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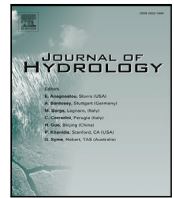
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Research papers

Decreasing trend of groundwater recharge with limited impact of intense precipitation: Evidence from long-term lysimeter data[☆]

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ABSTRACT

Groundwater recharge is a key component of the hydrological cycle but it is a complex process difficult to observe. Direct observations are essential to improve our understanding of this process, and lysimeters are the only powerful tools to reach this goal. In this study, we analyze 45 years of drainage data from 10 lysimeters located in the north-east of France (Fagnières) in order to understand the mechanisms controlling groundwater recharge in this region. These observations enable to assess groundwater recharge behavior as a function of several factors: climate, land use and agricultural practices. In this study, we first parse the long-term evolution of the groundwater recharge as a function of all these factors, and secondly we conduct a specific analysis on the impact of intense precipitation events on lysimeters drainage. A decreasing trend of the groundwater recharge over the last 45 years (average of $-2.5 \text{ mm year}^{-1}$) is found in relation to an increase in evapotranspiration which is in turn mainly driven by an increase in near surface air temperature and solar radiation, and a decrease of relative air humidity. Crop type and some agricultural practices (duration of rotation, catch crops) also impact the recharge rate. Finally, intense precipitation events represent 15% of annual precipitations and on average 15% of the recharge, while most of these events do not generate recharge because they occur mainly in summer. Only a few intense precipitation events in spring or summer time generate an important recharge event, and are associated with the most important accumulated precipitation.

1. Introduction

Groundwater is the primary source of freshwater on earth (Douville et al., 2021). It is therefore important to understand how and when it is recharged, and how it responds to both a more unfavorable water balance and increased occurrence of intense precipitation events or severe droughts which are expected under climate change. Groundwater recharge occurs through diffuse and focused mechanisms, the diffuse one being mostly associated with the infiltration of the precipitation over a large area, while the focused one occurs mostly from surface water bodies as rivers and lakes and is more localized (Healy, 2010). In temperate climate, as in France, the diffuse process is the main source of groundwater recharge. This recharge, also called soil water drainage, corresponds to the portion of precipitation that percolates through the unsaturated zone to the water table mostly via matrix flow, and escapes as evapotranspiration. Groundwater recharge is a complex process within the critical zone (Vereecken et al., 2008; Gaillardet et al.,

2018) and is affected by climatic conditions, crop type, topography, water table level, and soil characteristics.

Groundwater recharge is rarely observed, which makes it difficult to estimate (Moeck et al., 2020). Due to the limited number of observations and the difficulty to indirectly quantify it, the estimation of the groundwater recharge is one of the 23 unsolved problems in hydrology (Bloschl et al., 2019).

To respond to this challenge, several methods are deployed with specific objectives (Scanlon et al., 2002). Lysimeters are the only tools able to measure the drainage flow at the local scale, which can be considered as a good indicator of the diffuse groundwater recharge. They can be used in laboratory and field conditions where soil, crop type and meteorologic variables are monitored. There are several types of lysimeters, with many forms and sizes, from buckets to meter-sized containers (Pütz et al., 2018). Meter-sized lysimeters can be filled with undisturbed soil, or built around the original soil. One of the great

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advantages of lysimeters is that it is possible to install probes that provides continuous measurements at fine frequency (10 min-days) over several depths (e.g.: temperature, water content, matrix pressure) together with drainage flow at the bottom of the lysimeter. It is also possible to measure total mass, giving access to total water variations over the entire column. Some lysimeters are equipped with pressure-controlled porous plates at the bottom to adjust boundary conditions to those of surrounding soil (Singh et al., 2018).

Lysimeters have been deployed for many purposes while most of the lysimeters in France were installed to study chemical leaching (nitrate, pesticide) (Renaud et al., 2004; Yin et al., 2020). They can also be used to monitor the evolution of soil properties (Tifafi et al., 2017). Lysimeters give access to groundwater recharge but also to evapotranspiration (*ET*) using a simple water mass balance (Mustonen and McGuinness, 1967; Liu et al., 2002; Teuling, 2018; Voortman et al., 2015). Multi-year evolutions of the evapotranspiration associated with land use were obtained with lysimeters in the United States (Harrold and Dreibelbis, 1958; Bonta and Müller, 1999; Seyfried et al., 2001; Ochsner et al., 2018) and in Europe (Sims and Riddell-Black, 1998; Seneviratne et al., 2012; Groh et al., 2020; Müller and Bolte, 2009). More specifically, Seneviratne et al. (2012) reveal multi-year effects of the drought of 2003 in Switzerland on water balance and recharge, which reach up to spring–summer 2004. These results are also confirmed by Groh et al. (2020), who found that the 2015 drought in Germany limited the recharge in the next winter season. Intense precipitation is also analyzed, because it is one of the major concerns linked to climate change highlighted by the IPCC, since a warmer climate will most likely lead to an increase in the frequency and intensity of intense events (IPCC, 2022). These events can have important consequences for human activities with major floods (Tirado et al., 2010; Wheeler and Von Braun, 2013; Ben-Ari et al., 2018), such as in France and Germany in June 2016 where more than 150 mm of precipitation was recorded in 3 days (Piper et al., 2016; Van Oldenborgh et al., 2016; Philip et al., 2018). For example, two studies with lysimeters reporting the analysis of one event (Cheng et al., 2021) and three events by Sakura (1983) found a faster response of the recharge on loamy soil than on sandy soil, contrary to what one might expect. To be able to study several intense precipitation events, it is required to have observations over a long period. Therefore, most of the studies on the impact of intense precipitation on recharge were based on indirect observations, using piezometric data with the water table fluctuations method (Tashie et al., 2016; Fuamba et al., 2019; Pavlovskii et al., 2023; Corona et al., 2023).

The goal of this study is to (i) analyze the influence of climate and vegetation cover on long-term recharge and (ii) identify how intense precipitation intensity and frequency impact recharge. To do so, we analyzed 45-year of recharge of 10 lysimeters covered by standard regional crop types or crop rotation located in the Fagnières experimental station (France). An original method was developed to characterize intense precipitation events and associated recharge. A machine-learning approach was used to identify factors that drive recharge during these events.

2. Data

2.1. Experimental site

The INRAE Fagnières experimental station is located in northeastern France (Fig. 1), in a place designated as the chalky Grand Est region (49° 95 N; 4° 31 E). It began to collect data in 1973, mainly to study nitrogen transfers in the unsaturated zone (Ballif et al., 1983, 1996; Beaudoin et al., 2016). The station is equipped with a meteorological station and twelve lysimeters (Ballif et al., 1996) built around 2 m by 2 m soil monoliths, that collect the flow at 2 m depth (Fig. 1). Among the 12 lysimeters, one is shallower (1.5 m deep) and one is not disconnected to the deep soil, and is therefore a wick lysimeter. So,

Table 1

Soil properties of the Fagnières lysimeters: Bulk density, Organic matter (OM), Silt, Clay and Sand were measured in each available horizon before soil decarbonation (Ballif et al., 1996).

Layers	Thickness (cm)	Bulk density (g cm ⁻³)	OM (g kg ⁻¹)	Silt (%)	Clay (%)	Sand (%)
Ap	0–28	1.25	34.4	41.5	32.1	26.4
A1	28–35	1.60	9.3	39.9	17.9	42.2
C1	60–80	1.55	1.35	38.2	11.9	49.9
C2	90–100	1.40	0	34.9	16.1	49
C3	140–150	1.40	2.2	70.9	14.4	14.7
R1	150–160	1.40	0	37.9	27.3	34.8

in this study, ten lysimeters are selected. There is a seepage condition at the bottom of the lysimeter, without suction/temperature-controlled lysimeters. The soil is a rendosol, a hyper-calcareous rendzina overlying a chalk layer altered by cryoturbation and an undisturbed chalk substratum which is classical of the region (Table 1). The upper layer contains very high levels of calcium carbonate and a small quantity of mineralogical clay. Microporosity is less than 2 µm in diameter and originated from coccolithes, while macroporosity mainly originated from paleo-cryoturbation. On average, the former porosity was 0.35 m³ m⁻³ and the latter was 0.10 m³ m⁻³. These soils are characterized by a low sensitivity to compaction and a good hydraulic conductivity. In these soils, it was demonstrated that water transfer generally occurred in the soil matrix (Philippe et al., 2011; Yin et al., 2020).

Percolation of water is collected at a depth of 2 m through a perforated plate made of inox steel. The water collected reaches tipping buckets with a measurement precision of 0.1 mm. No puddles were observed on the ground surface.

The site was mainly dedicated to the monitoring of the nitrogen transfer, and made it possible to quantify the uptake of nitrogen by the plant of nitrogen applied (around 2/3), the part that is stored in the soil and the part that is leaching (around 10%) (Sebilo et al., 2013) as well as to improve and assess agronomic models (Constantin et al., 2010; Yin et al., 2020). The dataset was not yet used to analyze the long term hydrological recharge.

In the region, the main aquifer is the Seno-Turnonian chalk, and is generally located on a plateau. Piezometric levels fluctuate widely due to seasonal cycles marked by rainfall: rapid recharge at the beginning of the year, and regular emptying as soon as effective rainfall ends in May. The close-by Grandes Loges well (code BSS000LVDM) is analyzed. Its piezometric depth fluctuate from 7 to 29 m. This is a reference piezometer, considered to be representative of the region, with daily observations since 1969.

2.1.1. Agricultural practices

Among the 10 studied lysimeters, one was maintained on bare soil since the beginning (L6), two lysimeters were first covered with perennial vegetation (L2 with vineyard between 1975–1991; L4 with grass between 1975–2003). During the 45-year period, at least 6 lysimeters were cultivated with 3 different crop rotations representative of the region, that lasted at least 13 years and are presented Fig. 2. Winter wheat (*Triticum aestivum* L., noted W), sugar beet (*Beta vulgaris* L., noted S), spring barley (*Hordeum vulgare* L., noted B), pea (*Pisum sativum* L., noted P) were the main crops in the rotations, and radish (*Raphanus raphanistrum* subsp. *sativus* L.) was the main catch crop used in the rotation. The mean sowing dates were October 15th for winter wheat, March 15th for spring peas or spring barley; April 13th for sugar beet, September 6th for radish as catch crop. Ammonium nitrate was the principal chemical fertilizer used during the experiment. The mean fertilizer rates were 148, 131 and 141 kg N ha⁻¹ for winter wheat, sugar beet and spring barley, respectively.

