Hydrological dynamics of snowmelt induced streamflow in a high mountain catchment of the Pyrenees under contrasted snow accumulation and duration years

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Abstract

Snowmelt drives a large portion of streamflow in many mountain areas of the world. However, the water pathways since snow melts until water reaches the streams, and its associated transit time is still largely unknown. Such processes are important for drawing conclusions about the hydrological role of the upstream snowpack after melting. This work analyzes for first time the influence of snowmelt on spring streamflow in years of different snow accumulation and duration, in an alpine catchment of the central Spanish Pyrenees. A multi-approach research was performed, by combining the analysis of climatic, snow, streamflow, piezometric levels, water temperature, electrical conductivity and isotopic ($\delta\ ^{18}O$) data. Results show that snow played a preeminent role on the hydrological response of the catchment during spring. Liquid precipitation during the melting period also determined the shape of the spring hydrographs. When snow cover disappeared from the catchment, soil water storage and streamflow showed a sharp decline. Consequently, streamflow electrical conductivity, temperature and $\delta\ ^{18}O$ showed a marked tipping point towards higher values. The fast hydrological response of the catchment to snow and meteorological fluctuations, as well as the marked diel fluctuations of streamflow $\delta\ ^{18}O$ during the melting period, strongly suggests soil storage was small, leading to short meltwater transit times. As a consequence of this hydrological behavior, independently of the amount of snow accumulated and of melting date, summer streamflow remained always low, with small runoff peaks driven by rainfall events. The expected reduction of snow accumulation and duration in the area in a next future will bring an earlier snowmelt and rise of stream water temperature. However, given the low storage capacity of the catchment and the contribution of rainfall events to spring runoff, the annual water balance and the runoff seasonality of the catchment would not change drastically.

1. INTRODUCTION

Snowmelt plays a critical role on streamflow generation in cold-regions mountain headwaters (Barnhart et al., 2016; Li et al., 2017) and provides large amounts of water for ecosystems and human uses in their surrounding lowlands (Viviroli *et al.* , 2020). During the last years, intense research has been conducted in order to improve observational and modelling capabilities, and to better understand the physical mechanisms that connects the snow dynamics and the streamflow generation (Gordon et al., 2022). One of the most challenging aspects of this research topic is to determine the timing and routing from the snowmelt onset into the river flow (Ceperley et al., 2020). Routing may involve processes such as water percolation through the snowpack, the portion of snowmelt that quickly reach the streams as surface runoff, and water that infiltrates to aquifers or circulates as subsurface flow (Carroll et al., 2019). The difficulty to analyze such routing dynamics relies partly on the complexity of maintaining hydrological and hydrometrics measurements in snow dominated areas (Ala-aho et al., 2017).

Depending on the dominant hydrological processes, the transit time of melted snow to reach the stream at each catchment will vary and consequently will strongly determine its vulnerability to drought periods and climate change scenarios (Jeelani et al., 2017; Taylor et al., 2013). Some studies suggest that snowmelt dominated catchments show higher runoff coefficients than ephemeral snowpack and rain dominated catchments (Barnhart et al., 2016; Berghuijs et al., 2014; Li et al., 2017; Lone et al., 2023). However, other studies have not found any strong relationship between changes in the snowpack duration and magnitude of the annual runoff (López-Moreno et al., 2020). The transit time of snowmelt water in a catchment determines to which extent the accumulated snowpack during the precedent winter(s) and spring season(s) will affect the streamflow during summer time. Some studies have identified a clear role of the antecedent snowpack to explain anomalies in summer streamflow (Carroll et al., 2019; Godsey et al., 2014; Rebetez & Reinhard, 2008). For example, summer low flows in Czechia are driven by seasonal precipitation and evapotranspiration but also by previous winter snowpack dynamics (Jenicek and Ledvinka, 2020). On the opposite, the analysis of 380 Swiss catchments revealed that snow water equivalent and winter precipitation plays a minor role in the magnitude and timing of the warm season low flows (Floriancic et al., 2020).

The comparison between streamflow diel cycles and snow depletion time series also provides useful information about the snowmelt contribution to the total streamflow and their transit time (Holko et al., 2021; Jin et al., 2012; Kirchner et al., 2020; López-Moreno et al., 2023; Miller et al., 2020). During the melting season, rain provides a large streamflow contribution, and the meltwater contribution is often difficult to infer. Stable water isotopes (generally δ^2H and $\delta^{18}O$) have resulted extremely useful to better understand the contribution of snowmelt to streamflow and the residence time of melting water in the catchments (Leuthold et al., 2021; McGill et al., 2021; Penna et al., 2017), thanks to the more depleted values of snow isotopy compared to streamflow (McGill et al., 2021; Vystavna et al., 2021). However, a full separation of the contribution of each component is difficult to obtain, since it requires a very intense spatially and temporally isotopic sampling of each component. Further, at the catchment scale there is still a high spatial, as well as temporal (inter- and intra-annual) variability of the isotopic signal of the snowpack, precipitation (liquid and solid) and streamflow water (Wenninger et al., 2011). For this reason, the available literature often uses the water isotopy evolution to perform qualitative rather than quantitative analyses, in combination with other source of data such as water characteristics (i.e., water temperature or electrical conductivity, geochemistry) and piezometric levels (Woelber et al., 2018).

