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Acknowledgments

The postdoctoral grant of Sébastien Santoni and accompanying research action are financially supported by the "Culletività di Corsica" through the GERHYCO interdisciplinary project dedicated to water management, ecology, and hydro-ecosystem services in insular context. The authors would like to thank the Municipality of Moltifau and the forest managers from the ONF (Office National des Forêts) for their support and contribution to the implementation of the project. The authors acknowledge Guillaume Chevalier for the help provided during the field campaigns and André Renucci for the Moltifau rainwater monthly sampling.

Keywords

Watershed; Hydrogeology; Isotope Hydrology; Recharge; Integrated Water Resource Management; Corsica.

1. Introduction

Wetlands are essential for humankind as they provide food security and climate change mitigation through ecosystem services such as water regulation and biodiversity conservation. Peatlands, which make up an integral component of wetlands, are also known for significant carbon storage capacity through peat accumulation. During the period 1970-2013, the area of wetland worldwide decreased by 35%. This loss was more pronounced in the Mediterranean, with up to 48 % of wetland surface loss (Gardner et al., 2018) in spite of the fact that wetlands constitute biodiversity and endemism hotspots. The drastic wetland surface loss is mainly attributed to water withdrawal and agricultural land extension (Parish et al., 2008; Kløve et al., 2011; Malek et al., 2018). The aridity of the Mediterranean climate implies wetlands such as peatlands are expected to be threatened by ongoing and future climate change impacts. Extended drought periods may involve a decrease in the water table, enhancing mineralization of organic matter and turning these peatlands into a source of carbon and drylands (Urák et al., 2017; Huang et al., 2018).

The crucial need to preserve such peatlands is reflected by a large number of regional to supranational governmental and non-governmental initiatives promoting the need for sustainable development. These include the United Nations Convention to Combat Desertification (UNCCD, 1992), the Paris Climate Agreement (2015), the

United Nations Sustainable Development Goals (SDGs, 2015) and more specifically the Ramsar Convention (1971), the MedWet Mediterranean Wetlands Initiative (1991) and the Aichi biodiversity targets (2010). In concrete terms, these initiatives aim to identify and mitigate human pressures on the environment. All of them point out that it is critical to obtain detailed knowledge for each site, and specifically on geomorphological, geohydrological and hydroclimatic conditions that are by definition interconnected. It is therefore essential to develop strategies and methodologies able to identify the boundary conditions necessary to sufficiently understand peatlands functioning at the hydrosystem scale. This crucial step will guide sustainable development strategies and help to design integrated water resource management procedures to protect these wetlands and preserve their ecological value (Vlachopoulou et al., 2014; Hettiarachchi et al., 2015; Erostate et al., 2020).

Although peatlands are present in most of the countries bordering the Mediterranean Sea, they remain seriously under-investigated: not all are inventoried, their spatial extent and functioning are not properly reported and recharge mechanisms are largely unknown. What knowledge does exist, suggests Mediterranean peatlands are shaped by their local environment, making them small, scattered, and with most presumed to be groundwater-dependent (Finlayson et al., 2018). Nevertheless, peat and gley soils extend over approximately 64,000 km² over the Mediterranean, which means peatlands may cover up to 29 to 42 % of the total known wetland surface (Parish et al., 2008; Gardner et al., 2018). Thus additional information on the peatlands could help delineate their hydrological vulnerability and resilience capacity to climate change.

One of the most important knowledge gaps is in characterization and quantification of the water balance components necessary for biodiversity conservation and peat

accumulation. Peat accumulation occurs through the maintenance of water levels close to the surface irrespective of seasonal climate variation and over the long term, especially under the semi-arid conditions that characterise the Mediterranean area. Approaches combining complementary methods such as water level monitoring, hydrogeochemistry, and isotope hydrology tools have been widely employed to characterize the origin, periodicity, and recharge mechanisms of very large and well-developed wetlands mainly in cold humid climates (Howie and Van Meerveld, 2013; Isokangas et al., 2017). The same approach to investigation of more seasonal and inhomogeneous recharge mechanisms of Mediterranean peatlands is largely missing.

In this study, the Moltifau peatland on the island of Corsica (France) was investigated to characterize the seasonal recharge mechanisms of a low-altitude Mediterranean peatland exposed to extended low precipitation period during the summer. Water level monitoring was combined with major ion hydrochemistry as well as ^{18}O, ^{2}H, ^{3}H, and $^{87}Sr/^{86}Sr$ isotopes to identify and quantify complex water flows supplying a hydrosystem connected to a larger watershed. The results are used to evaluate the vulnerability and hydrogeological resilience of Mediterranean peatlands based on the origin and renewal dynamics of water bodies contributing to their recharge. Finally, the results are evaluated against existing water and aquatic environmental management policy frameworks. Effective policies are essential to protect the hydrogeological functioning of Mediterranean peatlands and in particular their potential vulnerability to future climate change.

2. Study site

The Moltifau peatland was selected for its strategic location in Corsica (France), a mountainous island in the western Mediterranean basin. According to the Köppen climate classification (Peel et al., 2007), Corsican coastal regions are characterized by a Csa climate (hot-summer), mid-mountain regions by a Csb climate (warm-summer), and small areas of highest altitude by a subarctic Dfc climate (snow with dry and cool summer). Such a Mediterranean hydroclimatic context also implies strong inter-seasonal and inter-annual heterogeneity of temperature and rainfall conditions. Corsica is therefore an excellent observatory island giving access to all continental hydrological processes on a small spatial scale.

The Moltifau peatland, which extends over 40,000m^2, lies on an alluvial plain between 240 and 270 m a.s.l, within the Ascu River valley, an alpine watershed of 365 km^2 reaching a maximum elevation of 2706 m. a.s.l. Its inland location at low altitude implies a Csb climate with severe summer drought conditions, the intensity, and duration of which are continuously increasing due to climate change which in turn increases the risk of the peatland drying out. The peatland is delimited by the Ascu River at the north, and by the Punta di Ciufellu massif (820 m. a.s.l.) at the south. The average annual temperature is 14.4°C (from +4°C in winter to +25 °C in summer), and the average annual rainfall amount is 726 mm (from 13 mm in summer to 99 mm in fall). The Ascu River has a torrential regime with a mean annual flow of about 5.1 m^3/s, from 0.8 m^3/s in summer to 8.9 m^3/s in fall. The Ascu regime is also influenced by the high altitude Dfc climate involving spring snowpack melting contribution to the flow. Private housing settlements, which are part of the alluvial plain upstream, extend to the west of the peatland (Figure 1). Over the Moltifau area, population and urbanism are growing strongly, by around +56% in 49 years and +245% in 47 years, respectively. The drinking water supply mainly comes from the

Ascu River (upstream of the peatland) and numerous private boreholes pump the alluvial groundwater for crop production.

The peatland shelters a high plant and animal biodiversity including species protected at National, European, and International levels as well as several endemic species justifying its internationally recognized ecological value (Reille, 1997; Burguet-Moretti et al., 2011). It is referenced as the largest active raised bog on Corsica, is mainly acidic (pH ~4-5), young (^{14}C dating ~ 515 +/- 45 years), and of little thickness (1 to 2.5 m). Although there are some residues remaining from past landfill activities around the alder forest (glass, rubble, and car bodies), the peatland area itself can be considered as “pristine” (Poher, 2017). However, the peatland area is not delimited by any barrier, signage, or other physical materialization and most of the inhabitants of the town of Moltifau consider the peatland as an unhealthy place and underestimate its ecological value.

The peatland is underlain by well-fractured, pink perthitic granites that are part of the Punta di Ciufellu massif (Figure 1). Undifferentiated colluvium, resulting from the erosion of the Ciufellu massif accumulates on its piedmont to a thickness of a few meters and extends in the south of the peatland (Figure 1).The alluvial plain is made of river alluvium organized in terraces of different ages deposited on the granitic bedrock with a thickness of up to several tens of meters and permeability of about 6.4×10^{-4} m/s. Deposits consist mainly of more or less altered pebbles, nested in a clayey orange paleosol close to the piedmont or a grey sandy matrix close to the riverbed (Rossi et al., 1994).