The entire experimental period was divided into four periods involving specific crop sequences (Yin et al., 2020). The experimental set up made it possible to have three couples of lysimeters with the same

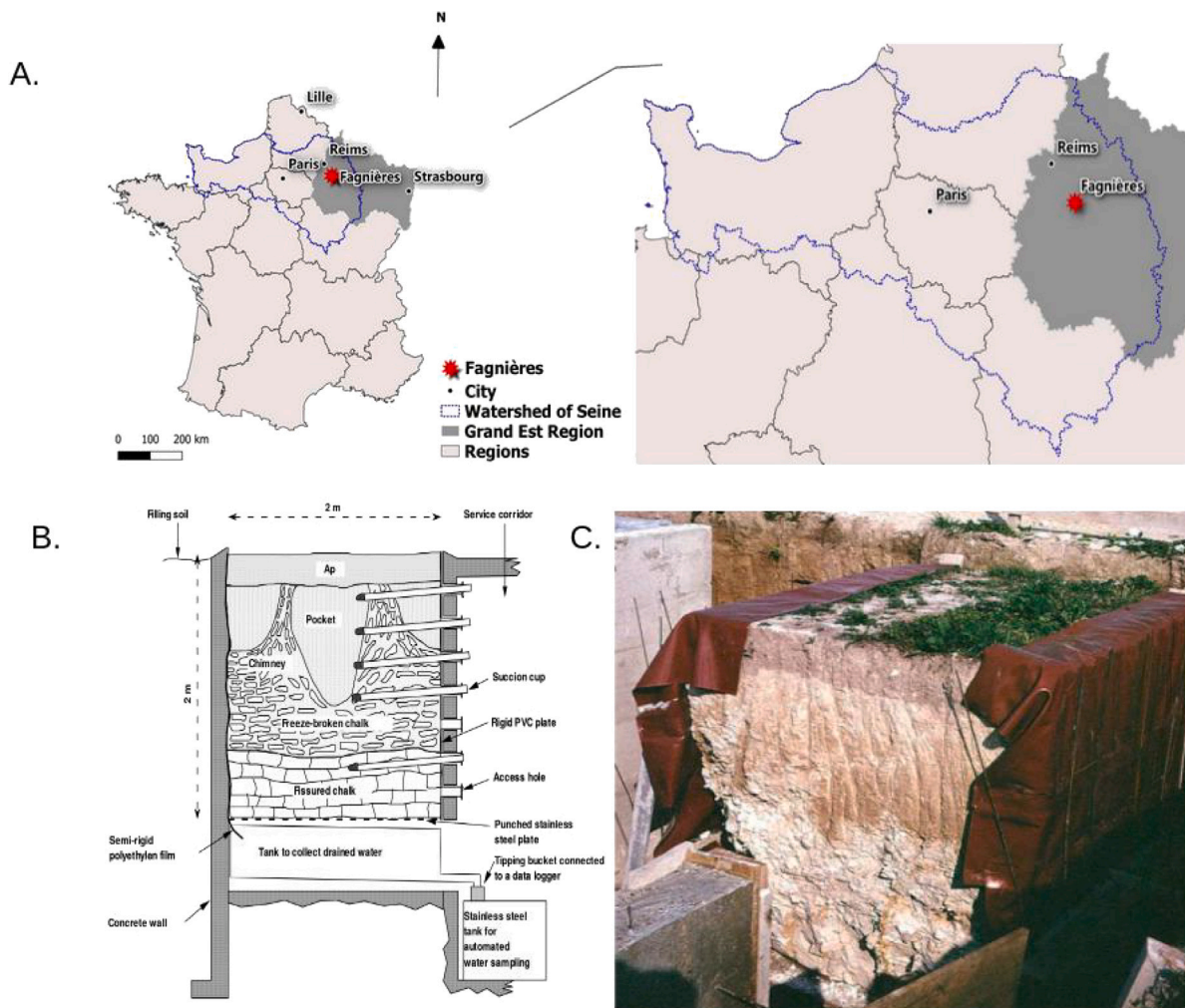


Fig. 1. A. Localization of the experimental site of Fagnières. The contour of the Seine catchment area is shown in blue. B. Horizon diagram for these soils from Ballif et al. (1996). C. Photo of a soil monolith cut on site before inclusion in the Fagnières lysimeters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

crop sequences since 1991, with and without catch crop: L1 and L3, L8 and L9, L11 and L12, respectively. Each pair starts its rotation one year apart. The soil was tilled to a depth of 20 cm each year. Thus, four periods can be distinguished:

- Period P1: from 1975 to 1990: 2-year rotation, composed of a winter wheat sown between September/October and harvested in May or June, then, bare soil, followed by Sugar beet, sown in March and April and harvested in September/October. Finally, a short period of bare soil can occur before the next rotation begins.
- Period P2: from 1991 to 2002: 3-year rotation, that complete the previous 2-year rotation with peas sown from March or April and harvested in July/August. Catch crop (radish) is introduced for three lysimeters, in order to shorten the bare soil duration. Thus 3-pairs of lysimeter, one with and one without catch crop are monitored, each one beginning with a different crop (L1-P, L8-W, L12-S without catch crop, L3-P, L9-W, L11-S with radish as catch crop).
- Period P3: from 2003 to 2012, same as P2 period but barley is used instead of pea.
- Period P4: from 2013 to 2020, same as P3 period but catch crops are used on all lysimeters (except L6).

3. Methods

3.1. Water budget

The water budget of the lysimeter is expressed as:

$$P = ET + Q + R_{unoff} + \Delta W \quad (1)$$

where P is the precipitation (mm), ET the evapotranspiration (mm), Q the drainage considered as the diffuse recharge (mm), R_{unoff} the runoff (mm), and ΔW the soil water volume change in the lysimeter (mm). The runoff is null on these lysimeters because they are not built on a slope. At the annual scale, the soil water volume change is negligible. Thus, the annual evapotranspiration can be easily deduced from the available measurements.

3.2. Trend analysis

The data from 1975 to 2020 are analyzed using hydrological year, i.e. from September of year Y to the end of August of year $Y+1$. Trends are calculated with the Mann–Kendall test (Kendall, 1948; Mann, 1945). It is a non-parametric rank-based method that makes no assumptions on the underlying distribution of the data. This test is generally used for climatological analyses (Karmeshu, 2012; Ringard et al., 2019) and has the advantage not to be influenced by extreme values.

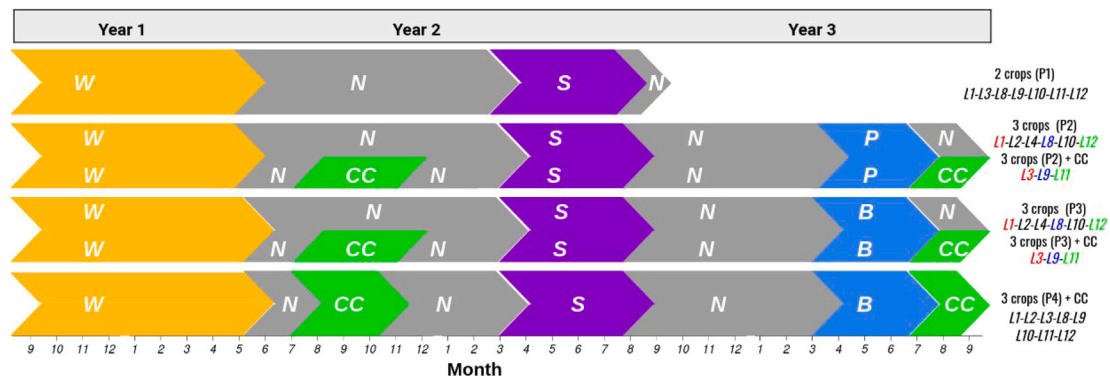


Fig. 2. Evolution of the major crop rotations at Fagnières. The scheme extends on 3 years, with the month of the year given on the bottom (1: January, 12: December). The main types of vegetation are presented by a letter: Winter wheat (W), Sugar beet (S), Pea (P), Spring barley (B), Bare Soil (N). 4 rotations are presented: a short crop rotation W–S during the period P1 (1975–1988), two long crop rotations W–S–P or W–S–B during the periods P2 (1989–2002), P3 (2003–2012) and P4 (2013–2020) respectively. For periods P2 and P3, catch crops (CC) are present on some lysimeters, while they are present in all lysimeters in P4. Paired lysimeters are distinguished by color (L1–L3; L8–L9; L12–L11). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

This method mainly gives three types of information. The Kendall tau measures the monotony of the slope and varies between -1 and 1 . The Sen slope, estimates the overall slope of the time series and corresponds to the median of all the slopes calculated between each pair of points in the series. These statistical scores are then evaluated in terms of significance, with the p -value ($< 5\%$). These tests are performed using R software and the `mk.test` and `sens.slope` functions.

Abrupt changes are detected using the Pettitt test (Pettitt, 1979), a non-parametric test that detects change where a point in the mean and variance a time series. This test is performed using R software and the `pettitt.test` function.

In addition, two precipitation indices proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI; Peterson et al., 2001) are computed: the maximum number of consecutive wet days (CWD) and the maximum number of consecutive dry days (CDD).

3.3. Characterization of intense precipitation and groundwater recharge events

Intense precipitation events are identified as the 99th quantile of the daily precipitation for the rainy days, i.e. the days with a precipitation rate above 1 mm day^{-1} . Most of the intense precipitation events are not isolated, but occur during a spell lasting several days, so that their responses in terms of recharge could begin after and last a longer time (Fig. 3).

Each intense precipitation event is thus characterized by: (i) the duration of the event $P_{Duration}$ (day), which is the number of consecutive wet days including the intense event with a daily precipitation rate above 1 mm day^{-1} (in blue Fig. 3); (ii) the cumulative precipitation P_{Vol} (mm) over the duration of the event; (iii) the maximum precipitation intensity P_{max} (mm day^{-1}) (in yellow) which by definition should be above the 99th quantile. In addition, accumulated precipitation over 10 days prior to the day with maximum precipitation intensity of the event P_{10} (mm) is also determined (in red), giving a proxy for initial soil conditions. This proxy is often used by the scientific community (McQuigg, 1954; Zêzere et al., 2005; Buczko et al., 2007; Schoener and Stone, 2020) and validated on other lysimeters in the region (Sobaga et al., 2023).

In order to interpret the recharge response, which may arrive with a delay, and therefore be influenced by several days of rainfall, we include the entire precipitation event in the analysis. A daily scale is therefore sufficiently accurate to study the intense rainfall events and their associated recharge.

The recharge response is characterized as follows: the recharge duration $Q_{Duration}$ (day) corresponds to the duration with a recharge rate above or equal to 1 mm day^{-1} , the accumulated recharge volume

Q_{Vol} (mm) over this event, and the maximum recharge intensity Q_{max} (mm day^{-1}) for each lysimeter and each intense precipitation event.

Such characteristics may differ slightly from Tashie et al. (2016) or Fuamba et al. (2019). The originality of the present method is based on a direct observation of the recharge via lysimeter whereas other studies (Corona et al., 2023; Pavlovskii et al., 2023) are generally based on groundwater level.

3.4. Multivariate regression tree

The reaction of the recharge to the intense precipitation depends on various characteristics, from the intensity, duration, accumulated volume of the event, to the soil moisture, soil cover, etc. To properly discriminate the most important characteristics that drive the variability of each variable of interest, we used a data mining method, the Multivariate regression tree (MRT).

MRT is a machine-learning developed by De'Ath (2002) that can be used to describe and analyze relationships between several groups and their characteristics. This method is generally used in ecology (Smith et al., 2019) and, more recently in hydrology and ecosystem services (Ndong et al., 2020, 2021).