In line with this, we analyzed the streamflow response of a snow dominated basin in the central Spanish Pyrenees, in combination with water table data, streamflow and precipitation isotopy, and additional information of water temperature and electrical conductivity. The general objective was to better understand the hydrological dynamics induced by snowmelt in this experimental catchment (Izas catchment), which is representative of large subalpine sectors in the Pyrenees. The results of this study are important to better predict the future hydrological response of similar catchments in the Pyrenees when snow duration and accumulation will decrease as a consequence of temperature scenarios for the next decades (López-Moreno et al., 2013, 2017). The specific objectives of this work were:

1. To improve the knowledge on the time in which snowmelt is converted into runoff.
2. To determine the possible influence of the cumulative winter snowpack on the observed hydrological behavior during spring and early summer.
3. To assess the extent to which the annual hydrologic balance and hydrograph might change in a likely future with less snow.

2. STUDY AREA

The Izas Research Experimental Catchment (42º44´N, 0º25´W) is located in the headwaters of the Gállego River in the central Spanish Pyrenees (Figure 1). The catchment has an area of 0.33 km^2 with altitudes ranging from 2075 m a.s.l. (gauging station) to 2325 m a.s.l. Landcover is dominated by subalpine meadows with some rocky outcrops. Slopes are gentle all over the catchment (mean slope [?] 16o) (Lopez-Moreno et al., 2013). Grasslands are mostly composed by *Festuca eskia, Nardus estricta, Trifolium alpinum, Plantago alpine and Carex sempervirens* (Revuelto et al., 2017). Soils are generally well developed presenting an approximate depth of 1 meter, with some areas accumulating deeper soils where some ephemeral springs are active during spring and early summer. Saturated soils during the melting period produce numerous solifluidal forms such as active lobes and terracets (Garcia-Ruiz et al., 2021).

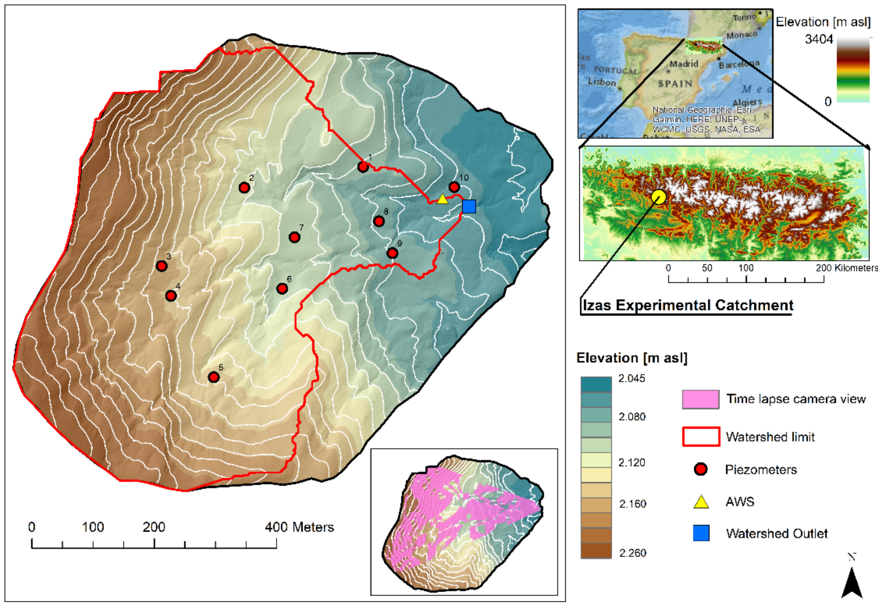

FIGURE 1. Izas catchment and the location of the automatic weather stations (yellow triangle) and gauging stations (blue square) and piezometers (red circles). Red line outlines the drainage area of the gauging station. Pink areas in the small map indicates the surface covered by the time lapse camera.

Snow covers most of the catchment for long periods, with the onset of snow cover being generally observed along November and melting starting in April or early May. Snow cover depletion is normally completed by the end of May or early June, even if snow patches occasionally last until late June. Snow depth shows a large interannual variability and also strong spatial variability, the later mostly driven by a combination of wind transport and the influence of elevation and topography on shortwave radiation (Revuelto et al., 2014). More than half of the annual precipitation (2000 mm yr^{-1}) falls as snow (Anderton et al., 2004). The catchment benefits from a transitional climate from Atlantic to Mediterranean, where winter and spring are the most humid seasons while summer is the driest, when precipitation is mostly the result of convective thunderstorms (del Barrio et al., 1997). Annual mean temperature is +3ºC, with mean daily temperature below 0ºC for an average of 130 days per year (Revuelto et al., 2017).