Alder forest extending over 120,000 m² surrounds the peatland and hosts tiny temporary streams supplied by runoff flows from the Ciufellu massif but also by numerous cold-water springs on the ground. The cold-water springs origin is not

documented and probably related to the alluvial aquifer and colluvium discharge. The water level in the alluvial aquifer and the peatland displays little variation within the peatland irrespective of the season. The peatland is interpreted to be fed upstream by alluvial groundwater overflow due to a topographic threshold affecting alluvium terraces (Genevier et al., 2014).

3. Method

Five quarterly field surveys were conducted under contrasting hydrological conditions to represent a complete hydrological cycle from: May 2018 and June 2019 for spring, August 2018 for summer, December 2019 for fall, and February 2019 for winter. Data acquisition includes hourly monitoring of water level in the peatland (T4) and in the alluvial aquifer (F4) from June 2018 to June 2019. Secondly, it includes a monthly sampling for $\delta^{18}O$ and $\delta^{2}H$ of the river (R18) and Moltifau rainwater from May 2018 to June 2019 to constrain the local $\delta^{18}O$ variation. Thirdly, the data acquisition includes a quarterly survey for *in situ* measurements all over the study area of physico-chemical parameters (EC, HCO_3^-) and sampling for major ions (NO_3^-, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+}, K^+), stable isotopes of the water molecule ($\delta^{18}O$, $\delta^{2}H$), and tritium (^3H). A network of 25 points (Figure 1) was developed including the river (R18, R3, R7, R8), the alluvial aquifer (boreholes F1, F3, F4, F5, F7, F8; alder forest springs R10, R11, R12, R16, R19), the granitic massif (F6), the local rainwater (rain gauge near F6), the peatland water (piezometers T1, T2, T4, T5, T6) and its outlets (R1, R5, R6). Alluvial aquifer boreholes develop within the alluvium without reaching the granite bedrock, are not exploited and are used here as piezometers. Their depth increase with distance to the river: 5.7 m at F1, 3.0 m at F3, 6.7 m at F4, 8.2 at F5, 10 m at F8, 30 m at F7, and 103 m at F6. Peatland piezometers develop only within the peat, with a

depth of about 1.24 m at T1, 1.20 m at T2, 1.45 m at T4, 0.51 m at T5, and 1.27 m at T6. Water table elevation of the alluvial aquifer and the peatland is averaged between 247 and 253 m a.s.l during the studied period (Figure 1 and Figure 2). For the spring 2018 campaign, ^{3}H was not sampled. During the June-2019 campaign, a sample for dissolved inorganic radiocarbon ($^{14}C_{DIC}$) in F6 was collected, and strontium isotopes ($^{87}Sr/^{86}Sr$) were measured in 15 samples representative of all water bodies.

Water Electrical Conductivity (EC) and temperature were measured with a WTW Cond 3310 meter (WTW GmbH, Weilheim, Germany) in the field, and alkalinity was determined in the field using a HACH digital titrator (HACH Company, Loveland, USA). Water sampling was made after purging the piezometers (renewal of at least 3 times the volume of the water column) and stabilization of the physic-chemical parameters. Samples for major ions were filtered through 0.45 µm nitrocellulose membranes before collection in two 50 mL polyethylene bottles, with one of them acidified for cation analysis using ultrapure HNO_3. A Dionex ICS 1100 chromatography (Thermo Fischer Scientific, Waltham, USA) was employed for the ionic content determination at the Hydrogeology Department of the University of Avignon, France. The analysis is considered valid for an ionic balance deviation of less than 5 %. Samples for $\delta^{18}O$ and $\delta^{2}H$ analysis were collected in 20 mL amber glass bottles avoiding any head-space. The measurements were performed with a liquid-water stable isotope analyzer DLT-100 (Los Gatos Research, San Jose, USA) according to the analytical scheme recommended by the International Atomic Energy Agency (Penna et al., 2010) at the Hydrogeology Department of the University of Corsica, France. The isotopic analysis is considered as valid for a standard deviation condition about 0.1 ‰ for $\delta^{2}H$ and 0.01 ‰ for $\delta^{18}O$. Samples for ^{3}H were collected in

176 0.5 L polyethylene and analyzed by electrolytic enrichment and liquid scintillation
177 counting method according to Thatcher et al. (1977) at the Hydrogeology Department
178 of the University of Avignon, France. Sampling for $^{14}C_{DIC}$ was performed on-site by
179 precipitating water sample carbonates using barium chloride. The ^{14}C activity of the
180 solid inorganic carbon obtained was determined by the liquid scintillation counting
181 method after benzene synthesis according to Clark and Fritz (1997) at the
182 Hydrogeology Department of the University of Avignon, France. Analysis for $^{87}Sr/^{86}Sr$
183 ratio was performed using a thermal ionization mass spectrometer (Finnigan MAT
184 262, Thermo Fischer Scientific, Waltham, USA) fitted with a multi-collector array
185 consisting of five faraday cups. Corrections for mass fractionation were performed
186 normalizing the $^{87}Sr/^{86}Sr$ ratio to the NBS 987 standard which value is 0.710250.
187 These analyses were performed in the Department of Geological Sciences, at the
188 University of Cape Town, South Africa.
189

190 ## 4. Results and discussion

191 ### 4.1. Recharge components identification

192 The river flow and the alluvial aquifer water level are strongly correlated with the
193 monthly rainfall amount (Figure 2-A). Three peaks corresponding to high river water
194 level events are observable in the alluvial aquifer during Nov-2018, Feb-2019, and
195 Jun-19. The water level in the peatland appears quite stable but two peaks were
196 recorded and correlate with the two high river water level events of Nov-2018 and
197 Feb-2019. There is no time-lag between these events and the water level varies in
198 the alluvial aquifer and the peatland on a monthly timescale. Except during summer,
199 the EC in the peatland is generally lower than in the alluvial aquifer most likely due to
200 a greater rainfall contribution. The high river water level events are always associated

with a decrease in the EC in the alluvial aquifer with values tending towards those observed in the peatland. This information coupled with the observation of the water level map (Figure 1) highlighting a clear continuity over the alluvial plain and the peatland area argue in favour of a strong groundwater-dependence of this peatland. Furthermore, the water level in the alluvial aquifer is generally higher than in the peatland, except during Aug-18 and Sept-18 (Figure 2-B). This highlights the contribution of other water bodies to recharge to the peatland and the possibility for the alluvial aquifer to be fed by the peatland.

Most of the samples from Aug-2018 and Dec-2018 plot along the Western Mediterranean Meteoric Water Line (WMMWL) of Celle-Jeanton et al. (2001) whereas those of May-2018, Feb-2019 and June-2019 plot closer to the Moltifau meteoric water line defined as $\delta^2H = 7.30 (\pm 0.49) \times \delta^{18}O + 7.37$ (OLSR approach; n = 12; $r^2 = 0.96$; Figure 3). No significant $\delta^{18}O$ enrichment is observed, indicating that evaporation processes are negligible despite the usual severe low precipitation period during the Mediterranean summer (Jasechko, 2019). Usually, water in peatland appears depleted in ^{18}O and ^{2}H during the high flow period and turns more enriched in $\delta^{18}O$ and δ^2H during the low flow period, typically due to the increase in atmospheric temperature and associated evaporation processes (Sprenger et al., 2017). However, in the setting of the present study the reverse is observed: the most enriched peatland water samples are found during Dec-2018 (δ^2H_{mean} = -50.5 ‰; $\delta^{18}O_{mean}$ = -8.11 ‰) and Feb-2019 (δ^2H_{mean} = -52.47 ‰;$\delta^{18}O_{mean}$ = -8.11 ‰), whereas the most depleted ones are found during May-2018 (δ^2H_{mean} = -63.7‰;$\delta^{18}O_{mean}$ = -9.82 ‰), Jun-2019 (δ^2H_{mean} = -58.7 ‰;$\delta^{18}O_{mean}$ = -8.93 ‰), and Aug-2018 (δ^2H_{mean} = -56.9‰;$\delta^{18}O_{mean}$ = -8.93 ‰). The most depleted peatland signatures are rather related to the colluvium, the granite, and the river samples than to the local rainfall