We used the R software and the `mvpart` library (De'ath, 2007). A validation procedure for the results is carried out directly by the `mvpart` library, based on K-means cross-validation (Hamerly and Elkan, 2003), i.e. by dividing the data into k groups in such a way as to minimize the sum of the squares of the distances from a point to the mean of the points in the group, and then by searching for elements with similar variations (ACP).

We applied MRT to all intense precipitation events and for each crop type. The method requires to provide exploratory and response variables.

- exploratory variables:** season of event, characteristics of intense precipitation ($P_{duration}$, P_{Vol} , P_{max} , P_{10}), crop in rotation (Wheat, Sugar beet, Pea, or Barley).
- response variables:** recharge characteristics generated by intense rainfall ($Q_{duration}$, Q_{Vol} , Q_{max}). Each set of variables is normalized between the minimum and maximum values to enable comparison (Ndong et al., 2020).

4. Results

4.1. Evolution of the groundwater recharge over 45 years

4.1.1. Trend and evolution

Fig. 4 presents the evolution of the mean annual precipitation, temperature, as well as recharge and evapotranspiration for both the

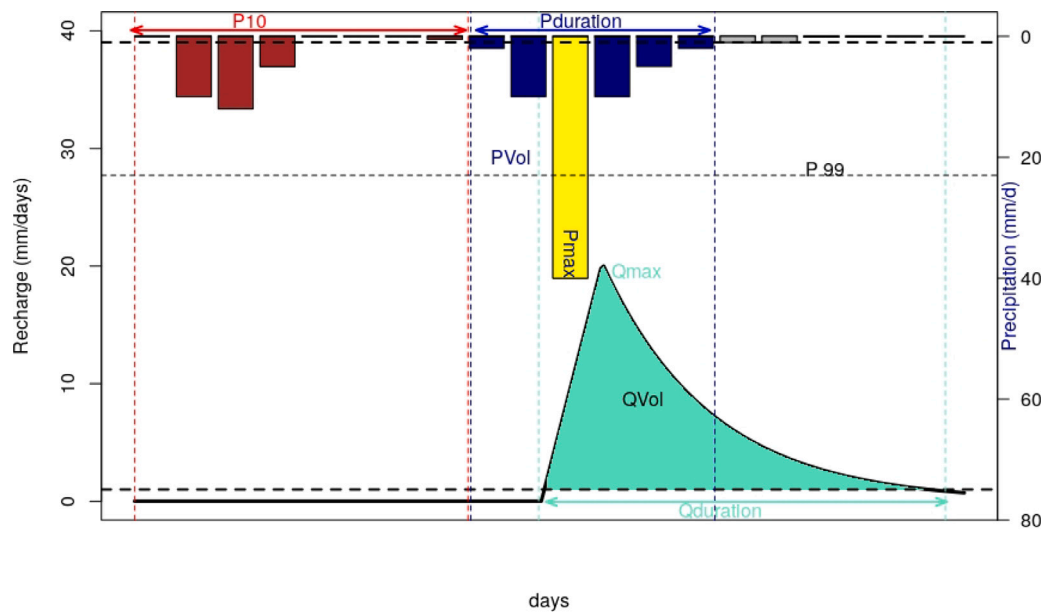


Fig. 3. Characterization of an intense precipitation event (in blue) by its maximum intensity (P_{max} , in yellow), its volume (P_{vol}) and its duration ($P_{duration}$). The volume of precipitation preceding this event is also calculated over 10 days (P_{10} , in red). Similarly, the recharge generated by an intense precipitation event is characterized (Q_{max} , Q_{vol} and $Q_{duration}$, in green). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

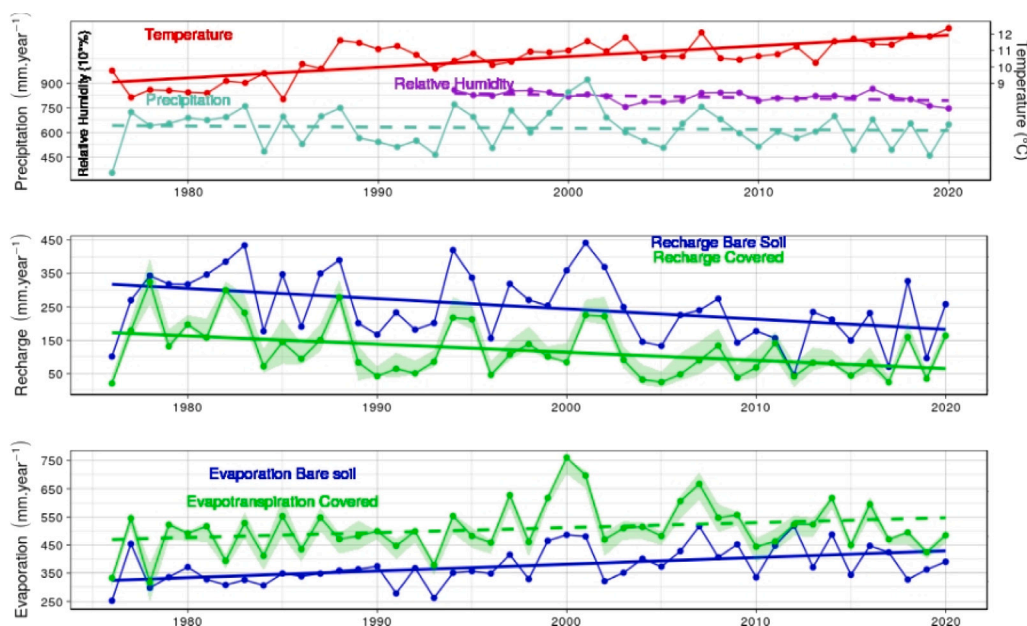


Fig. 4. Top: Mean annual 2 m air temperature (red), precipitation (light blue) and relative humidity. Middle and bottom: Mean annual recharge and mean annual evapotranspiration, respectively, for the bare soil lysimeter (blue) and vegetated lysimeters (green, with the 80% confidence interval shown in light green). Trends are computed over the hydrological years at the Fagnières site between 1975 and 2020 and are plotted as solid lines if they are statistically significant, dotted lines otherwise. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bare soil lysimeter and the vegetated lysimeters. Evapotranspiration is estimated via Eq. (1). The Mann Kendall trends are also plotted (Fig. 5).

At annual scale, the mean atmospheric temperature at 2 m (avg: 10.5, min: 8.0, max: 12.5 °C) is marked by a statistically significant increase (+0.42 °C every 10 years). The relative humidity (available only from 1994) decrease with a non-significant trend, which is associated with a rather stable specific humidity. The mean annual solar radiation (avg: 1186.0, min: 1005.0, max: 1370.0 W m⁻²) has a significant positive trend of 30.44 W m⁻² every 10 years (Fig. 5).

The annual precipitation (avg: 616.1, min: 353.0, max: 922.0 mm year⁻¹) have a non-significant decreasing trend (-15.15 mm every 10 years). Only 10% of the years have more than 750 mm year⁻¹ of precipitation. The maximum number of consecutive wet days (avg: 12, min: 6, max: 22 days year⁻¹) has a significant decrease (-1.25 days every 10 years).

On a seasonal scale, we find generally the same trends (Fig. A.15). Temperature rises significantly in all seasons except winter. The greatest increase is in summer (+0.59 °C every 10 years). Summer is also the only season with a significant decrease of the relative humidity.

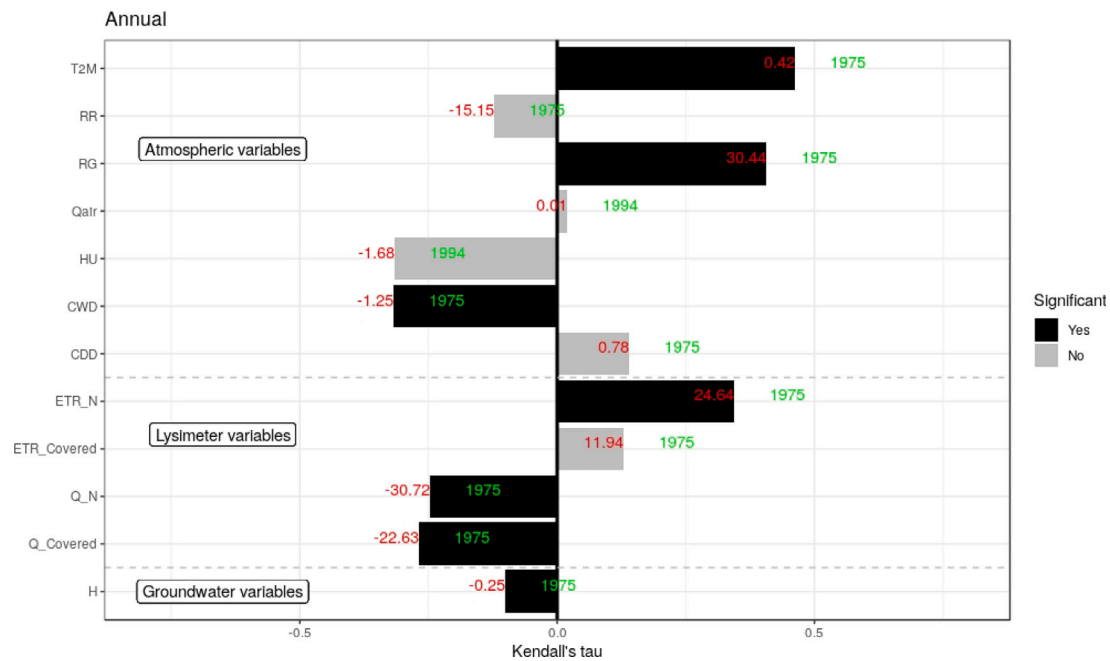


Fig. 5. Mann-Kendall trends in observation of 2 m air temperature (T_{2M} , °C), rain rate (RR , mm), radiation (RG , $W m^{-2}$), 2 m relative humidity (HU , %), 2 m specific humidity (Q_{air} , $g kg^{-1}$), consecutive wet days (CWD , days), consecutive dry days (CDD , days), recharge under cover soil ($Q_{covered}$, mm) and bare soil (Q_N , mm), and evaporation under cover soil ($ETR_{covered}$, mm) and bare soil (ETR_N , mm). Groundwater level is also studied (H , m). On the abscissa, Kendall's tau represents the rank correlation coefficient between the variable and time. The Sen slope (in red), is the median slope in units per decade. The year in green gives the start of measurement. A black color indicates a significant trend for a confidence interval of $p = 0.05$; and a gray color a non-significant trend. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

There is still no significant trend in mean precipitation at seasonal scale, although the maximum number of consecutive wet days decreases significantly at all season except autumn, with a larger trend in winter (-0.91 days every 10 years). The consecutive dry days increases significantly in spring ($+1.58$ days every 10 years) and decreases significantly in autumn (-0.92 days every 10 years).

On the bare soil lysimeter (L6, blue), the mean annual recharge is $250 mm year^{-1}$, with a maximal annual recharge reaching $440 mm year^{-1}$ in 2000–01 and a minimal recharge in 2011–12 ($46 mm year^{-1}$). The mean annual recharge of lysimeters with vegetation cover (green) is reduced to 53% ($118 mm year^{-1}$).