3. DATA AND METHODS

Table 1 shows the different measurements collected during the period between water years 2017 and 2020 and used in this study to assess the hydrological response of the Izas catchment during the melting period and the subsequent weeks. The data gaps correspond to sensor failures or changes of the measurement technology.

3.1 Meteorological and snow data

We used temperature, precipitation (Geonor T-200B with wind shield) and snow depth (ultrasonic sensor) data from the automatic weather station located in the catchment (Revuelto et al., 2017). Data were recorded at 10 minutes interval and were aggregated into daily values. Time series from 1st April to 1st July were extracted to characterize the main melting period of the catchment.

TABLE 1. Data available for this study for the temporal period analyzed. Water year spans from October to September.

Measured variables	WY17	WY18	WY19	WY20	Analysed period
Precipitation and air temperature	X	X	X	X	April-June
Snow depth (Terrestrial Laser Scan)	X	X			Scan in closest date to ma
Snow depth (Unmanned Aerial Vehicle)			X	X	Flight in closest date to m
Snow cover (daily photos)	X	X	X	X	April-June
Piezometric levels			X	X	April-May
Streamflow	X		X	X	April-June
Streamwater temperature	X	X	X	X	April-June
Streamwater electrical conductivity			X	X	April-June
Streamwater and precipitation isotopy (water sampler)	X	X	X		15^{th} May-31^{st} July
Streamwater isotopy (distributed sampling locations)	X	X	X	X	15th May-31st July

Daily information of snow cover area was retrieved from a digital camera (Campbell CC640 digital camera) with a resolution of 640 × 480 pixels that allows to cover around 90% of the catchment (Figure 1). Daily photos were orthorectified and binarized into snow cover maps (presence/absence of snow). Data affected by low clouds were not included in the analysis. The daily photos were used to create series summarizing the snow cover area that authors consider fully representative of the conditions over the entire catchment (Revuelto et al., 2020). In addition, periodic field surveys were performed to derive distributed information on snow depth. In 2017 and 2018, snow maps were made using a terrestrial laser scanner (TLS) at dates close to the maximum snow accumulation (Revuelto et al., 2014). Normally, snow depth maps of the catchment were made by merging point clouds from two different scan positions (Figure 1). However, due to the harsh meteorological conditions of the 2018 snow season, we only obtained information from one scan position for this year. Therefore, the 2018 snow depth map presents large areas affected by topographic shadows. In 2019 and 2020, snow depth maps were created by photogrammetry based on Structure from Motion (SfM) algorithms with photos retrieved from a fix wing unmanned aerial vehicle (Ebee+) following the methodology presented by Revuelto *et al.* (2021). Meteorological and snow information were used to characterize the meteorological conditions and the magnitude and persistence of snow in the catchment during spring over the 2017-2020 period.

3.2 Hydrological data and water sampling for isotopic analyses

Water level was measured every 5 minutes at the gauging station (V-shape weir), using a CT2X Seametrics probe (Seametrics, USA). Water level data were corrected from barometric pressure fluctuations using the software Aqua4plus 2.2 and converted into runoff (l s^{-1}). The water level information for 2018 was missing due to a sensor malfunctioning. Water temperature and temperature-corrected electrical conductivity were also measured with the same probe. Electrical conductivity data were only available in 2019 and 2020 years when a proper calibration provided reliable values.

Nine piezometers were drilled at different locations within the catchment (see Figure 1) to monitor the fluctuations of the water table levels with LevelScout sensors (*https://www.seametrics.com/product/levelscout/*) that were also corrected from barometric pressure fluctuations. In this study, we focused on water table data from 1st April to 1st July to assess water table dynamics from before the onset of the main melting period until some weeks after snow has completely melted in the catchment.

An ISCO 3700 automatic water sampler (*https://www.teledyneisco.com/en-us/water-and-wastewater/3700-sampler*) was used to sample streamwater at the gauging station twice daily in 2017, 2018 and 2019. The sampler malfunctioned in 2020 and also caused data gaps in 2019. The sampler was programmed at 6 AM and at 6 PM in order to capture the diel cycle from inexistent or very low snowmelt conditions (6 AM), and to very high input from snowmelt (6PM). After early July, when melting did not drive daily runoff cycles, the sampler only collected one sample per day (12 AM). Water sampler had storage capacity of 24 bottles, making necessary to collect water samples every 12 days. During the days we collected ISCO samples, 11 water samples from different streams and springs across the basin were also collected following a fixed itinerary that started at 12 AM, aiming to reduce the impact of daily cycles in water isotopy. At the same time, we also collected bulk precipitation fallen between two sampling days using a water collector designed to prevent evaporation (Gröning et al., 2012). For all samples, 15 ml of water were conserved in narrow neck propylene tubes and stored in an isothermal bag with cold ice packs to avoid evaporation during the 4 hours of transport to the laboratory facilities. In the laboratory, the water tubes were kept in a fridge at +6^{o}C. A Picarro L2130-i isotope analyzer was used to measure δ^{18}O isotopes in streamwater and precipitation samples. The isotopic values were determined from the eight replicates of the same sample to minimize sample carryover effects (Penna et al., 2012). A total of 553 samples of streamflow and 19 for precipitation were analyzed for this study.