signature. Such depleted signatures may be explained by the influence of snowpack melting supplying the upstream river as previously measured (δ^2H = -85.7 ‰, $\delta^{18}O$= -12.77 ‰) by van Geldern et al. (2014). Since the snowfall is significantly depleted in heavier isotopes compared to the summer rainfall, the average isotopic composition of snowpack remaining is also generally depleted despite the enrichment effect of sublimation and snowmelt (Beria et al., 2018). The snowpack melting, normally occurring in the watershed head during the spring and the beginning of the summer season, generates very depleted signatures into the river compared to the local rainfall that is then transferred into the peatland through the alluvial aquifer. To summarise, the $\delta^{18}O$ local framework revealed several potential contributors to recharge for the peatland: by the rain, a river, shallow groundwater from the colluvium, and by deep groundwater from the fractured granite.

4.2. Recharge component renewal dynamics

The amplitude of variation of the isotopic signature of the different recharge components highlights their renewal dynamics (Table 1). The local rainwater samples have elevated values about 10.12 ‰ for $\delta^{18}O$, and 8.5 TU for ^3H. The river has lower values about 1.90 ‰ for $\delta^{18}O$, and 2.4 TU for ^3H that are similar to the colluvium springs values of around 2.05 ‰ for $\delta^{18}O$, and 0.9 TU for ^3H. These values indicate homogenization of the local rainfall input within the colluvium reservoir. Nevertheless, to the extent that these sources dry up in summer, it can be concluded that the renewal of the colluvium reservoir is seasonal to annual. Lastly, the granite groundwater is the recharge component displaying longer renewal dynamics: ^3H values are always less than 0.5 TU and with a $^{14}C_{DIC}$ activity about 4.5 pMC, the groundwater residence time can be estimated to be around 25,500 years. Since no major $^{14}C_{DIC}$ source/sink within the granites may be expected, the groundwater age

estimation does not require correction and can be based solely on the radioactive decay of $^{14}C_{DIC}$ assuming piston flow from the recharge area to the sampling point F6. This estimate can be further validated against the stable isotope signature shift of about ≈ -2 ‰ for $\delta^{18}O$ and about ≈ -15 ‰ for $\delta^{2}H$ between the locally weighted mean isotope signature in rainfall and the granite groundwater revealing a clear paleo-climatic effect on a 25 K year scale. This shift is in the same order of magnitude as that observed in many aquifers hosting paleo-groundwater near the study site (Jiráková et al., 2011). Hence, the potential recharge contributions display a wide range of renewal dynamics: very fast for the local rainwater and the river, seasonal to annual for the colluvium springs, and up to millennial for the granite groundwater.

During a full hydrological cycle, the $\delta^{18}O$ signatures of alluvial aquifer, peatland, and its outlets do not match with only one end-member (the local rainwater, the river, the granite groundwater, or the colluvium springs). They are usually between the river or the granite groundwater and the colluvium springs signatures, except during the summer when they are closer to the colluvium springs and the granite groundwater (Figure 4). These observations highlight complex mixing processes within the alluvial aquifer and the peatland. Furthermore, the isotopic signal within the alluvial aquifer, the peatland, and its outlets displays the same evolution pattern with comparable order of magnitude (Figure 4), implying a rapid water turnover within the peatland. Therefore, hydro-climatic conditions can potentially influence the seasonal recharge mechanisms (Figure 2), i.e. the mixing rates between the local rainfall, the river, the colluvium springs, and the granite groundwater over the seasons.

4.3. Quantification of the contribution of recharge components

4.3.1. Tracer choice

Peatlands hydrochemistry is usually complex and major ions can be expected to be non-conservative especially due to redox conditions leading to processes such as denitrification, or sulphate reduction (Bertrand et al., 2012). For the present study, it is hypothesized that Na^+, abundant and primarily granite-sourced (up to 116 mg/L in F6), is one of the most conservative major ions and can be considered for mixing proportions calculation. In contrast, fewer geochemical processes usually affect the isotope tracers, making their interpretation less ambiguous than the simultaneous changes in the geochemical content (Santoni et al., 2016). Given the location of the study site within a strong altitudinal gradient watershed, it is possible to take advantage of the resulting $\delta^{18}O$ signatures contrasts to discriminate the rainwater, the river, the colluvium springs and the granite groundwater coming from varying altitudes. Nevertheless, the $\delta^{18}O$ signatures may be ambiguous from a water body to another one due to temporal variations, as this is the case for the river and the granite groundwater or between the local rainwater and the colluvium springs (Figure 4).

To better discriminating these water bodies, the ^3H content can also be considered. Over the past decades, natural ^3H variations in meteoric waters were masked by the input of high levels of ^3H derived from atmospheric testing of thermonuclear weapons. This anthropogenic ^3H has now largely decayed away leaving a natural baseline level in precipitation. Excluding any source from nuclear energy power plants, this natural baseline level in precipitation is principally controlled by stratospheric production and fall-out rates, dilution from evaporation of oceanic water and continental moisture recycling (Tadros et al., 2014; Juhlke et al., 2020). Like stable isotopes of the water molecule, many so-called ‘effects’ may affect the distribution of monthly integrated ^3H samples of precipitation. The seasonal effect is

likely to be the most pronounced in the present study and is characterised by increased ^{3}H contents during spring and early summer (Juhlke et al., 2020). As a consequence, and considering a half-life of 12.32 (±0.02) years, the ^{3}H contents may be considered as a hydrological tracer of water origins at the sampling time step (month) of this study.

Coupled with $\delta^{18}O$, $^{87}Sr/^{86}Sr$ ratio is a very efficient tool to differentiate recharge components and calculate mixing proportions by avoiding inaccuracies due to hydrochemical processes (Santoni et al., 2016). In the present study, the $^{87}Sr/^{86}Sr$ analysis was conducted during a spring survey (June 2019) because the maximal dilution of the hydrosystem at this moment may result in a loss of hydrochemical signal for other tracers and thus potentially a source of mixing proportion calculation problems. The $^{87}Sr/^{86}Sr$ ratio is then expected to validate the mixing proportions calculated from using the Na^{+}, $\delta^{18}O$, and ^{3}H tracers, which are easier tracers to implement but having specific limitations as explained earlier.

4.3.2. End-member mixing analysis settings

A end-member mixing analysis can be developed to explain the isotopic ($\delta^{18}O$, ^{3}H) and hydrochemical (Na^{+}) compositions of the alluvial aquifer and peatland water samples in terms of local rainwater, colluvium springs, granite groundwater and river water contribution for each season. According to Carrera et al. (2004), a four-member mixing model can be expressed by end-members as follows:

$$1 = f_a + f_b + f_c + f_d \quad (1)$$

$$[X]_{sample} = f_a \times [X]_{rainwater} + f_b \times [X]_{colluvium} + f_c \times [X]_{granite} + f_d \times [X]_{river} \quad (2)$$

where f refers to the relative fraction, subscripts a, b, c, and d refers to the selected end-members among the rainwater, the colluvium, the granite, and the river, and the [X] can be either the Na^{+}, $\delta^{18}O$, ^{3}H, or $^{87}Sr/^{86}Sr$ content. The end-members can be

characterized as follows (Table A1): (1) the rainwater as the quarterly weighted means of $\delta^{18}O$ at Moltifau. For the Na^+, ^3H, and $^{87}Sr/^{86}Sr$ contents, data are respectively harvested from the Bonifacio, Corte, and Nîmes rain gauge stations close to the study site (Khaska et al., 2013; Santoni et al., 2016; Juhlke et al., 2020); (2) the sampling points R10 and R11 are considered as representative of the colluvium springs. During the Aug-2018 campaign, R10 and R11 springs were dry, the nearest sampling point R12 was then selected; (3) the sampling point F6 is considered as representative of the granite groundwater; (4) the upstream sampling point R18 is selected as representative of the river water. During the summer season, the sampling point distribution on the Na^+, and ^3H *vs* $\delta^{18}O$ graphs (Figure 5) suggest the contribution of another recharge component within the peatland. According to Siegel et al. (1995), pore fluids may be flushed from peat during low water levels due to the decrease in the rainfall amount occurring in summer. In the present study, a 'peat' end-member needs then to be considered for the Aug-2018 campaign. Since pore fluids were not sampled, the Na^+, $\delta^{18}O$, and ^3H values for the peat end-member are graphically determined also by an iterative process according to Hooper et al. (1990) to be 7.1 mg/L, -9.56 ‰, and 6.76, respectively (Table A1).