The atmospheric trends have an impact on the recharge, with a significant downward trend for the bare soil lysimeter ($-30.7 mm$ every 10 years: -12%) and for cover lysimeters ($-22.6 mm$ every 10 years: -15%).

In bare soil, the decrease is only due to the climate effect. For covered lysimeters, the attribution to climate trends is less straightforward due to changes in cropping patterns. But, the numbered of covered lysimeters (x9) enable to calculate a variability around the mean values for each year. With an 80 percent confidence interval, the variability for recharge and evapotranspiration stays low and confirm the average trends.

Recharge decreases at all season for all land uses (Fig. A.15), but is only significant in autumn, which can be related to the long lasting low moisture during summer (Beaudoin et al., 2008; Sobaga et al., 2023). Conversely, the water profile being usually replenished at beginning of winter, the decreasing trend of the winter recharge is not significant although it corresponds to the largest decrease in volume. In summer, recharge is already very low, so the reduction is limited.

The decreasing trends in the observed recharge is consistent with the one observed at the Grandes Loges well, with a significant decreasing trend on the piezometric level of 0.25 m every 10 years.

4.1.2. Influence of cultural practices

Fig. 6 presents the mean monthly recharge for the 4 periods for each soil cover or crop rotation. For bare soil, the maximum mean monthly

recharge occurs in December and January, and reaches 50 mm in P1, 55 mm in P2, 38 mm in P3 and 42 mm in P4.

The presence of vegetation reduces monthly recharge compared to bare soil (L6, L4 from 2003 to 2013). Maximum recharge is delayed by one month for the W-S and W-S-P rotations in P2, and even by two months for the W-S-B rotation in P3. In addition, maximum intensities are lower for covered soil (from -30 to -63%). Recharge periods are also reduced compared to bare soil, with a reduction of the number of recharge days per year that ranges from 20 to 66%. The full annual volumes are reduced compared to bare soil from 3% (2011–12) to 82% (2005–06). Annual volumes declined for all cover crops between periods P1 and P4 (except for Bare Soil in P4), and the gap with bare soil increased.

A reduction in recharge is clearly seen with the introduction of catch crops, particularly in autumn during P2, and in winter and spring during P3 (Fig. 6). Introduction of catch crops reduces annual recharge by an average of $24 mm year^{-1}$ over the two rotations (WSP P2 and WSB P3), with a more marked difference over the P3 period, for the W-S-P rotation ($28 mm year^{-1}$, $\approx 10\%$). For this period, the differences are significant between January and March (up to $8 mm month^{-1}$ in February), underlining the memory effect of the soil, since the catch crops are destroyed in November or December. However, the results differ over the P2 period, for which most of the differences are observed between October and January ($10 mm month^{-1}$ in December), corresponding to a period when catch crops are implemented.

4.2. Intense precipitation events

4.2.1. Occurrence and trends

At Fagnières, from 1975 to 2020, the 99th quantile of the precipitation used to discriminate intense precipitation reaches a rate above $23 mm day^{-1}$, which corresponds to 85 events. The mean of the daily intense precipitation is $31.0 mm day^{-1}$ (min: 23.1, max: 65.5). Intense precipitation events last on average 4.5 days (min: 1.0, max: 8.0), with an associated mean volume of 52.0 mm (min: 27.0, max: 98.0). The

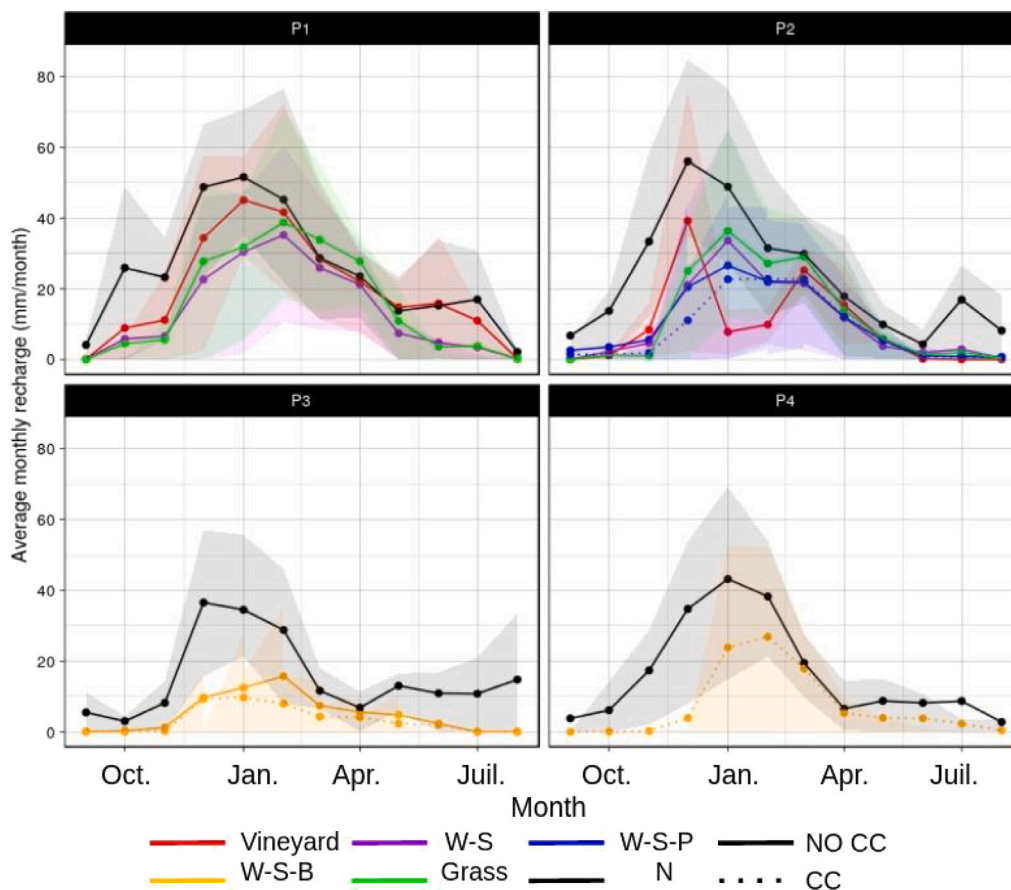


Fig. 6. Annual cycle of recharge for each soil cover and crop rotation over the periods P1 (1975–1988), P2 (1989–2002), P3 (2003–2012) and P4 (2013–2020) per cover. The presence of catch crop is shown as a dashed line, and the absence of catch crop is shown as a solid line. The 80% confidence interval is shown in the corresponding color range. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

average antecedent of precipitation is 17.9 mm (min: 0.0, max: 70.4). These events account for a small number of rainy days (4.5%), but are responsible for 15% of the total precipitation. 1982–83 is the year with the higher frequency of precipitation events (x5), and 2000–01 recorded the maximum daily rainfall intensity (65 mm j⁻¹) in July, 5th (Fig. 7).

Only the average intensity of these events decreases significantly (−0.23 mm day⁻¹ every 10 years, Fig. 8), while the volume of precipitation and the number of events remain stable.

As for annual recharge, the response range of the bare soil lysimeter is very wide: from no response at all (1995–96) to all precipitation drained to the groundwater (2007–08). Thus, the recharge from intense precipitation is rather stable through years although the annual recharge presents a significant decrease over years. As the annual recharge decreases significantly, the proportion of recharge from intense precipitation increases (+2.72% every 10 years), but is not significant.

4.2.2. Impact of soil cover

For the bare soil lysimeter L6, the part of the intense precipitation generating recharge, $\frac{Q_{P_{intense}}}{P_{intense}}$, is slightly greater than the part of the annual precipitation generating recharge, $(\frac{Q}{P_{annual}})$, with about 42% of the intense precipitations generating recharge compared to around 39% on average over the full period (Fig. 9).

However, when there is a vegetation cover, the relative proportion of precipitation generating recharge is in most cases slightly lower for intense events than for annual precipitation. Fig. 9 shows that as soon as there is a vegetation cover, the two ratios $(\frac{Q}{P_{annual}})$ and $\frac{Q_{P_{intense}}}{P_{intense}}$ are below 28%, except for L2 in P1, certainly because it was covered by

young vineyard during the period P1. The weakest ratios are for the lysimeters where catch crop is present (L3, L9, L11 for P2–P3 and all for P4). During the periods P2 and P3, the part of the recharge from intense precipitation on the total recharge is more important for lysimeters with catch crops than for lysimeters without catch crops because annual recharge volume is smaller, while the contribution of intense rainfall to the recharge is similar.

The recharge associated to intense precipitation events represent from 22% (L6) to 11% (L8, P1–P4) of the annual volume drained (Fig. 9), which means it is lower than the ratio of intense precipitation to the total precipitation (15%), except for the bare soil lysimeter L6.

Thus, even if these events account for an important part of the annual recharge, intense precipitations are less efficient to produce recharge than other precipitation events.

To deepen the analysis, the average intense precipitation events and recharge responses are plotted for each period (P1, P2, P3 and P4) by season and soil cover (Fig. 10).

Most of these events occur in summer and autumn (46 and 26%, respectively). Precipitation events last 8 days on average, and start generally 4 days before their maximum precipitation intensity. The average maximum precipitation intensity is 30 mm day⁻¹ which is slightly above the Q99 threshold, with a larger value during the P2’s winter and a smaller one during the P3’s winter. The recharge reaches its maximum shortly after maximum precipitation in winter, i.e. with only one day’s delay. During other seasons this delay is larger and can reach 2 or 3 days. In summer/autumn, the responses of recharge are very moderate, sometimes to the point of no recharge response at all.

