and hydrologic systems across diverse landscapes, including the Swiss Alps, Finnish Lapland, Svalbard, and the Himalayas. Central to CryoSCOPE's mission is the investigation of hydrologic partitioning—how precipitation divides into streamflow, groundwater, and evapotranspiration—in snow dominated regions. Using stable water isotope measurements, evapotranspiration data from mobile flux towers, along with comprehensive hydrometeorological data, the project seeks to quantify these partitioning processes across seasonal and interannual timescales. This presentation will feature a case study from Davos, a Swiss alpine site, highlighting the observed seasonal trends in hydrological partitioning.

Building on the legacy of the WATSON COST Action, CryoSCOPE aims to expand stable water isotope data collection efforts in snow-dominated ecosystems. This expansion will significantly enhance our understanding of hydrologic processes in cold environments, fostering the development of more accurate predictive models and ensuring sustainable water management strategies in regions heavily influenced by snow and ice. Through these efforts, CryoSCOPE endeavours to provide vital insights into the dynamics of water movement and distribution in cold regions, ultimately contributing to hydrologic process understanding and informing policies for effective water resource management.

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Spatial variability in water isotope signature in three high elevation Alpine catchments

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In this work, we present a dataset of water stable isotopes collected in the framework of the SEHAG (SEnsitivity of High Alpine Geosystems to climate change since c. 1850) project between 2022 and 2024. The purpose of the isotope sampling campaigns is to investigate the spatial and temporal variability in the isotopic signature of different water sources (groundwater, river water, snow, rain and glacier melt) in three high-elevation Alpine catchments: Horlachtal (Austria), Kaunertal (Austria) and Martelltal (Italy). In particular, we are interested in comparing the spatial variability of the isotopic signature within and among the three catchments considering that they vary in terms of glacier covered area and elevation. Quantifying the variability of the isotopic signature within the river network can be beneficial to optimize the sampling locations and their number. Moreover, we can compare the spatial variability of the isotopic signature of the different water sources showing how the river network integrates and homogenizes different information. Finally, for the Martelltal catchment, in which we have the best data availability, we can use the isotopic data to develop a conceptual model of the hydrological functioning of the catchment and better understand how groundwater-surface water interaction occurs in high elevation Alpine river basins.

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Assessment of physiographic and hydrometric predictors of the fraction of young water in mesoscale Precambrian shield, Northeastern Ontario, Canada.

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Boreal water resources in the Canadian shield of Northeastern Ontario, Canada, are increasingly stressed by changing land use, population growth, and climate change. The region's water resources, already vulnerable to natural variability, are experiencing changes in seasonal water availability, and an increased frequency of extreme weather events. Understanding the dynamics of catchment water retention and discharge is crucial for effective water resource management. This study focuses on assessing physiographic and hydrometric predictors that influence the fraction of young water (F_{yw}) in mesoscale watersheds within this region, characterized by heterogeneous overburden thickness, bedrock outcrops, and extensive surface water storage in lakes and wetlands. Field measurements of isotopic composition in streams and precipitation, physiographic and hydrometric variables analysis, hydrological modeling, and statistical analyses were employed to quantify and interpret the relationships between predictors and the fraction of young water, providing insights into the hydrological processes specific to Precambrian shield environments. We assessed Fyw using 3 to 5 years of precipitation and streamflow isotope ($\delta^{18}O$) data from 11 catchments within the Sturgeon-Nipissing-French River basin, with drainage areas ranging from 27 km^2 to 6,919 km^2. Our findings indicate F_{yw} values between 18% and 51%, with no significant difference between unweighted and flow-weighted $\delta^{18}O$ values. There were positive correlations between F_{yw} and surface storage (wetlands), quick flow index, coefficient of variation, sparse treed, and low runoff potential soil percentage area covered. Conversely, negative correlations were observed with drainage area, mean elevation, mean slope, baseflow index, and coniferous tree cover. Hierarchal partitioning analysis highlighted that sparse treed, mean elevation, coefficient of variation, and baseflow index were important predictors for F_{yw} across this mesoscale catchment. The findings contribute to advancing understanding of water cycling dynamics in similar geological contexts and inform sustainable water management strategies in Northeastern Ontario and similar regions globally.