4.4. Mediterranean peatland recharge mechanisms

The results and interpretation of the EMMA are here presented for both the alluvial aquifer supplying the peatland and the peatland itself.

4.4.1. Spatial trends

In the alluvial aquifer, the proportion of local rainwater is maximal near the surface (75-88% at F8) and decreases with depth and distance to the riverbed. The proportion of river water is maximal close to the riverbed (58-92% at F1 and F3) and

decreases toward the Ciufellu granite massif. This is well supported by the piezometric map in Figure 1 and also in agreement with Genevier et al. (2014). The proportions of local rainwater and river decrease is compensated by an increase in the proportion of colluvium water in the vicinity of the Ciufellu granite massif (0-76% at F4) as well as by an increase in the proportion of granite groundwater with depth (20-62% at F7). The same trends are observed for the peatland water samples. T1 and T2 are more influenced by the river (36-82%), T4, and T6 by the colluvium springs (16-48%) and to a lesser extent by the granite groundwater (0-17%). All these mixing proportion calculations based on the Na^+ *vs* $\delta^{18}O$ *vs* ^3H approach is in very good agreement with those obtained with the $^{87}Sr/^{86}Sr$ *vs* $\delta^{18}O$ *vs* ^3H approach (Table A2). This can be explained by a strong altitude gradient and hydroclimatic seasonality influencing $\delta^{18}O$, and ^3H and by the lithology contrasts within the watershed influencing Na^+ and $^{87}Sr/^{86}Sr$ (Santoni et al., 2016). The only noticeable difference is that using the $^{87}Sr/^{86}Sr$ ratio allows a better detection and quantification of a low granite groundwater contribution to the peatland recharge. As an example, this contribution reaches 9 % at the T2 sampling point against 0 % using the Na content. As a consequence, even if the peatland is little extended, it appears as dependent on varied ground and surface water bodies. Nevertheless, since supplied by the alluvial aquifer and developing at the same water level, the peatland appears more influenced by the shallowest alluvial groundwater flow lines and by surface water bodies than by the deep granite groundwater flow lines.

4.4.2. Seasonal trends

A conceptual model of the recharge mechanisms in the peatland and the alluvial aquifer may be proposed for each season (Figure 6). In both the alluvial aquifer and

376 the peatland, the local rainwater and colluvium proportions are directly related to the
377 rainfall scheme: the higher the rainfall amount is, the higher the proportions are.
378 These proportions are maximal during fall (27% and 24%) and winter (32% and
379 28%), and minimal during spring (9% and 10%) and summer (4% and 12%). These
380 results point out the peatland's dependence to water bodies different from the local
381 rainfall. Furthermore, in both the alluvial aquifer and the peatland, proportions are
382 related to the river flow: the higher the flow is, the higher the proportions is. These
383 proportions are then maximal during fall (49%), winter (40%), and spring (81%). This
384 means that the three main water level peaks observed in the alluvial aquifer after the
385 fall and winter floods as well as after the snowpack melting in the high watershed part
386 during spring contribute mainly to the recharge. Moreover, as explained in the spatial
387 trends section, the granite groundwater proportion varies in space but appears
388 season-dependent. Within the alluvial aquifer, the proportion is maximal during
389 summer, decreases in fall, and is minimal in winter and spring. This means that the
390 higher the local rainwater, the colluvium springs, and the river contributions are, the
391 higher the dilution of the granite groundwater recharge component is. Within the
392 peatland, the granite groundwater recharge component is noticeable only during
393 summer (up to 16%, with a mean about 4 %), the peat pore water being the most
394 representative component due to the water reservoir function of the peatland. Based
395 on these observations, it is possible to establish a recharge component succession
396 from one season to another. The high watershed river is the first recharge component
397 involved. The rain and the shallow flow through the mountainside colluvium constitute
398 subsequently the second recharge component providing support during drier periods.
399 The granite groundwater constitutes the fourth and last recharge component able to
400 supply the peatland during summer throughout the alluvial aquifer. During summer,

401 the peatland continues to be fed by the alluvial aquifer (Figure 2). However, during
402 the summer low precipitation period, the peatland seems to support the flow of the
403 alluvial aquifer downstream, as shown by the chemistry of alluvial groundwater
404 (Figure 5) and the inversion of water tables (Figure 2B).
405
406 **4.5. From hydrogeological resilience to the vulnerability of Mediterranean**
407 **peatlands**
408 At first glance, the peatland's hydrogeological resilience to climate change appears
409 limited because the river-alluvial aquifer system on which the peatland depends is
410 highly responsive to the seasonality of hydroclimatic conditions. In particular, there is
411 no significant time lag between the rain events and the alluvial aquifer water level
412 response supplying the peatland. This finding testifies to the high reversibility of the
413 peatland hydrological status and vulnerability to low precipitation period during the
414 Mediterranean summer. However, the peatland has proven to be resilient during the
415 low precipitation period, as shown by the water level monitoring (Figure 2). This can
416 be explained by the reservoir function of the peat (pore water) and by the multiple
417 groundwater sources supplying the peatland, making it not solely dependent on
418 precipitation feeding into the alluvial aquifer and the river. The peatland benefits from
419 low but perennial inflows from reservoirs with longer renewal dynamics (colluvium
420 and granite groundwater) as well as from the more important but very short time
421 inflows from summer storms governing the river flow.
422 The hydrogeological functioning of Mediterranean peatlands is an intrinsic asset
423 making them well adapted to the Mediterranean climate. From a qualitative point of
424 view, groundwater bodies with long renewal dynamics constitute perennial and
425 presumed good quality recharge components. However, their connection with surface

426 water bodies makes them vulnerable to any land-use changes likely to affect water
427 quality and quantity within the watershed: population and urban growth (drinking
428 water supply, sanitation), agricultural practices (irrigation, fertilizers, phytosanitary
429 products) as this is more widely the case in the Mediterranean. During the summer
430 low precipitation period, the river, the colluvium, and the granite groundwater may be
431 insufficient to maintain a sufficient water level in the alluvial aquifer to support
432 peatland hydrological functioning, leading to a water table inversion (Figure 2B).
433 During such unfavourable hydrological conditions, the peatland survival relies on the
434 peat reservoir function. This demonstrates the precarious hydrogeological equilibrium
435 within the peatland. Any increase in the water table inversion duration can then lead
436 to the peatland drying up. Critically, the drying up of peatland, even temporarily, is
437 likely to permanently alter the plant and animal species it contains. As a
438 consequence, any slight external pressure on the alluvial groundwater level from
439 abstractions to support irrigation and drinking water supply, or through climate
440 change (by increasing the temperature or the drought length, and decreasing or
441 modifying the rainfall scheme) can result in the drying up, where the worst-case
442 scenario is complete desiccation.
443

444 ### 4.6. Implications on peatlands sustainable management strategies in the
445 Mediterranean region

446 The Moltifau peatland can be considered a representative peatland from the western
447 Mediterranean region at low altitude, where worsening vulnerability to drought
448 conditions has been documented (Parish et al., 2008). As part of the territory of
449 France, one of the Mediterranean rim countries offering the strictest legislative

framework in favour of wetlands preservation, the peatland provides an important perspective on deficiencies in the legislation and management of such ecosystems.