Focusing on the bare soil lysimeter, during the period P1 the ratio $(\frac{Q}{P})_{P_{int}}$ ranges from 11% in summer to almost 100% in winter. It is rather similar in P2, however, for the later periods, since 2003, it

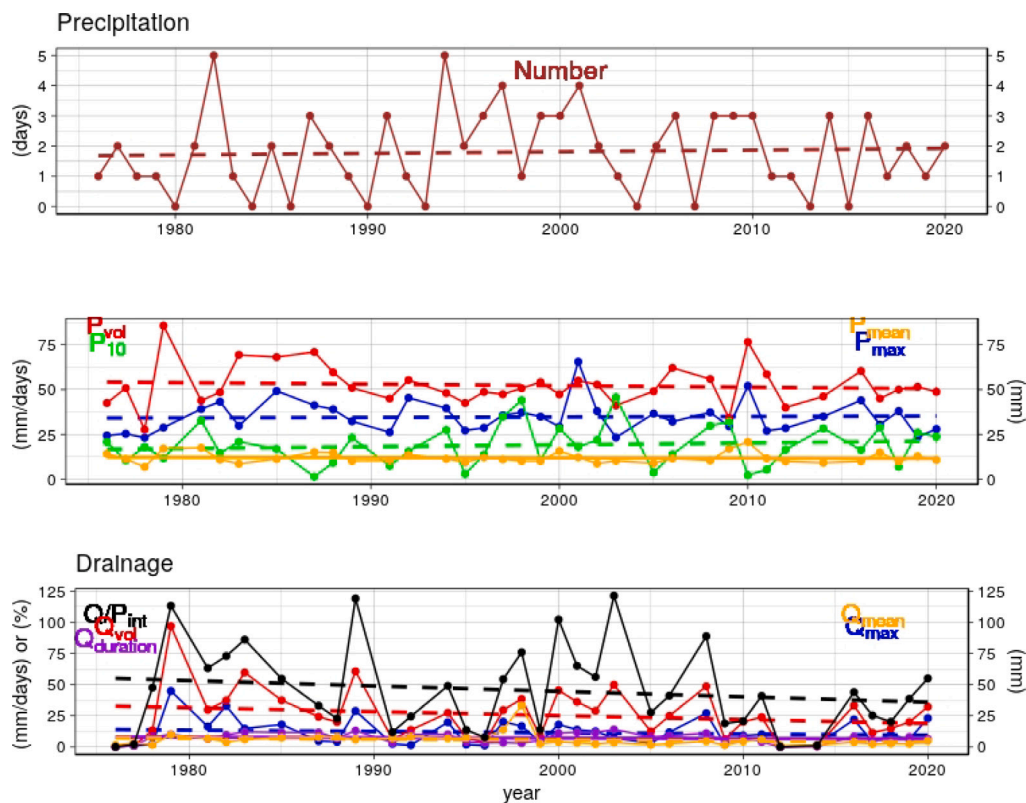


Fig. 7. Evolution of the intense precipitation events characteristics : the number of intense precipitation events by year (*Number*, brown), precipitation volume (P_{vol} , mm, red), maximum daily precipitation (P_{max} , mm day⁻¹, blue), antecedent precipitation (P_{10} , mm, green), mean daily precipitation (P_{mean} , mm day⁻¹, orange). Also shown for the bare soil lysimeter L6: recharge volume (Q_{vol} , mm, red), maximum daily recharge (Q_{max} , mm day⁻¹, blue), recharge duration ($Q_{duration}$, day, purple), mean daily recharge (Q_{mean} , mm day⁻¹, orange) and Recharge/Precipitation ratio (Q/P_{int} , %, black). These evolutions are plotted for the hydrological years from 1975 and 2020 at Fagnières. If there are many intense precipitation events in the same year, then the respective average values are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

can be seen that the bare soil generates a weaker response to intense precipitation, with a winter peak reduced to about 2/3 of the maximum precipitation, and a response similar to the other lysimeters.

Overall, the difference with and without catch crop is not significant (volume: -1.5 mm, duration: -0.5 days). However, differences are more pronounced in autumn (-4.9 mm and -1 days), during the season where catch crops are present, although the differences are not significant.

A special attention is given to a specific event that occurred in spring 2016 (period P4) in France and Germany with exceptional rainfall and heavy flooding (Van Oldenborgh et al., 2016; Piper et al., 2016; Philip et al., 2018).

At the Fagnières site, the intense precipitation event lasted 8 days, from May 26 to June 3, 2016, with a cumulative rainfall of 91.5 mm (Fig. 11). The maximum daily intensity was 44 mm day⁻¹ on May 30th. Recharge varies according to crop type. For all land uses except wheat, maximum daily recharge occurred the day after maximum rainfall, with intensities of 22.5, 17 (8–25.8), 14 (8–16) mm.day⁻¹ respectively for bare soil, sugar beet and barley. Wheat, on the other hand, did not react. This may be linked to the state of crop development since the previous month had been cold and wet, limiting the development of sugar beet and barley, unlike wheat, which was sown in winter and was therefore already well developed. Cumulative drained volumes are relatively similar for bare soil and sugar beet. They are reduced by 6 mm for sugar beet, 32 mm for barley, and is negligible for wheat.

The recharge dynamic is similar to that observed at the close-by Grandes Loges piezometric well. A very rapid rise of the water table is observed on May 31st (+2.27 m), followed by four days of stable piezometric level. The sudden rise of the piezometric head occurs at the same time as the most important rise of the recharge at Fagnières. Then,

the piezometric head stays at its maximum value for few days, probably due to the fact that there is an equilibrium between the recharge and discharge (i.e. groundwater flow). From June 6th, the important decrease of the daily recharge observed in Fagnières is consistent with the faster decreasing head at Grandes Loges.

Complementary to the observed lysimetric fluxes, an estimation of the groundwater recharge was made using the water-table fluctuation (WTF) method (Healy and Cook, 2002) for the event of May 2016. With a specific yield between 0.005 and 0.01 estimated in this region (Habets et al., 2021), the recharge was estimated at a range from 11.35 to 22.70 mm. Although the dynamic is similar to lysimeter data, this method leads to an underestimated recharge compared to lysimeters (45 mm on average). To obtain a recharge similar to the lysimeters, the Sy coefficient should be set to 0.022, which remains consistent with chalk soils (Price et al., 2000), but below the values used in this region. This difference in the recharge can be explained by (i) the spatial heterogeneity of soil/vegetation, especially since the wheat generated very few recharge, (ii) the potential interactions of groundwater with other fluxes at regional scale (ex. discharges, capillary rise, groundwater-river interaction).

4.2.3. Processes favoring groundwater recharge

Recharge response to intense precipitation varies for each event: 70% of events generate no recharge, while only 10% of events generate a strong response, i.e. a recharge greater than 30 mm that corresponds to the 90th quantile of volume drained during intense events.

To identify the processes favoring the genesis of a strong response, the MRTs described in Section 3.4 are used.

As an example, a MRT for a W-S-B rotation with catch crop is presented (Fig. 12). In this case, all the lysimeters with this crop

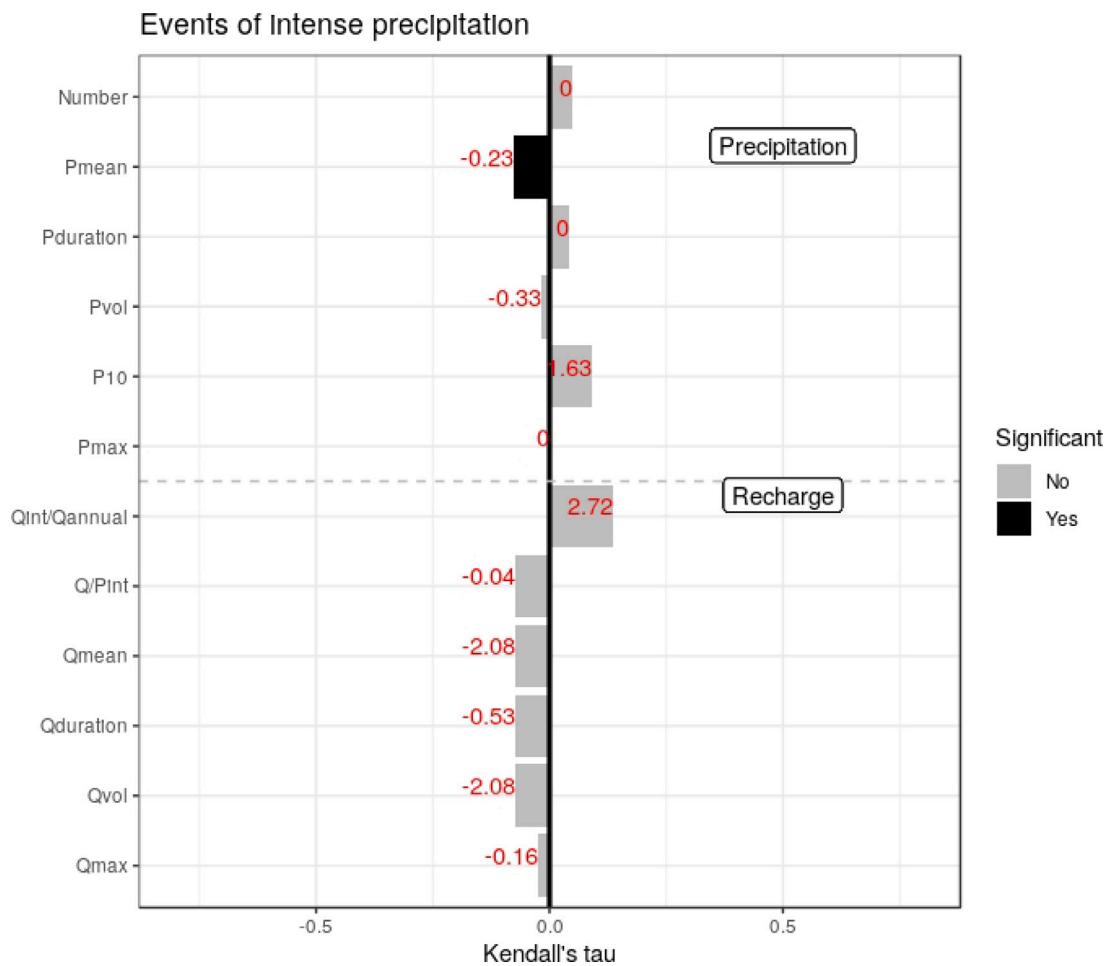


Fig. 8. As Fig. 5 but for intense precipitation events and associated recharge. The characteristics studied are as follows: the number of intense events by year (Number, -), the mean of intense precipitation and recharge (Pmean, Qmean, mm day⁻¹), the duration of precipitation events and recharge (Pduration, Qduration, days), the sum of the volume of precipitation events and recharge (Pvol, Qvol, mm), the mean volume of precipitation 10 days before the events (P10, mm), the maximal intensity of intense precipitation and recharge (Pmax, Qmax, mm day⁻¹) and the proportions of intense precipitation that generates recharge (Q/Pint, %) and the recharge from intense precipitation for each year (Qint/Qannual, %).

rotation are considered in P3 and P4. A MRT should be read from top to bottom. It shows the explanatory variables that correspond to the limiting factors, with their conditions and the groups of response variables, with their associated mean values in each group of the tree. In each group (“leaves”), the number of associated situations is given as well as the mean values of the response for each variable.

The first conditions found to have a strong recharge response to the intense precipitation event is a seasonal condition, as winter events react differently than the other seasons. There is a single condition in winter, it is to have an accumulated intense precipitation volume higher than 58 mm (12 cases). In such case, the mean recharge reaches 56 mm with a mean peak reaching 17.6 mm day⁻¹ and the recharge responses lasted 11.8 days. The 6 other cases occurring in winter generated a mean recharge of 13 mm, with a recharge peak of only 3.4 mm day⁻¹ and are not associated to intense response.

Only 3 strong responses occurred at another season, and are characterized by a duration of the intense precipitation event exceeding 7.5 days (right-hand branch) conditioned with the presence of sugar beet (the 3 cases all occurred during the event of June 2016 (Fig. 11)). The recharge associated to this event is similar to the ones occurring in winter: total recharge volume of 62 mm, with a peak of 19.8 mm day⁻¹ and a duration of 13 days. As a total, on 162 observations of intense precipitation on a W-S-B rotation with catch crop, only about 10% generated an intense recharge event.

The conditions for a strong response in terms of recharge vary with the soil cover and the season, as summarized (Fig. 13).