4. RESULTS

4.1 Meteorological and snow conditions

The four analyzed spring seasons (April-June) exhibited strong contrasts in terms of meteorological (temperature, precipitation) and snow conditions (snow depth and snow covered area) (Figure 2). April 2017 started with more than one meter of snow depth at the ultrasonic sensor of the AWS, but it melted fast in the subsequent weeks. In early May a significant portion of the catchment (40%) was snow free and with very few spots where snowpack exceeded 2 m (Figure 3). During May, no major snow events occurred and the basin was almost free of snow by 1st June. Two heavy precipitation events, mostly as rain, where observed in early and mid-May. Spring 2018 was the snowiest year. By early May, almost 1.5 m of snow depth was measured in the AWS, and by mid-May, 100% of the catchment was still covered by snow, with large areas covered by more than 3 m of snow.

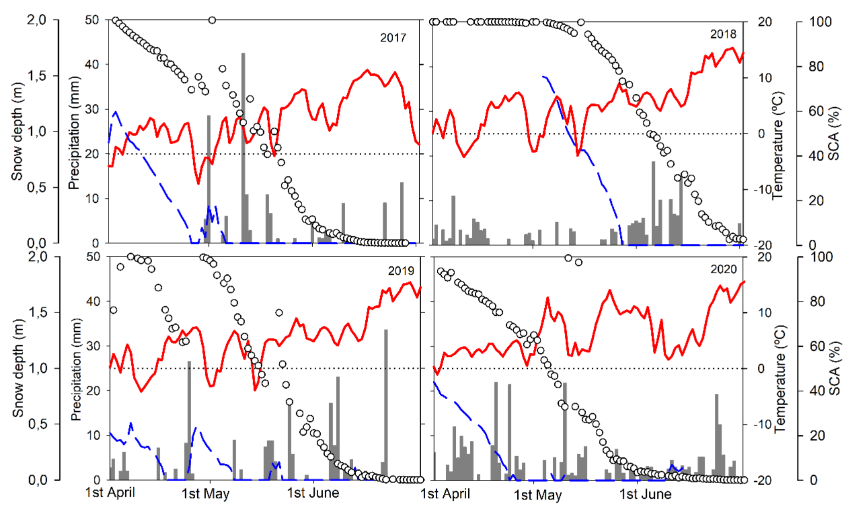

FIGURE 2. Daily values of mean temperature (red line), precipitation (grey bars?) and snow depth (blue line) measured at the in Izas catchment automatic meteorological station during the period April 1st to July 1st (2017 to 2020). Dots shows of the snow covered area (SCA in % of the area covered by the camera) obtained from time lapse photography.

Despite the occurrence of many rainy days in late May and June, a significant snow cover lasted until mid-June and snow remnants lasted until early July. In spring 2019, snow was also relatively abundant compared to 2017 and 2020. The intense snow melting recorded in April, caused the snow depletion and 40% of the catchment was free of snow by early May when new snowfalls covered again the whole catchment, exceeding 2 m of snow in some locations. May was dominated by intense melt, interrupted by new snowfall events at the end of the month. June started with a 50% of the catchment covered by snow which mostly disappeared in the next two weeks. In spring 2020 a relatively regular and continuous but not very intense melt was observed in April. At the beginning of May 80% of the catchment was covered by snow, but with a shallower snowpack than the two precedent seasons. May and the first days of June where particularly warm, driving a fast melt. Melting was interrupted by an ephemeral snowfall event in mid-May.