At the peatland scale, management strategies are theoretically developed to preserve its ecological value. Nevertheless, the lack of willingness, financial resources as well as the involvement of several environmental institutions such as the French national forestry board (ONF) and the Directorate of the Environment (DREAL) make policies ineffective. Added to this are potential administrative difficulties that might arise through the transfer of wetland management strategies to the local authorities through the Regional Environmental Office (OEC). This situation is due to the State decentralization which recognizes the Corsica administrative Region as fully in charge of environmental management and conservation, blurring the situation and making coordination even more complicated from the European to the local level.. Furthermore, the preservation strategy presently developed only deals with biodiversity aspects and is applied only within the strict area of the peatland. None of the strategies takes into account the need to preserve the water body it contains and those inter-connected to it in a wider context. Indeed, the peatland water body does not appear in any management document for aquatic environments related to the local transcription of the European Water Framework Directive of 2000 (WFD, 2000/60/EC). The fate of the peatland is therefore in the hands of the local authorities who are forced to reach compromises between the peatland ecosystem services preservation, and the necessary socio-economic development of the territory. Due to its small size and lack of visibility, both in the landscape (no barriers, signage, or other physical materialization) and in the minds (little communication and education about its ecological value), this peatland is suffering from increasing human pressure.

The WFD is widely accepted as the most ambitious and substantial European sustainable development legislation to date. By nature, the WFD aims at reaching qualitative and quantitative “good status” for identified surface and groundwater bodies supplying wetlands by the end of the second or third management cycles extending during 2015-2012 and 2021 to 2027, respectively. Although this approach attempts to address the most serious health-threatening impacts on the environment, many wetlands of international importance remain outside the WFD. On the one hand, as the number of water bodies is defined according to political criteria, most often in the way to reduce costs (Moss, 2008), the managed groundwater body size covers generally wide areas, unadapted for the preservation of small and scattered Mediterranean peatlands. As an example, the Moltifau peatland represents less than 1/80,000 of the groundwater body's total size. On the other hand, pollution sources being often multiple in nature and difficult to constrain due to the complexity of human activities on the territory, basic measurements for water body quality indicators as established in the WFD appear insufficient to assess pressure and impact, leading to a misunderstanding of the water bodies status (Voulvoulis et al., 2017).

As demonstrated in this study, Mediterranean peatlands are groundwater-dependent (GDE) and well connected to the whole hydrographic network. In its present form, the WFD requires the establishment of separate Programmes of Measures (PoMs) for groundwater and surface water bodies without taking into account the complex hydrological functioning of such transitional environments. Water flow connects the different components of the peatland with the whole watershed area, making them particularly vulnerable to a wide range of human-induced impacts. This specificity requires planning of PoMs, not at a water body scale, but at the hydrosystem scale

500 by understanding the relationship between land and water under different socio-
501 economic drivers (Varela-Ortega et al., 2011; Vlachopoulou et al., 2014). Such an
502 integrated and coordinated approach should be implemented in the WFD by the
503 establishment of appropriate policy for inland GDE such as Mediterranean peatlands.
504 This implies a knowledge gain to define around the hydrosystem an area called
505 "optimal functioning conditions zone", identifying and coordinating the people acting
506 over the relevant territory, and finally identifying relevant indicators for evaluating the
507 status of the hydro-ecosystem (Carvalho et al., 2019). Encouraged by cooperation
508 projects, several UE and non-UE countries of the Mediterranean rim successfully
509 initiated the Integrated Water Resources Management, mainly focusing on highly
510 anthropized and regional river basins (Tavakoly et al., 2019). On a smaller scale, as
511 is the case for the Moltifau peatland, it is difficult to implement this approach because
512 of the lack of willingness and coordination between all environmental institutions and
513 land users. A solution would be to propose the concept of scientifically-piloted PoMs
514 at the hydro-ecosystem level for the third WFD cycle (2021-2027). Based on the
515 present study, its delimitation would be based on the peatland's "optimal functioning
516 conditions zone" including both surface and groundwater. Quality indicators would
517 facilitate assessment of the whole ecosystem status, including new groundwater
518 degradation trends and impacts on GDEs by the implementation of relevant research
519 tools such as the monitoring of water levels, physico-chemical parameters,
520 hydrochemistry, and isotopes (Erostate et al., 2020). The advantage of this proposal
521 is also the consideration of heterogeneities in hydroclimatic conditions and
522 groundwater contribution at seasonal and inter-annual timescales in the context of
523 increasing human and climate pressures threatening more and more the peatlands,
524 one of the main biodiversity hotspots within the Mediterranean.

5. Conclusion

This study represents one of the first comprehensive analyses of the seasonal recharge mechanisms of a representative Mediterranean peatland, integrating a range of geochemical and isotope hydrology tools (Na^+, $\delta^{18}O$, ^3H, $^{87}Sr/^{86}Sr$). Such an approach is relevant to identify and quantify complex water flows supplying Mediterranean peatlands and could be adopted in other peatlands worldwide potentially connected to multiple surface and groundwater bodies. This study confirmed the groundwater-dependent status of Mediterranean peatlands, emphasizing the strong seasonal heterogeneity of the recharge component contributions despite a very stable water level throughout the year. Peatlands are dependent on surface and shallow flows during fall, winter, and spring, and are highly dependent on shallow and deep groundwater during summer. This important finding suggests, on the one hand, an intrinsic resilience to low precipitation period during the Mediterranean summer and on the other hand, the connectivity between all surface and groundwater bodies of the watershed. This important hydrological functioning makes the peatlands vulnerable to any change in land use within the watershed or in hydroclimatic conditions as expected in the context of global change. The peatland vulnerability is also increased by poor consideration of their specific functioning into water and aquatic environment management policies such as the European WFD. A paradigm-shift with management based on the hydrosystem concept is necessary and implies a downscaling adapted to Mediterranean peatlands size and their transitional situation connecting surface and groundwater. Aquatic environments, surface, and groundwater bodies currently being managed independently, need to be coordinated and efforts between environmental institutions

and land users need to be improved to define "optimal functioning conditions" based on new quality indicators to enhance and maintain Mediterranean peatlands ecosystem services.

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List of Figures (color should not be used for any figures in print)

Figure 1: Map of the study site with the sampling point network, geology, and potentiometric levels.

Figure 2: Time series of water level and EC parameters within the peatland (T4) and the alluvial aquifer (F4) compared with the local monthly rainfall amount and with the monthly river flow from May-2018 to Jul-2019 (A) with a particular focus on water levels in the peatland and the alluvial aquifer during the summer (B).

Figure 3: $\delta^{2}H$ vs $\delta^{18}O$ plot of all water samples. The GMWL is the Global Meteoric Water Line after Craig (1961), the WMMWL is the Western Mediterranean Meteoric Water Line after Celle-Jeanton et al. (2001) and the LMWL is the Local Meteoric Water Line in Moltifau. The river water sample for the watershed head is given in van Geldern et al. (2014).

Figure 4: Seasonal evolution of $\delta^{18}O$ signatures within the alluvial aquifer, the peatland, and its outlets according to the monthly rainfall amount, the monthly river flow and the local isotopic framework (local rainwater, river, granite groundwater, and colluvium springs) during a full hydrological cycle.

Figure 5: Na+, ^{3}H, and $^{87}Sr/^{86}Sr$ vs $d^{18}O$ plots of the alluvial aquifer and peatland samples for the fall, winter, spring, and summer campaigns according to the local rainwater, river, Colluvium springs and granite groundwater end-members.