In summer, only 30% of the intense precipitation events generate important recharge if the crop type is bare soil or young vineyard. For long crop rotations, only 2% to 5% of the intense precipitation events not occurring in winter generate a strong recharge. There is even one condition that seems to prevent a strong recharge associated with intense precipitation events: the long rotation with pea and catch crop (Period 2), in summer and autumn (0 strong reaction over a total of 75 cases).

In winter, the behavior is different. Intense precipitation events are rare (8% of the cases, Fig. 10), but 40% of them generate strong response. Two soil covers strongly react to each of the 3 winter events in P2: the grass, and the long rotation W-S-P.

The conditions to have a strong recharge after an intense precipitation event may differ depending on crop type and season. For example, accumulated precipitation volume above 58 mm during the intense event seems to be a sufficient condition for bare soil, vineyard, short rotation and grass for all seasons, as well as for long crop in P3 and P4 (with barley+catch crops) in winter.

A duration of the intense event greater than 7 days seems also to be a sufficient condition to generate strong recharge on bare soil in all seasons except summer (17/58 cases), and in long crop rotation with barley in winter except when there are catch crops (5/14 cases). Antecedent 10-day precipitation should be above 25 mm for the long crop rotation with pea (Period P2) to react to all seasons, and even if there are catch crops in spring (3/18 cases), or with barley (in summer

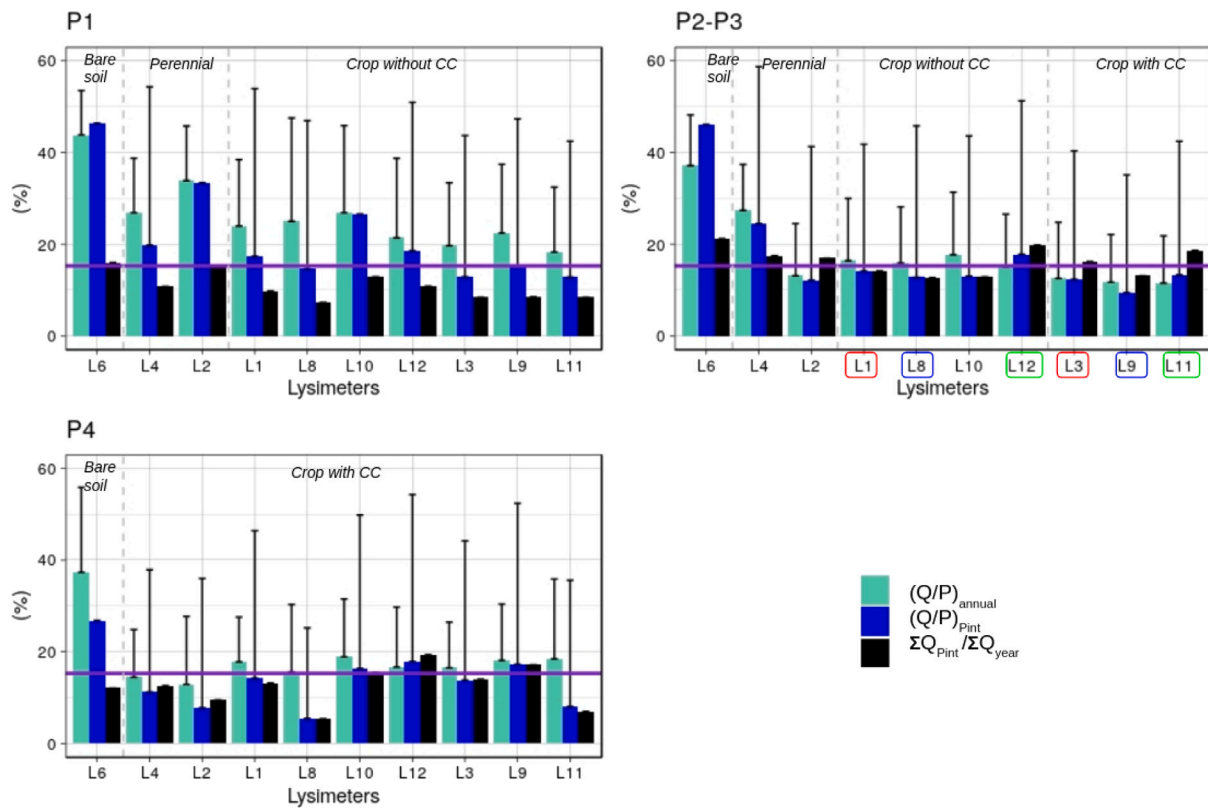


Fig. 9. For periods P1, P2, P3 and P4, the mean ratios of Recharge versus Precipitation (%) on annual scale ($\frac{Q}{P}$)_{annual} (azure), and during intense precipitation events ($\frac{Q}{P}$)_{intenses} (blue). Percentage of total recharge related to intense precipitation ($\frac{\sum Q_{intenses}}{\sum Q_{total}}$) (%) (black). Bars represent data variability estimated by standard deviation. The ratio of intense precipitation to total precipitation is represented by the purple line (%). Coupled lysimeters are distinguished by color for the period P3 (L1–L3; L8–L9; L12–L11). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and autumn) (4/75 cases). The presence of a given crop appears to be required to generate strong recharge in the long crop rotation: wheat for the W–S–P rotation (P2) in summer and autumn if antecedent precipitation is above 25 mm (4/75 cases), and sugar beet on the W–S–B rotation in all season except winter if the duration of the event exceed 7 days (3/144 cases).

To assess the ability of MRTs to detect strong responses, two a posteriori criteria were computed: the good detection rate (high response events well anticipated by MRTs), and the false alarm rate (low response events observed whereas MRTs anticipated a high response).

Good detection reaches on average 77% and even 94% for W-S rotations (Fig. 14). False alarms ratio are rare, only 6% of the cases. False alarms are lower for lysimeters with rotations (ex.: 0% for W-S-P-CC) than for bare soil (20%), which may be due to the fact there are more strong reactions and few criteria for the bare soil.

5. Discussion

5.1. Ability to use lysimeters to study groundwater recharge

The results presented should be interpreted keeping in mind some limitations of lysimeters (Pütz et al., 2018).

First, since there is no runoff, the groundwater recharge could be overestimated. Second, the bottom of the lysimeter is exposed to atmospheric pressure, excluding deeper capillary rise, and leading to the development of a water saturated zone in the deepest layer (seepage condition). It was shown however in a numerical analysis (Sobaga et al., 2023) that this does not strongly affect the recharge of different soils with similar climate.

Although deep capillary rise (below the first 2 m of soil) can sometimes occur in the region, its effect is not considered in lysimeters,

due to existence of the punched stainless steel plate (Yin et al., 2020) (supplementary materials). This can result in relatively drier soils in the lysimeters and could therefore limit possible recharge.

Changes in soil physical properties can also be observed in some lysimeters (Seneviratne et al., 2012; Tifafi et al., 2017). Yet, in the lysimeters of Fagnières, the soil is an undisturbed original monolith, and known to have a low sensitivity to compaction (Yin et al., 2020).

Finally, lysimeters are a powerful tool that can provide data on many processes with precision and give direct and local access to the diffuse recharge, over long period. They are experimental tools for studying environmental processes in soils under controlled yet realistic conditions. Lysimeters provide multiple replicates, allowing the effect of spatial variability of soils over short distances to be considered. They are particularly well adapted to study complex soil processes (Putz et al. 2016), but stay limited to regarding heterogeneity at regional scale, like fissure networks. These observations can support our research on the determinism of the groundwater recharge and allow to improve models (Xu and Chen, 2005; Moeck et al., 2016; Collenteur et al., 2021; Sobaga et al., 2023). Despite the aforementioned limitations of lysimeters tool, there is no doubt these experimental devices are suitable to assess long term trends of water balance.

5.2. Comparison of the climatic trends

In Fagnières, annual atmospheric trends (Figs. 4 and 5) are similar to those detected by a previous study in the nearby Ile de France region (Ringard et al., 2019). However, the absence of an increasing trend in intense precipitation (Figs. 7 and 8) might be surprising.

Indeed, a warmer climate will most likely lead to an increase in the frequency and intensity of intense events worldwide (IPCC, 2022). In France, the evolution of intense precipitation is still uncertain.

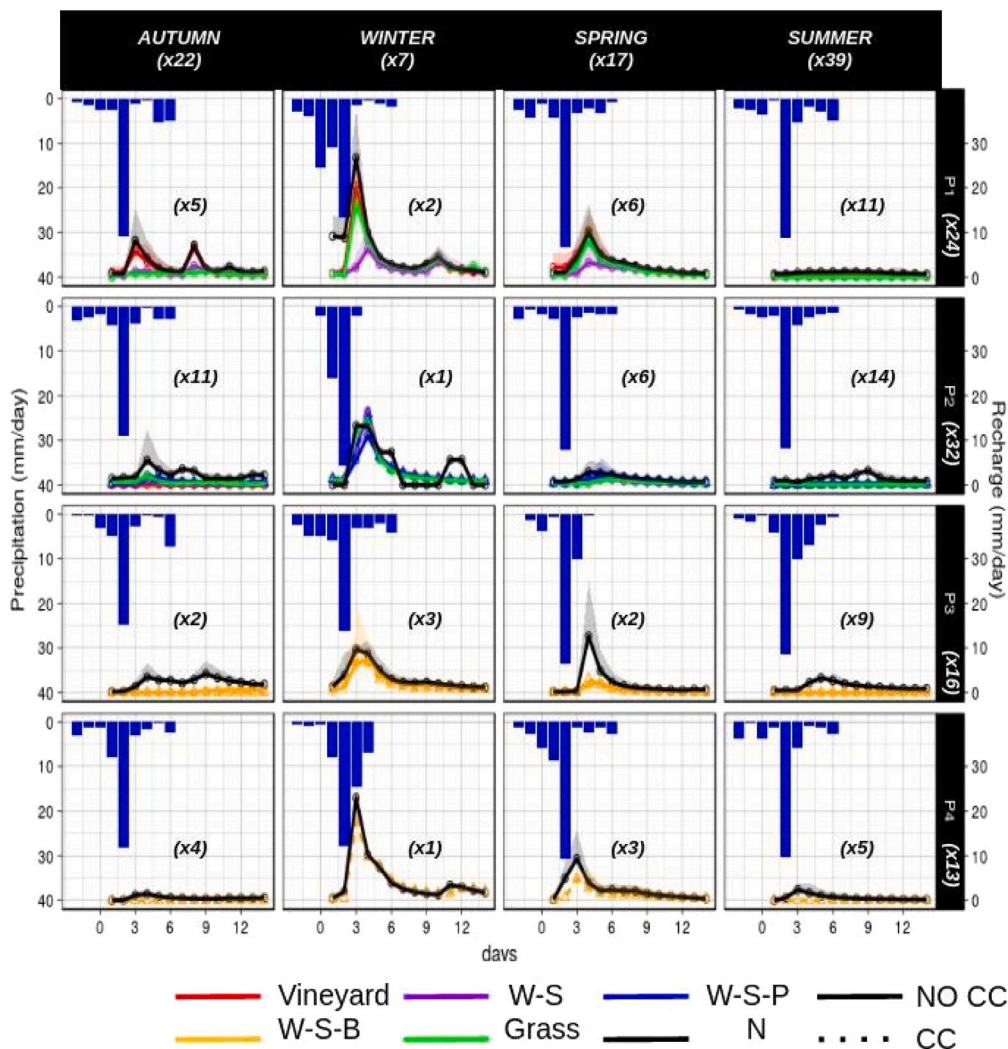


Fig. 10. Average characteristics of intense precipitation (blue barplot) and associated recharge according to the available cover (colored line) by period (P1, P2, P3 and P4 vertical) and season (autumn, winter, spring and summer, horizontal) at the Fagnières site. The number of intense precipitation events is also indicated. The 80% confidence interval is shown in the corresponding color range. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