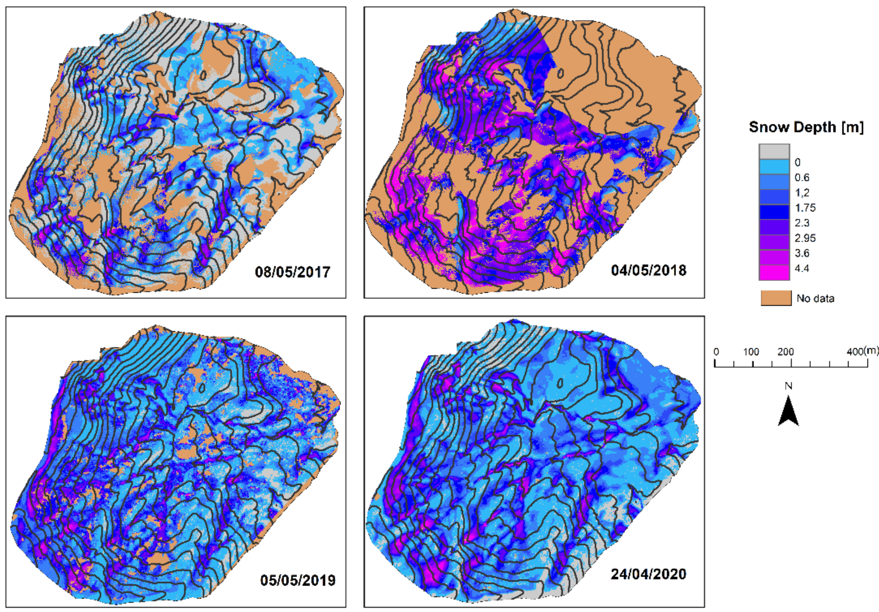

FIGURE 3. Snow depth for different dates with available data closer to the annual maximum snow accumulation. Snow depth records are acquired by using a TLS (2017 and 2018) and a UAV (2019 and 2020).

4.2 Hydrological response

The comparison between the hydrological (streamflow, water temperature and electrical conductivity of the stream water, Figure 4) and the snow and meteorological conditions (Figures 2 and 3, and the Supplementary Figures 1 to 4 for an easier comparison) reveal that the spring streamflow was determined by a mixed influence of snowmelt and precipitation (mostly as rain) events. In 2017 and 2019 a double streamflow peak was observed, caused by 2 melting periods in April and May, interrupted by a period of low flows due to low temperatures and snowfall events. The highest spring streamflow peak recorded during the whole studied period occurred in 2017, triggered by the fast melting of a shallow snowpack related to a heavy rain on snow event (Figures 2 and 3). The streamflow in 2020 also showed two small peaks, in response to a mix of melt and frequent precipitation events in late April and mid-May, interrupted by a period of low temperatures. The three years analyzed show that the streamflow evolution in late May and June was mostly determined by the persistence and the melting of snow cover in the catchment during these months. Thus, the streamflow in 2019 remained in late May and June higher than in 2017 and 2020, due to the longer persistence of the snow cover in 2019. In 2017 and 2020, runoff already decreased markedly by the end of May. However, the streamflow in 2017 continued decreasing along June due to limited rain events, whereas in June 2020 the streamflow increased again and showed a fluctuating behavior in accordance to the frequent rain events. The three years analysis suggest that the streamflow is controlled by rain events after mid-June, independently of the snowpack accumulation and its duration in spring.

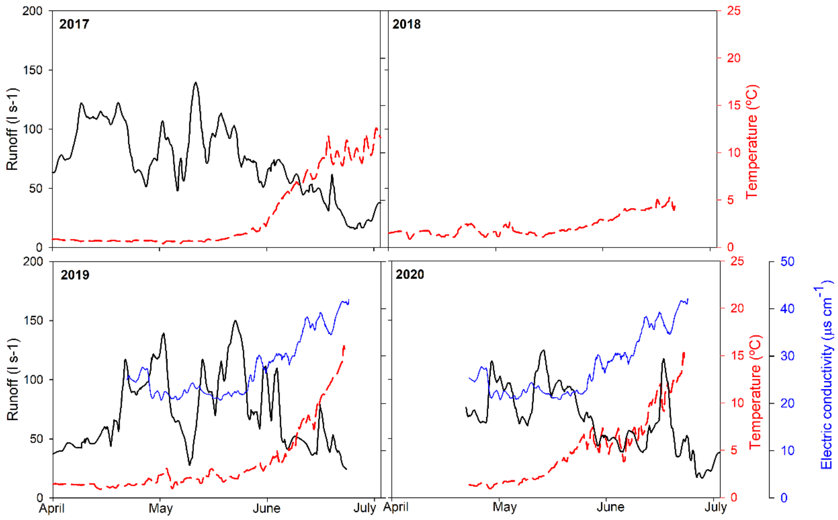

FIGURE 4. Daily values of mean discharge (black line), streamwater temperature (red line) and electrical conductivity (blue line) during the period April 1st to July 1st at the Izas gauging station.

Water temperature also allowed to assess the relevance of snow melting in streamflow generation. Water was noticeably cold (normally < 3º C, interrupted by some rainfall events and very warm days), and ruled by the snowmelt dynamics during the period encompassing mid-May to mid-June. Only when the snow cover area was less than approximately 10%, did water temperature increase quickly until reaching 15-20ºC by the end of June. This was not the case in June 2018, when the deep and longest-lasting snowpack limited the temperature increase of streamflow water even in late June.

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FIGURE 5. Time series of mean daily depth to water table (2019 red line and 2020 blue line) observed at 9 locations during the period April 1st to July 1st in the Izas catchment. Red (2019) and blue (2020) dots show the mean snow depth measured with a UAV around (10 m^2) each location.

During 2019 and 2020, electrical conductivity and temperature of the streamflow water showed a very similar temporal evolution. In both cases, a regular increase associated to the melting of snow cover was detected around the snow depletion date. Comparison between 2019 and 2020 years reveals that the shallower and shorter snowpack during 2020, triggered an earlier and faster increase in conductivity during the melting period.