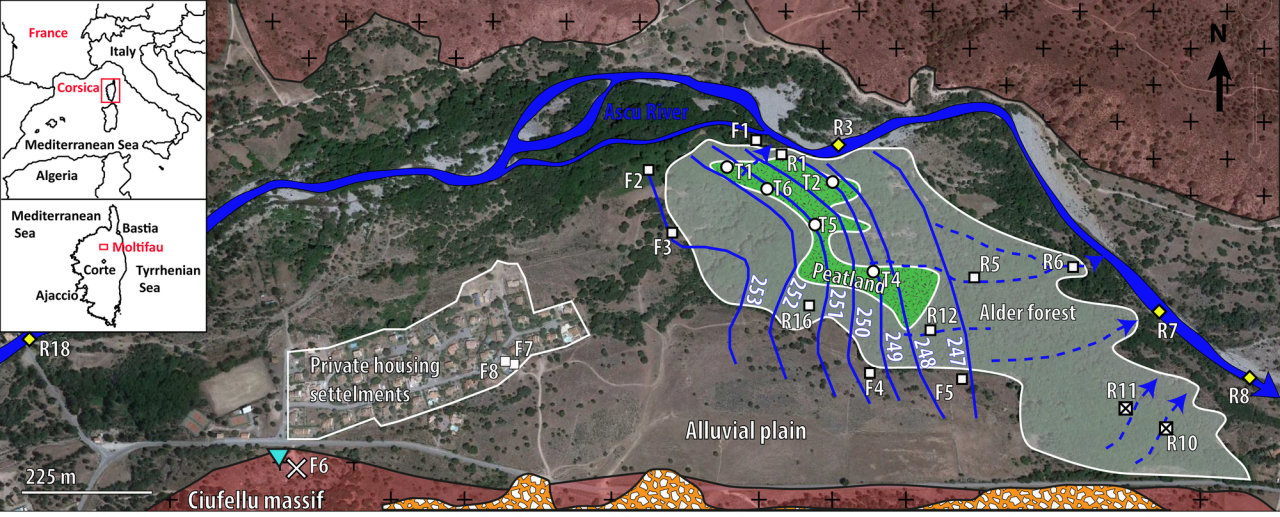
Figure 6: Conceptual model showing the quantification of seasonal variation of the contribution of water recharge components in the Mediterranean peatland. The pie chart indicates the quantification of seasonal variation of the contribution of water recharge components in the alluvial aquifer.

List of Tables

Table 1: Amplitude of variation of $\delta^{18}O$, and ^{3}H in the rainwater, the river, the colluvium springs and in the granite groundwater. The $^{14}C_{DIC}$ age is also given for the granite groundwater.

Table A1 (supplementary material): Na^{+}, ^{3}H, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ values for each end-member (local rainwater, colluvium, granite, river, peat) and each season (May-18, Aug-18, Dec-18, Feb-19, and Jun-19). Rainwater Na^{+}, ^{3}H, and $^{87}Sr/^{86}Sr$ contents are harvested from Santoni et al. (2018), Juhlke et al. (2020), and Khaska et al. (2013), respectively.

Table A2 (supplementary material): Peatland and alluvial aquifer mixing rates computed from Na^{+}, $\delta^{18}O$, and ^{3}H data in terms of local rainwater, colluvium springs, granite groundwater, river, and peat contribution for the Aug-18, Dec-18, Feb-19, and Jun-19 campaigns. In parenthesis, mixing rates computed from $^{87}Sr/^{86}Sr$, $\delta^{18}O$, and ^{3}H data.



Lithology

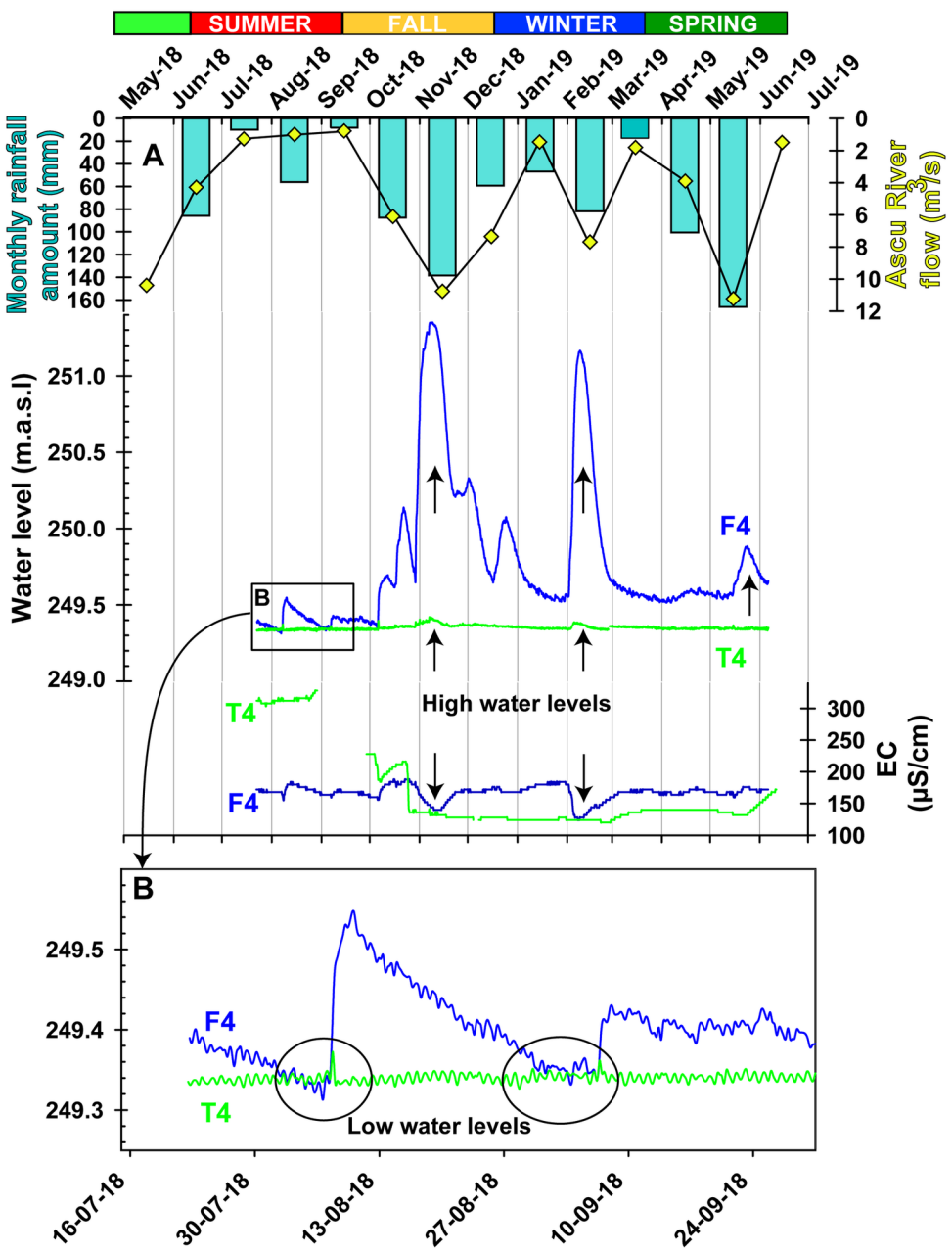
- Alluvium
- Colluvium
- Granite bedrock
- Peatland

Hydrology and hydrogeology

- Temporary stream flows
- 253 Water level (m a.s.l.)