June 2016

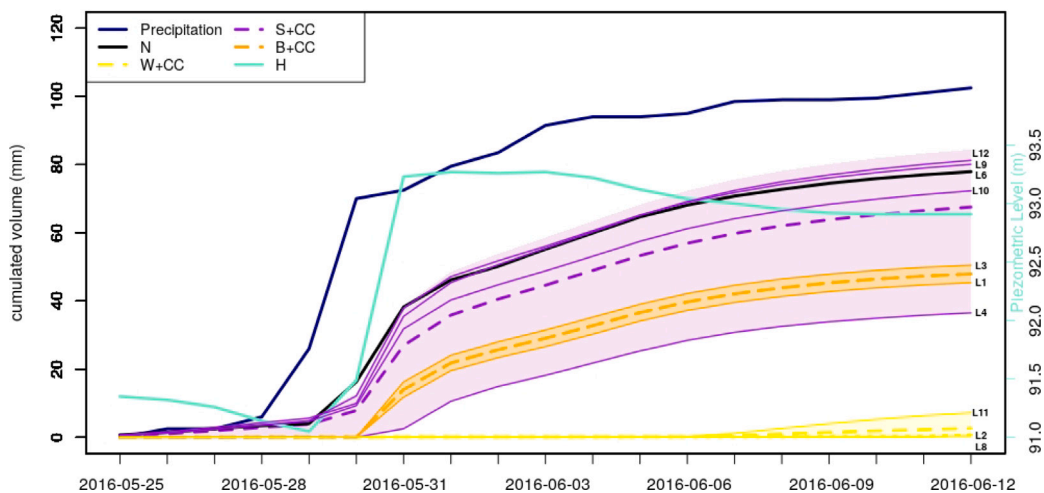


Fig. 11. Accumulated precipitation (blue) and associated recharge in June 2016 for each soil cover (bare soil, beet, barley and wheat, in black, purple, orange and yellow respectively). Plain lines correspond to a given lysimeter (with the number given on the right), dashed lines to the average recharge for a given crop type, and the colored areas to minimum and maximum values. Piezometric level observed locally at Grandes Loges is also plotted (azure). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

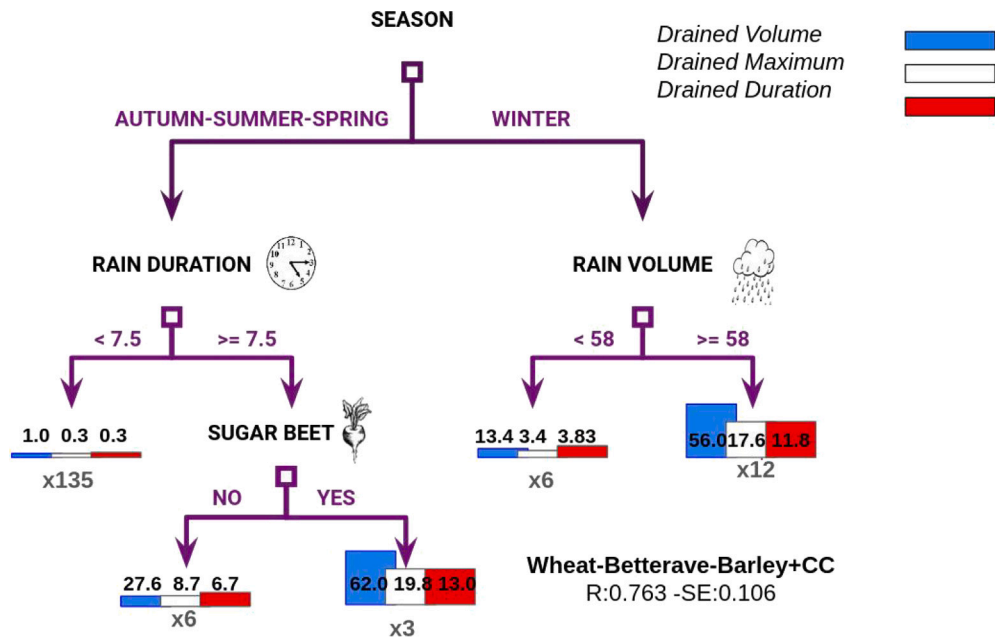


Fig. 12. Multivariate regression tree (MRT) for a W-S-B rotation with catch crop. The diagram is read from top to bottom. It shows the variables that emerge as explanatory factors and the characteristics of the response variables (Volume drained (mm) in blue, Maximum daily recharge (mm day⁻¹) in white, and recharge duration (d) in red). In each group, the number of associated situations is indicated (number preceded by a X). Overall statistical indices are given (R = correlation, SE = standard error of the 10 CV errors). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

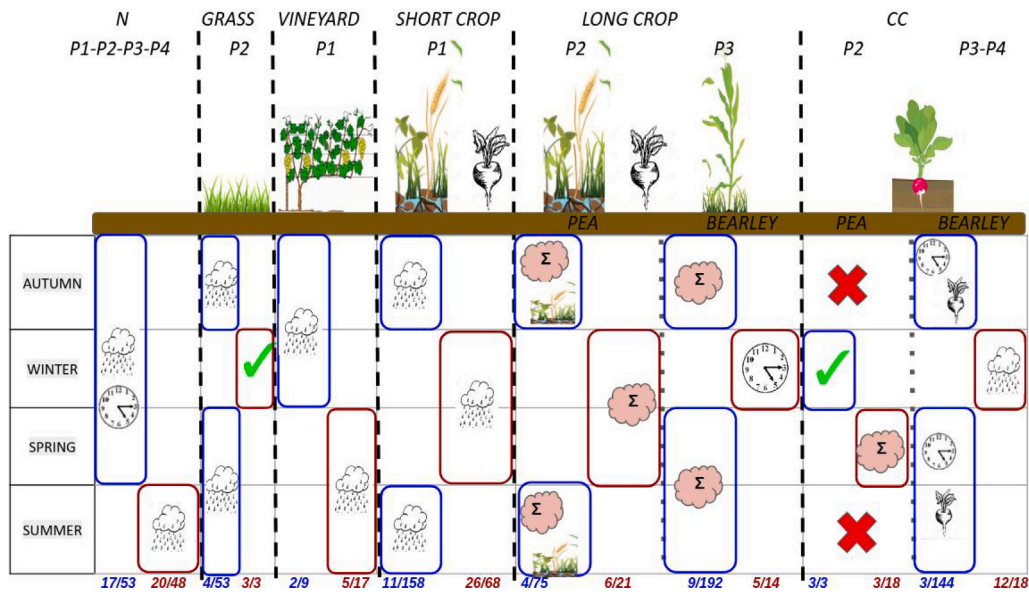


Fig. 13. Summary of the favorable conditions for a strong recharge response (> 30 mm) to intense precipitation events inferred by MRTs for each cover type in Fagnières. The conditions are represented by diagrams: cloud with rain for precipitated volume, red cloud for cumulative precipitation over 10 days prior to the intense precipitation event, clock for duration of the intense precipitation event, wheat/beet scheme for presence of wheat/beet, a green hook if no conditions are required, and a red cross if there are no strong responses. For each cover, several conditions are favorable to generate high recharge volume (in blue or red). In these groups, the number of events is shown on the total case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Some trends detected are not significant (Soubeyroux et al., 2015), in particularly because the data are patchy. On the contrary, the study of Van Uytven et al. (2020) highlights significant trends of intense hourly precipitation using the very long term chronicles in the city of Uccle (Belgium). These contradictory results may be related to the daily vs hourly scale analysis of precipitation. Our analysis is based on the daily scale. This is more consistent with the observed recharge, since the recharge starts after the precipitation event and lasts a longer time

(Fig. 3). To analyze if the time scale have an impact on the results, we performed a trend analysis of the intense precipitation at the hourly timescale. A statistically non-significant increase of the intensity of these events is found (+0.17 mm hour⁻¹ every 10 years).

5.3. Comparison of the recharge trends

In Fagnières over the period 1975–2020, we observed a decrease in annual recharge (Figs. 4 and 5). This trend is associated with

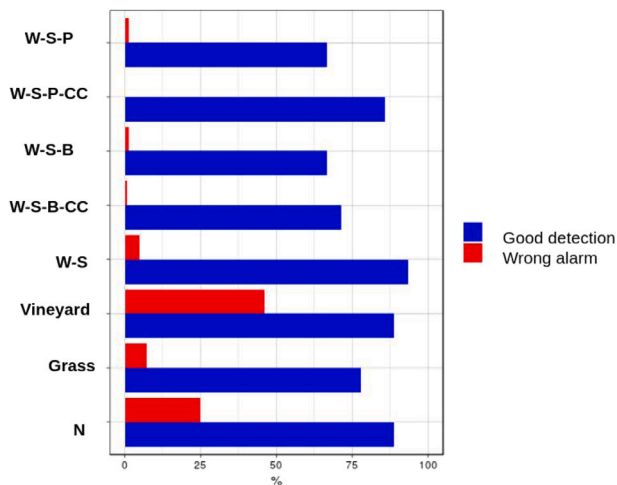


Fig. 14. Good detection (blue) and false alarm (red) rates (%) for strong recharge events according to land use. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the downward trends of the air humidity, that favor the evaporation demand, and by the decrease of the consecutive wet days (CWD) which makes it more difficult for the soil to be sufficiently moist to drain.

There are few other studies of groundwater recharge trends using lysimeters. In Castricum (Netherlands), a site characterized by an oceanic climate and covered by coastal dune vegetation or bare soil, Tollenaar and Ryckborst (1975) and Teuling (2018) found an increase of the recharge associated with an increase of precipitation, while the evaporation remains stable on the bare soil lysimeter. In this sandy soil, the water flows faster than in the soils of Fagnières, reducing the sensitivity to the evaporation. Thus, the recharge follows the trend of precipitation.

In a small pre-alpine watershed located in northeastern Switzerland, characterized by accumulation of snow in winter and with very humid conditions ($P: 1450 \text{ mm year}^{-1}$), Seneviratne et al. (2012) found a non-significant increasing trend of precipitation and evapotranspiration using a lysimeter. The non-significant trend of evapotranspiration is explained by two specific periods with opposite trends, following the variation of global radiation in this region.

In the north west of Germany, Harsch et al. (2009) find a non-significant decrease of evapotranspiration and recharge at a lysimeter covered by grass. These evolutions can be explained by a temperature increase mainly in winter, contrary to Fagnières, and also by changes in the surrounding environment of the lysimeter.