In combination with streamflow data, the depth of the water table (and local snow depth) observed at 9 locations in the catchment (2019 and 2020) yield some additional information about the snowmelt influence on the dynamics of spring streamflow in the Izas catchment (Figure 5). The depth of the water table showed contrasted responses between piezometers. However, several common dynamics may be observed. Before the start of the main melting season (April and May), the water table was low (i.e. deeper than 0.6-0.9 m) at all location. However, when melt starts rapid water table fluctuations are observed in most locations, leading to several short periods close to saturation. Water table reaching the surface only was observed for short periods during the main melting events. Overall, the 2019 year showed shallower water table, associated to a deeper and longer-lasting snowpack than in 2020. In 2020, the water table dropped significantly in most of the piezometers, by the end of May, when snow cover was almost depleted in the catchment. At the contrary, in 2019, during the same period, water table was still close to the surface in several piezometers coinciding with a much larger snow-covered area in the catchment (Figure 2). Despite this general pattern, higher water levels were observed in some piezometers that had greater snow depth in their surroundings in- 2020 than in 2019.

4.3 Streamflow and precipitation water isotopy

Average daily streamflow $\delta^{18}O$ values measured at the gauging station (Figure 6) remained low and relatively constant during the snow cover periods. They increased noticeably after the snow cover depletion date (during early, late and mid-June in 2017, 2018 and 2019, respectively).

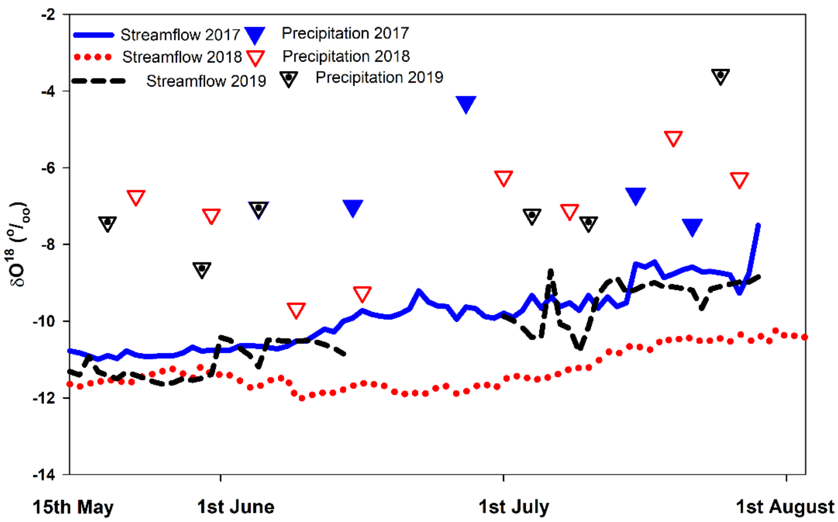

FIGURE 6. Precipitation $\delta^{18}O$ (average of the 12 antecedent days; triangles) and streamflow $\delta^{18}O$ (average of the morning and evening samples) measured at the Izas gauging station (lines).

During the period April-June, the streamflow $\delta^{18}O$ values were noticeably more depleted (ranging from -8 to -12 precipitation (mostly in liquid phase) $\delta^{18}O$ values (ranging from -4 to -10 and -8relatively steady, with slight day-to-day changes. The three years analyzed showed some interannual differences in streamflow $\delta^{18}O$ values, likely driven by the snowpack magnitude and duration. The lowest streamflow $\delta^{18}O$ values were observed in 2018 (a snow rich year). On the contrary, higher values were found in 2019 and 2020 (low and very low snowpack years, respectively). The differences in streamflow $\delta^{18}O$ values remained even weeks after snow cover was completely depleted from the catchment.

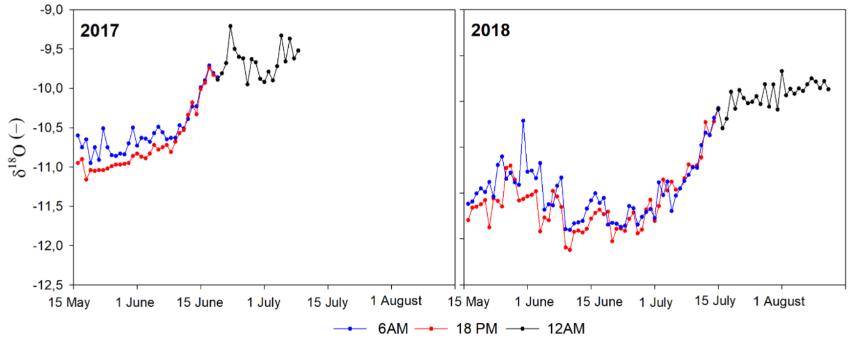

FIGURE 7. Daily streamflow $\delta^{18}O$ values measured at 6 AM, and 6 PM at the Izas gauging station during the years 2017 and 2018. $\delta^{18}O$ values measured once a day (12 AM) during the snow free period later in the season are also shown

Comparison between morning and evening streamflow samples (6 AM and 6 PM, respectively) shows higher $\delta^{18}O$ values in the latter, coinciding with a major influence of snow melting in the evening sample (Figure 7). This pattern occurred in the large majority of the days, regardless of rainfall events. The observed daily cycle disappears when snow cover depletes from the catchment (early and end June, for 2017 and 2018, respectively).