Sampling network

- Peatland water
- Alluvial groundwater
- Colluvium spring
- Granite groundwater
- River water
- Rain gauge


SUMMER
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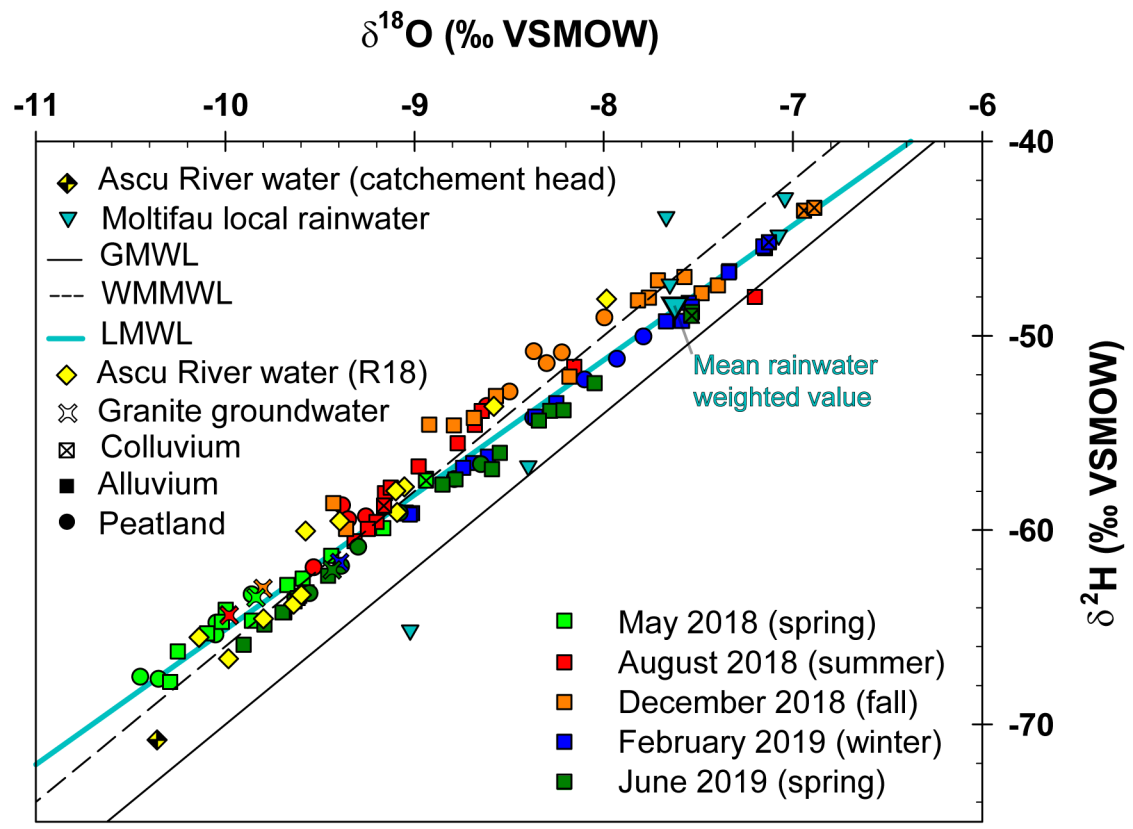
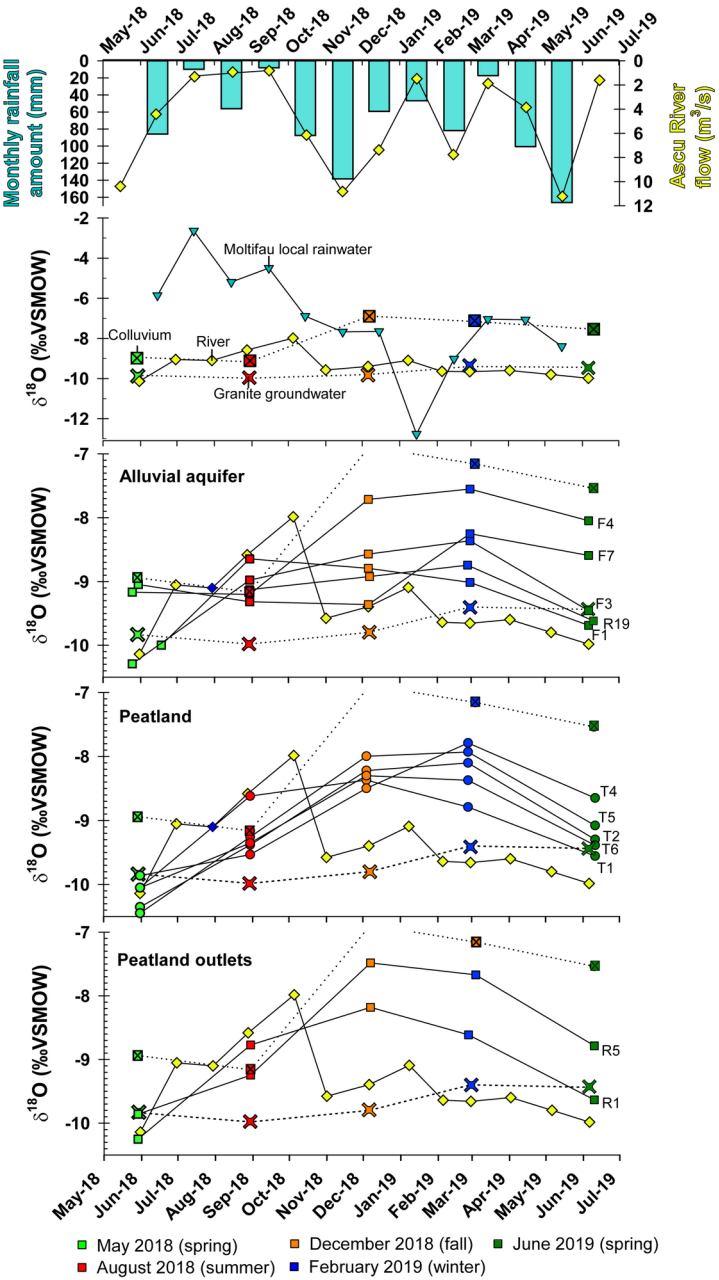
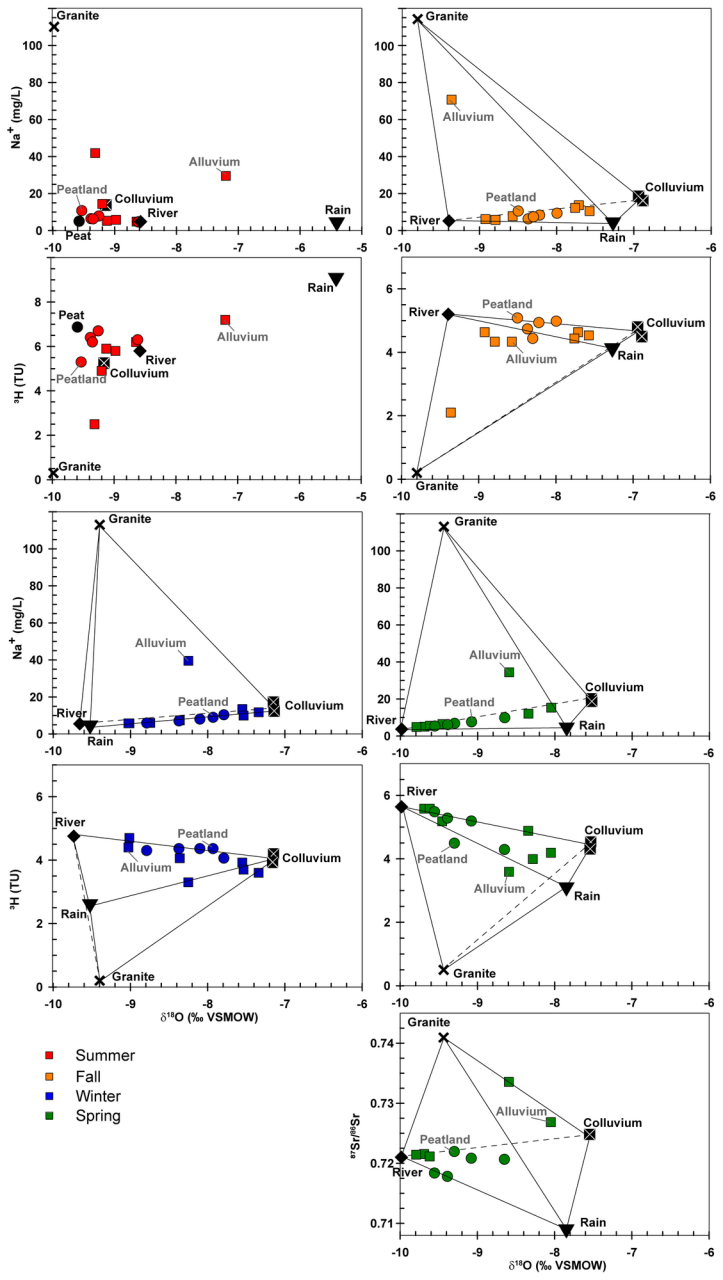
Jul-18
Aug-18
Sep-18
Oct-18
Nov-18
Dec-18
Jan-19
Feb-19
Mar-19
Apr-19
May-19
Jun-19
Jul-19
A
Monthly rainfall amount (mm)
Ascu River flow (m3/s)
Water level (m.a.s.l)
F4
T4
B
High water levels
EC (µS/cm)
Low water levels
16-07-18
30-07-18
13-08-18
27-08-18
10-09-18
24-09-18