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Ecohydrological processes at multiple scales in a small forested catchment

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Forested catchments play a key role on storing and releasing fresh water. Climate changes affect global hydrological and ecosystem processes but have also effect at small scales. In this context, understanding forest ecohydrological processes is pivotal to maintain water balance, improve forest ecosystem services, and promote water and soil conservation strategies. Stable isotopes of hydrogen and oxygen in the water molecule are widely employed to investigation water origin and circulation and water sources for trees.

In this study, we collected hydrometeorological and isotopic data in the Re della Pietra experimental catchment (2 km^2) located in the Tuscan Apennines (Central Italy) to understand the origin of stream water at different spatial and temporal scales, and the sources of water taken up by the forest vegetation. Starting from April 2019, we have been collecting water samples for isotope analysis ($\delta^{18}O$, $\delta^{2}H$) from precipitation, throughfall, soil (0-20 cm, 20-40 cm, 40-60cm), springs, stream at different sections (4 locations from upstream to downstream), and beech trees. Weather parameters, soil moisture at two depths (15 cm and 35 cm), groundwater level, stream discharge and electrical conductivity, and throughfall amount were monitored in the Lecciona subcatchment (0.3 km^2).

Preliminary results reveal noticeable seasonal and spatial variations of stable isotopes and electrical conductivity in stream, springs, and soil water. The sources of water vapour, modeled by HYSPLIT Trajectory, for precipitation include the North Atlantic, the Mediterranean, France, Germany and northern Italy, but do not show a seasonal variation, being more dependent on individual rainfall events. The main water components in the main stream were precipitation (17%), water from springs (48%) and tributaries (32%), and soil water (3%). The largest tributary, Lecciona stream, consisted of precipitation (17%), soil water (5%), and spring water (78%). Beech trees mainly took up soil water from the upper 0-20 cm of the soil profile. This study contributes to research on forest hydrology in the Mediterranean region under climate change and provides a theoretical basis for the management of forest and water resources.

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A multi-tracer method to better constrain the discharge sensitivity of young water fraction

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The young water fraction has been recently introduced as a metric which quantifies, directly from the seasonal cycles of stable water isotopes, the portion of the catchment runoff younger than roughly 2-3 months. Accordingly, the average young water fraction over the time-window of isotope sampling can be evaluated as the ratio of the amplitudes of seasonal isotope cycles in streamwater and precipitation, respectively. However, past studies revealed that the young water fraction is not a stationary quantity since it varies according to different catchment wetness conditions (which are reflected in varying stream discharge, Q). In these studies, the rate of increase in young water fraction with rising Q has been defined as the discharge sensitivity of young water fraction (S^*_d). S^*_d can be estimated as a parameter of an exponential-type equation, that describes how the young water fraction varies with Q, by fitting a sine function directly on streamwater isotope data.

Nevertheless, in catchments with sparse isotope data, the S^*_d estimation could be highly uncertain. The insights derived from isotope data are contingent upon the timing of sample collection. Consequently, low sampling frequency leads to information gaps that could potentially be bridged by incorporating additional tracers collected at higher temporal resolutions. In this study, we introduce a novel approach designed to enhance the S^*_d estimation by increasing the temporal resolution of young water fraction estimates through coupling the information derived from both stable water isotopes and the electrical conductivity (EC), here considered as a proxy of streamwater age.

This method was tested in three small catchments in the Alptal valley, Switzerland, yielding promising results. However, we stress the necessity of acknowledging the limitations of EC as a tracer and the specific characteristics of the catchments under study for the appropriate application of this multi-tracer method.

