Abstract

Since 1970, the use of isotope tracers in hydrology and ecohydrology allowed a groundbreaking revolution in understanding the age, the origin, and pathways of water in natural ecosystems. These conservative tracers are natural constituent of water molecules that enter the hydrological cycle with precipitation. The isotopic composition of precipitation reveals a seasonal cycle which is also observed for the isotopic composition of streamwater, soil water and xylem water. The relationship between output and input cycles reflects, depending on the scale, the filtering effect of the water storage, the influence of plant water uptake and the complex flow path distribution within the system under study. Therefore, these natural tracers can provide key information on ecosystems functioning at both different spatial and time scales.

The fraction of runoff younger than roughly 2-3 months, known as young water fraction, can be estimated from the ratio of seasonal cycles amplitude in streamwater and precipitation, respectively. High and steep mountain catchments surprisingly revealed low young water fractions: this is a counterintuitive result since the presence of the exposed bedrock and steep landscapes are expected to promote high water velocity. Accordingly, the hydrological processes hidden behind this result remain basically unclear. In this regard, by using data of 27 study catchments located in both Switzerland and Italy, we investigate the relevance of snowpack persistence, low-flow duration, catchment storage and Quaternary deposits with varying mean catchment elevation to explain young water fraction variations. The results of this analysis have been summarized in a *regional-scale* perceptual model that gives an account of the relevant hydrological processes, mainly related to snow, leading to this unexpected result.

Isotope seasonal cycles of streamwater and precipitation allow to estimate the average young water fraction over the period of isotope sampling in a catchment. However, the time-varying catchment wetness conditions lead to a higher/lower

degree of flow paths connectivity in a catchment which reduces/increases the runoff transit times. Indeed, the young water fraction resulted to be a no stationary quantity and its variations over time can provide useful insights on relevant hydrological processes occurring at the *catchment-scale*. Thus, by coupling the easy-to-measure streamwater electrical conductivity with stable water isotopes, we develop a novel method for estimating the young water fraction at high (daily) resolution. The method has been tested in three small Swiss catchments (a sub-set of watersheds used to develop the regional-scale perceptual model) returning promising results which suggest snow-related hydrological processes in agreement with our regional-scale perceptual model.

Another research question using soil and xylem water isotope content is: "What is the seasonal origin of water that supplies plants and streams?". By simulating one-dimensional water flow and solute transport with HYDRUS-1D in a soil profile (*plot-scale*) of a grassland located in the Aosta Valley at 2555 m a.s.l. (in a catchment among those used to develop the perceptual model), our results suggest a seasonal compartmentalization of water: summer rainfall supplies transpiration fluxes while winter water (i.e., snowmelt) supplies groundwater recharge that largely contributes to streamflow. The key role of snowmelt in recharging groundwater in snow-dominated environments has been largely documented in the past and it is a key process we identified in our regional-scale perceptual model. Interestingly, we observe a change in hydrological functioning during the 2022 drought where more snowmelt supplied plants transpiration with a consequent low groundwater recharge.

This work improved the scarce knowledge of how water is stored and released in alpine ecosystems, highlighting a consistency of hydrological processes, mainly related to snow, across different spatial and time scales. The progress in understanding the hydrological processes taking place in these remote environments is crucial for flood forecasting, pollutant contamination assessment, and water resources management under the current climate change scenario.