δ18O (‰ VSMOW)
-11
-10
-9
-8
-7
-6
-40
-50
-60
-70
δ2H (‰ VSMOW)
Ascu River water (catchement head)
Moltifau local rainwater
GMWL
WMMWL
LMWL
Ascu River water (R18)
Granite groundwater
Colluvium
Alluvium
Peatland
Mean rainwater weighted value
May 2018 (spring)
August 2018 (summer)
December 2018 (fall)
February 2019 (winter)
June 2019 (spring)


May-18
Jun-18
Jul-18
Aug-18
Sep-18
Oct-18
Nov-18
Dec-18
Jan-19
Feb-19
Mar-19
Apr-19
May-19
Jun-19
Jul-19
Monthly rainfall amount (mm)
Ascu River flow (m³/s)
Moltifau local rainwater
Colluvium
River
Granite groundwater
δ18O (‰VSMOW)
Alluvial aquifer
F4
F7
F3
R19
F1
Peatland
T4
T5
T2
T6
T1
Peatland outlets
R5
R1
May 2018 (spring)
August 2018 (summer)
December 2018 (fall)
February 2019 (winter)
June 2019 (spring)


Granite
Alluvium
Peatland
Colluvium
River
Rain
Peat
Na+ (mg/L)
3H (TU)
δ18O (‰ VSMOW)
87Sr/86Sr
Summer
Fall
Winter
Spring

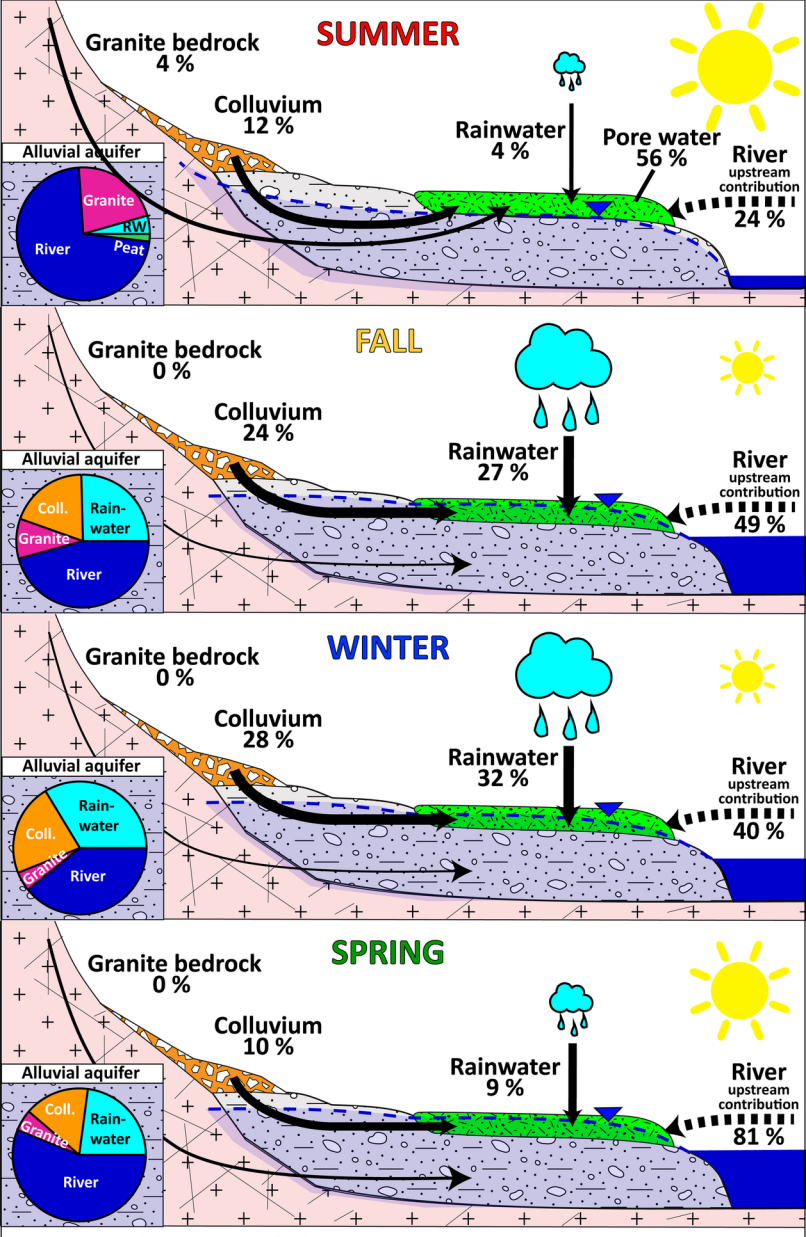

SUMMER
Granite bedrock
4 %
Colluvium
12 %
Rainwater
4 %
Pore water
56 %
River
upstream
contribution
24 %
Alluvial aquifer
Granite
RW
Peat
River
FALL
Granite bedrock
0 %
Colluvium
24 %
Rainwater
27 %
River
upstream
contribution
49 %
Alluvial aquifer
Coll.
Rain-
water
Granite
River
WINTER
Granite bedrock
0 %
Colluvium
28 %
Rainwater
32 %
River
upstream
contribution
40 %
Alluvial aquifer
Coll.
Rain-
water
Granite
River
SPRING
Granite bedrock
0 %
Colluvium
10 %
Rainwater
9 %
River
upstream
contribution
81 %
Alluvial aquifer
Coll.
Rain-
water
Granite
River
Peatland
Alluvium
Colluvium
Granite bedrock
Water table

Table 1: Amplitude of variation of $\delta^{18}O$, and ^{3}H in the local rainwater, the Ascu River, the colluvium springs and in the granite groundwater. The $^{14}C_{DIC}$ age is also given for the granite groundwater.

		$\delta^{18}O$ (‰ VSMOW)	^{3}H (TU)	^{14}C age (years)
Local rainwater	min	-12.76	1.6	
	max	-2.64	10.1	
	max-min	**10.12**	**8.5**	
Ascu River	min	-10.25	4.0	
	max	-8.35	6.4	
	max-min	**1.90**	**2.4**	
Colluvium springs	min	-8.94	3.9	
	max	-6.89	4.8	
	max-min	**2.05**	**0.9**	
Granite groundwater	min	-9.98		
	max	-9.40	**0.5**	25,500
	max-min	**0.58**		

Na^+

$\delta^{18}O$

^3H

$^{87}Sr/^{86}Sr$

Mediterranean peatland seasonal recharge through alluvial aquifer contribution