$\delta^{18}O$ values from water samples taken weekly across the catchment (Figure 8) showed a parallel evolution to those measured at the gauging station. The lowest and less variable $\delta^{18}O$ values were recorded when the catchment was snow covered. $\delta^{18}O$ values progressively increase during the snow free period (July), showing also a higher variability between locations towards the end of the snow season.

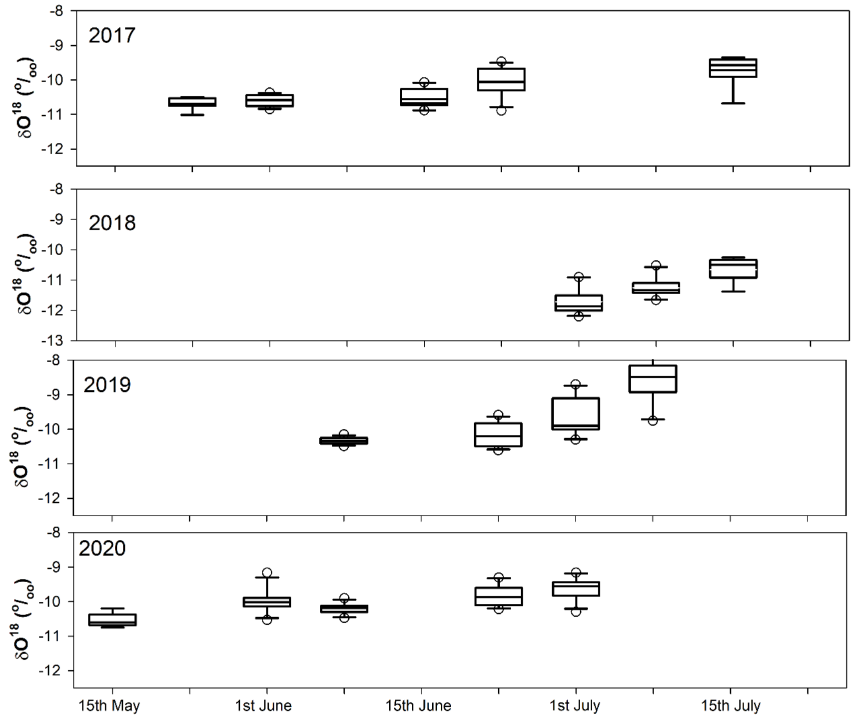

FIGURE 8. Variability of $\delta^{18}O$ values between 11 sampling points in ravines and springs sampled weekly across Izas catchment during the spring seasons (2017 to 2012020). The central line is the median, whereas the boxes and the whiskers inform about the 25th-75th and 10th-90th percentiles. The dots represent outliers.

5. DISCUSSION

This work combines several data sources, including snow measurements, meteorological information as well as hydrological records in order to better understand the hydrological response of the Izas catchment during the snow melting period. Results show that meltwater is the driver of the main soil water fluctuations and streamflow during the melting period, which is in accordance with results found in other cold mountain sectors (Barnhart et al., 2016; M. Feng et al., 2022; Schreiner-McGraw & Ajami, 2022). Liquid precipitation enhances the streamflow peaks controlled by melt, and keep the peak flows high once snow cover is almost depleted over the catchment (Gordon et al., 2022). This suggests that monitoring winter and early spring snow conditions is useful to better anticipate the spring water availability. Also, results provide evidence that liquid precipitation in spring can highly counterbalance snow poor years, since streamflow levels during rainy springs are comparable to snow abundant years. The importance of liquid precipitation for the spring hydrological response of snow-dominated catchments was also highlighted for alpine sites in the Dolomites (Penna et al., 2016).

The measurement of piezometric levels during spring in 2019 and 2020 revealed that the storage of infiltrated water from snowmelt in the catchment is very variable among different points of the basin. Meltwater infiltration is probably controlled by the soil types and the terrain slope (Woelber et al., 2018). In most cases, the water levels fluctuations are very fast. Water level increases when melting starts, even if the entire catchment is still snow covered. Saturation conditions (when water table reaches the surface) only happens during short periods. Saturation is often associated to the snow depletion period at each specific point. Afterwards, water levels decline considerably, and saturation conditions are not reached even in periods of heavy rain. Therefore, results suggest that under rainy conditions, the overland flow controls the hydrological response in the catchment.