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Using water isotopes to disentangle managed aquifer recharge in Polokwane city of the semi-arid Limpopo province, South Africa

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Managed aquifer recharge (MAR) schemes need to document the amount of artificially recharged water, and to secure proper quality and purification of the recharged water before its abstraction. In a MAR scheme near the city Polokwane, Limpopo province of South Africa, poorly treated waste water is discharged to a loosing stream, set in alluvial sediments and weathered fractured gneiss. Polokwane has a semi-arid climate. The GNIP precipitation record is dominated by the *amount effect* with enriched values and lowered *d*-excess in the mostly dry winters and lighter values with relatively higher *d*-excess in the warmer and more rain full summers. More than 90 percent of the city's drinking water is imported from dams far away from the catchment hosting the city, and less than 10 percent is groundwater abstracted locally along the stream; however, the local source implies a risk for drinking water contamination. Stable isotopes of water (^{18}O and ^{2}H) in precipitation, stream, ground-, pond, tap and waste water are used as tracers to disentangle the degree of waste water recycling in this MAR scheme and the quantitative effect of the important water on the local groundwater cycle. From the data so far collected, the signature of local groundwater is distinct from of groundwater from the immediately neighbouring, and apparently comparable, catchment. A scenario by which local groundwater has been displaced by the imported water is investigated. Imported water may be lost to groundwater by leaking drinking water pipes and sewers, or enter via streambed infiltration. Quantitatively, the amount of imported water during the past decades is comparable or greater than the under-the-city groundwater storage.

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Connectivity between overland flow and topsoil interflow: insights from tracer experiments during artificial rainfall

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Near-surface flow pathways can quickly transport water and solutes from hillslopes to the stream network. To improve our understanding of these flow pathways, particularly their connectivity, we conducted artificial rainfall simulation experiments on two large (>80 m^2) trenched runoff plots in a small headwater catchment underlain by Gleysols in the Swiss pre-Alps. One plot is located in a natural clearing in an open mixed forest and the other in a wet pasture.

We applied streamwater to the surface of the plots using sprinklers and applied tracers after overland flow and topsoil interflow had reached steady state. Deuterium-enriched water was applied to the surface of the plots via the sprinklers. Uranine and NaCl were applied to the surface as line tracers at various distances from the trench and NaBr was injected into the subsurface (at ~20 cm depth). Samples of overland flow and topsoil interflow were collected for several hours after tracer application.

Breakthrough curves for both plots highlighted the rapid transport of water and solutes, as well as the high interaction between overland flow and topsoil interflow. For instance, NaBr could be observed in overland flow and breakthrough curves of Uranine and NaCl showed minimal time differences for overland flow and topsoil interflow. Particle velocities of overland flow and topsoil interflow were high for both plots, and particularly in the clearing of the open forest, indicating the importance of preferential flow pathways. Our results highlight the high connectivity between overland flow and topsoil interflow, and the critical role of macropores and soil pipes in rapidly transporting water and solutes down the hillslopes.

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Understanding Hydrologic Pathways in High Elevation Mountain Systems: A Study from the Central Himalayas

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Mountains act as vital players in the global water cycle and as important sources of freshwater supplying river systems worldwide. Yet understanding of hydrological processes in mountainous terrain is still incomplete, even to the extent that the transit times of water through steep mountainous catchments are not well described. As a result, it remains difficult to predict how mountainous water supplies will respond to changing climate and to assess how steep topography associated with orogenesis regulates global water and geochemical cycles. To address this gap, high-frequency water sampling was conducted over a year-long period throughout the Melamchi Khola Valley, located in the central Himalayas of Nepal. This site serves as a naturally occurring experimental watershed; despite the relatively consistent lithology, there is a marked increase in landslide density, exhumation rates, steepness, and erosion from south to north. Stable water isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) of precipitation and streamwater samples were measured within sub-catchments along this gradient. Results show strong seasonal variations in meteoric samples reflective of the monsoonal climate regime. This precipitation signal was visible to a lesser degree in the streamwater samples, with dampening characteristic of catchment systems globally. Preliminary results suggest this dampening increased in the steeper, higher relief catchments. Based on data collected to date, calculations of catchment-based young water fractions (F_{yw}) preliminarily point to a shift towards groundwater-sourced discharge in the more active northern region of the watershed, suggesting deeper, lengthier, and more tortuous subsurface flow paths caused by greater relief, exhumation, and fracturing. This work is ongoing, and offers a direct look at the intersection of tectonics, rock properties, topography, hydrology, and geochemistry, and indirectly will provide insight into carbon fluxes, climate change, hazard management, and water availability in not only the Himalayas but other high elevation mountain systems.

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