The snow depletion triggers an increase in the water temperature, electrical conductivity and $\delta^{18}O$ values. Further, the piezometric levels and the streamflow show very low values two weeks after the snow depletion, independently of the snowpack magnitude and the duration of the snow season. Our results suggest that there is no clear relationship between winter snowpack and summer runoff flows, which is probably explained by the very fast hydrological response of the catchment to meteorological fluctuations. Similarly, the analysis of 380 Swiss catchments revealed that summer streamflow is controlled by the seasonal rainfall and evapotranspiration interannual variability (Floriancic *et al.* , 2020). The lack of relation between antecedent snowpack and summer streamflow contrast to other mountain snow-dominated sectors, where snowmelt drives the streamflow anomalies several months after the snow depletion (Godsey et al., 2014; Staudinger et al., 2017). Thus, streamflow reacts immediately to the onset of melt events, but also declines quickly when new snowfalls or cold periods occur. After these interruptions, streamflow rises quickly when conditions that favor melting returns, or rain events occur (Figure 2). The fast hydrological response of the catchment during the melting period is also suggested by the rather sudden change in water temperature, electrical conductivity and streamflow water isotopy after the snow cover depletes over the catchment. Such fast hydrological and water properties response to dominant climatic conditions is generally characteristic of many small alpine catchments with relatively shallow soils (Ceperley et al., 2020; Segura, 2021). Such behavior contrasts with other alpine and subalpine catchments, where thick soils or sedimentary deposits favor the existence of alpine aquifers (Cochand et al., 2019; Hayashi, 2020) and intense subsurface flow (Ceperley et al., 2020; Jin et al., 2012; Tague & Grant, 2009) that favor longer transit times and a slow hydrological response independently regardless the short term climatic fluctuations.

Streamwater isotopy showed marked diel cycles of water isotopy during the melting periods, with almost systematic low values during daily maximum snow melting rates, and high values when baseflow controls the runoff generation. This is a clear indication of the low transit time of water in the Izas catchment during melting period. However, groundwater storage and interflow processes are not discarded in the catchment. Direct in-situ observations suggest that that most of the tributary ravines to the main stream are completely dry during the driest period of the summer, but there is always some runoff at the gauge station thanks to lateral flow and few small perennial springs in deep soils in convergent by topographic zones.

This work confirms the relevance of the isotopy monitoring for the catchment streamflow evolution. The $\delta^{18}O$ magnitude and spatial variability across the catchment increases while the snow disappears, which is consistent with previous results (Dietermann & Weiler, 2013; X. Feng et al., 2002; Holko et al., 2013). The mean isotopic values of the recorded series show strong interannual differences, exhibiting higher (lower) values during the snow poor (rich) seasons. However, the application of hydrograph separation based on water isotopes is complicated by the lack of detailed control of isotopic variations in individual precipitation events, water stored in soils and groundwater, and distributed samples of snowpack isotopy (Kamensky, 1998; Lee et al., 2010; Leuthold et al., 2021; Schmieder et al., 2016). Such monitoring should be considered in further research.

Overall results point out that snow plays a strong control in the hydrology during the melt period the expected future with reduced and shorter snowpack and a major influence of rainfall (López-Moreno et al., 2013, 2017) may lead to shifts in the occurrence of the maximum peak flow, and an earlier rise of stream water temperature that may impact with river ecology (Kamarianakis et al., 2016). However, the fast hydrological response of the catchment, the limited water storage capacity of the ground, and the importance of spring rainfall suggest that the main characteristics of the annual water balance and its hydrograph would not change in a drastic way. These results must be considered as local and explained by the main lithological, edaphic and climatological characteristics of the studied catchment. Mountain regions where most of the precipitation only fall during the coldest months of the year and where melt plays a major role in groundwater recharge will show a major dependence with the amount of timing of snow dynamics (Fayad et al., 2017).

CONCLUSIONS

The combined study of meteorological, snowpack characteristics, piezometric levels, streamflow and streamwater isotopic values and other physical properties have permitted to deepen the understanding of the hydrological cycle of the Izas catchment during the melting period in years of contrasted snow duration and thickness. During spring, the hydrological timing and magnitude is mainly controlled by snow melting. Liquid precipitation during the melting period, however, strongly shapes the hydrographs and contributes to the highest spring peak flows. Once snow disappears from the ground, the piezometric levels quickly decline, and the streamflow values rapidly decrease. The increase of streamwater temperature, electrical conductivity and $\delta^{18}O$ isotopic values in combination with the strong diel variability of the $\delta^{18}O$ isotopic values during the snow cover period, which is linked to daily cycle of dominant snowmelt or baseflow in runoff generation, suggest a short transit time of the water in the catchment during snowmelt, and therefore a limited role of groundwater supply to the streamflow. Thus, the interannual variability of the snowpack has a limited role in the summer runoff evolution. Hence, snow rich years might not increase the catchment resilience to summer droughts. Streamwater isotopy has responded clearly to snow cover evolution over the catchment However, its strong interannual variability represents challenges to properly make a hydrograph separation and to infer quantitatively the contribution of snowmelt to total runoff.

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DATA AVAILABILITY

Data supporting the findings of this study are available from the corresponding author [JILM] on request.

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