Another approach often used to estimate the trends of recharge is to analyze the trends in groundwater levels. The groundwater level trends estimated by Baulon et al. (2022) in this region are consistent with those of lysimeters. But, these results are also highly dependent on the region studied. Baulon et al. (2022) did not find significant trend of groundwater levels in the north of France (Artois-Picardy), while in other regions the trends are decreasing. In Northeast Germany a little further east, a region with a maritime/continental climate, Natkhin et al. (2012) observed a decrease of groundwater level of 2.3 mm year^{-1} . This trend is attributed to a reduction in precipitation and an increase in evapotranspiration. In colder climates, such as Sweden and Finland, Nygren et al. (2021) revealed a decrease of groundwater levels. This is associated with the decrease in wet day frequency and effective precipitation in the frost-free season in southern Finland and southeastern Sweden. An increase of groundwater was found in the southern Sweden, following the evolution of precipitation.

At European scale, the trends computed with the GRACE data, derived from change of aquifer storage, are also decreasing with $\sim 2\text{--}3 \text{ mm year}^{-1}$ in the region of Fagnières (Xanke and Liesch, 2022;

Scanlon et al., 2023). They also confirm the non-significant trend of groundwater level in the north of France, the north-west of Germany, and in the Netherlands.

5.4. The contribution of intense precipitation

Intense precipitation events can have important consequences for human activities causing major floods (Tirado et al., 2010; Wheeler and Von Braun, 2013; Ben-Ari et al., 2018), such as in France and Germany in June 2016 where more than 150 mm was recorded in 3 days (Piper et al., 2016; Van Oldenborgh et al., 2016; Philip et al., 2018).

In Fagnières, with an oceanic climate (Csb according to Koppen climate classification), intense precipitation events represent 15% of annual precipitations and generate between 8% and 18% of annual recharge (Fig. 9). However, over 70% of these events do not generate recharge and only 10% generate more than 30 mm (Fig. 10). These results can be different in other climates. In a drier or tropical climate, groundwater is mostly recharged by intense rainfall events where infiltration is the combination of runoff and sometimes preferential flow (Taylor et al., 2013; Zhang et al., 2016; Jasechko and Taylor, 2015; Thomas et al., 2016; Goni et al., 2021). The fact that lysimeters do not allow to consider spatial heterogeneity, and that there is no preferential flow, could also explain these differences.

As shown in Figs. 9, 10 and 12, the efficiency of intense precipitation to generate recharge is low in summer and for long crop rotation. This is consistent with previous studies based on piezometric levels that found that groundwater recharge during intense precipitation events depends on season (Lee et al., 2006; Tashie et al., 2016; Beaudoin et al., 2021), initial soil humidity (Huang et al., 2013) and precipitation characteristics (Tashie et al., 2016). For example, Sarrazin (2012), Tashie et al. (2016) and Huang et al. (2013) found that groundwater recharge increases with duration, and decreases with the magnitude/intensity of the precipitation event.

The amount of recharge generated by intense precipitation event is quite stable (Fig. 7) although the annual recharge present a clear decreasing trend (Fig. 4). The consequence is that the part of the annual recharge coming from intense precipitation tends to increase at a rate of $+2.72\%$ per decade (Fig. 8), although the trend is not statistically significant.

The recharge generated by intense precipitation events occurs mostly in winter, but remains rare: only once every five years (Fig. 10). In order to benefit from such events, it is important to reduce the risk of surface runoff in winter (not present in the lysimeter by construction).

5.5. Impact of crop rotation on the recharge

Our results illustrate the importance of crop type on groundwater recharge (Figs. 6, 10, 11, 13). A major finding is that the type of vegetation and the choice of agriculture practice (perennial crops, length of rotation, catch crop) have an important impact on groundwater recharge. An increase of the covered period increases evapotranspiration and reduces groundwater recharge. To illustrate this statement, a comparison with a permanent bare soil was done (Figs. 4, 7), even if this is not a common land use.

Our results are consistent with previous studies: for example, the review of Basche and DeLonge (2019) stated that perennial plants improve the infiltration compared to intensive agriculture, where crop rotation is generally implemented.

Our analysis highlights the important impact on groundwater recharge of (1) the duration of the agricultural rotation (Figs. 6, 10) and (2) the vegetation type used in each rotation (Figs. 11, 13). This is in agreement with Ochsner et al. (2018), who demonstrated that soil covered by continuous corn drained less quickly than a corn-soybean crop at annual scale. Renger et al. (1986) also showed that groundwater recharge is larger on fallow soil than on crop land.

The crop types during the rotation is also important. Conversely to wheat, the presence of sugar beet for long crops rotations tends to increase groundwater recharge during intense precipitation events (Figs. 11, 12). This is probably due to the fact that sugar beet is sown in spring, and moreover, early growth of spring crops is dramatically delayed in this soil type, due to its high albedo. This finding confirms the results of Ndong et al. (2021), who also found that sugar beet in crop rotation has an important impact on groundwater recharge.

5.6. Impact of catch crop on the recharge

The presence of catch crop (CC), generally recommended to reduce N leaching and to increase C soil storage (Beaudoin et al., 2008; Yin et al., 2017, 2020), reduces the recharge by almost 10%. The main differences are observed when catch crop are presents, but the effect lasts a few weeks after the crops were harvested or destroyed (Fig. 6). This reduction in recharge can be associated to an increase in evapotranspiration due to the catch crops. This reduces soil moisture only in autumn and winter, and thus groundwater recharge is reduced.

Our results are in agreement with the literature that underlines catch crops are able to reduce groundwater recharge (Gabriel et al., 2012; Justes et al., 2012; Meyer et al., 2019; Ndong et al., 2020).

The impact of catch crops on recharge during intense precipitation events has rarely been estimated. During intense precipitation events, we could expect that the presence of roots favors preferential flows (Flury et al., 1994; Gerke, 2006; Allaire et al., 2009) and generate faster groundwater recharge. This is not the case in our study. On the contrary, vegetation reduces the recharge (Figs. 10, 13). In agreement with Huang et al. (2013) and Tashie et al. (2016), this reduction is particularly strong when the duration of precipitation and the antecedent of precipitation are low, corresponding to events which generally occur outside winter.

We found that catch crops have a more limited impact on recharge during intense precipitation events than at annual scale (Figs. 6 and 10). This could be expected as intense precipitation events generate few recharge for all crop covers, except in winter time, when the effect of the catch crop is less sensitive.

6. Conclusion

Long term lysimeters observations in Fagnières enable to observe soil water transfers and understand processes in the unsaturated zone. These lysimeters provide direct observations of groundwater recharge over a long period. It is essential to investigate both the long term trends and the intense events.

The main results are the following: (i) groundwater recharge significantly decreased over the last 45 years, in response to meteorological drivers resulting in more evapotranspiration; (ii) the presence of vegetation strongly reduces recharge compared to bare soil, and the implementation of catch crops mainly used to reduce nitrogen leaching reinforces this effect. So, this trend should lead the cropping systems of this region to be optimized according to both water nutrients challenges, together; (iii) although few intense precipitation events produce recharge, their contribution over time is rather constant, leading to a growing part of the annual recharge.

The Multivariate Regression Tree (MRT) machine-learning method was used to identify the condition in which intense precipitation events generate recharge. We found that few intense precipitation event in spring and summer can generate an important recharge, and that accumulated precipitation above 58 mm are required for covered lysimeter. Furthermore, important antecedent precipitation are requested for longer crop rotation. Although less predominant, intense precipitation in winter is more likely to generates important recharge.

From the point of view of preserving water resources by facilitating groundwater recharge, several recommendations can be advanced. First, the adaption of the type of vegetation. This could be done by

choosing crops that consume less water before and during the period of recharge, in order to preserve the water balance. For example, catch crops are not recommended for the driest years, because they can limit groundwater aquifer recharge. One way of reducing evaporation is to leave crop residues on the soil. These results can give an idea for adaptation of agriculture or basin management in this region, where the recharge decreases while precipitation is stable. It is essential to find a compromise between preserving water resources and water quality and to adapt these recommendations to each region, with their specific climatic trends, soils, land cover, etc.

This analysis supports the need to use lysimeters in hydrogeology, in particular to study soil infiltration and groundwater recharge. Furthermore, taking into account that intense precipitation events at Fagnières are not the most extreme of France (Boé, 2007; Drobinski et al., 2016), and that the soils characteristics have a major impact on the recharge (Kim and Jackson, 2012; Sakura, 1983), it is of great importance to develop a lysimeter network throughout France to study the evolution of present and future groundwater recharge.

CRedit authorship contribution statement

Antoine Sobaga: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Florence Habets:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nicolas Beaudoin:** Writing – review & editing, Writing – original draft, Data curation. **Joël Léonard:** Writing – review & editing, Writing – original draft, Data curation. **Bertrand Decharme:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Seasonal trends at Fagnières

See Fig. A.15.

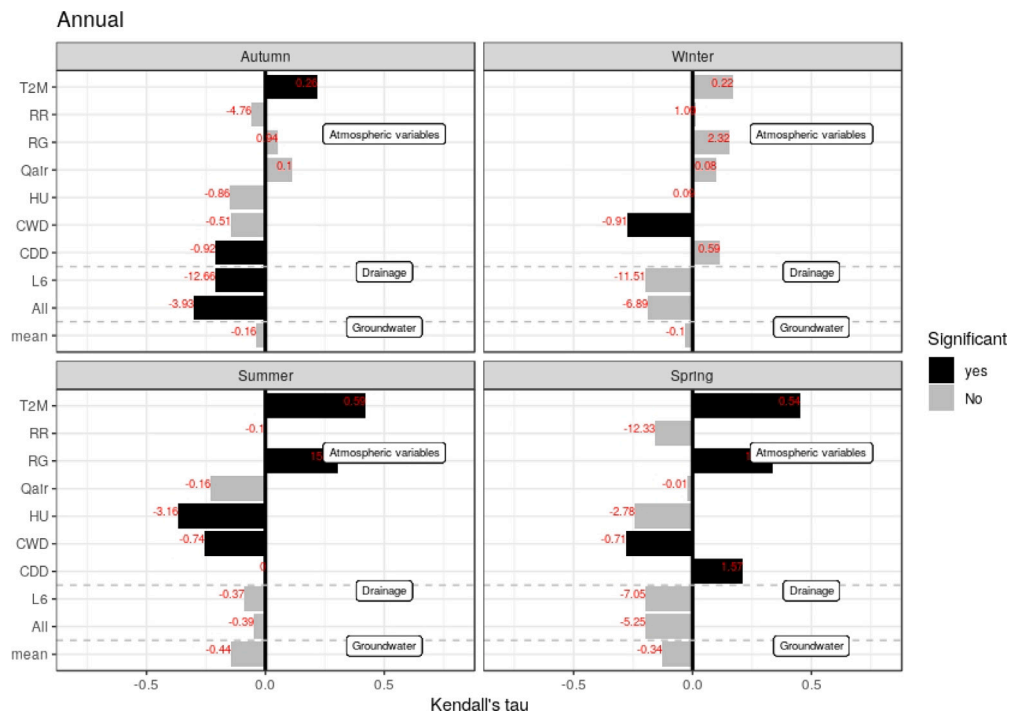


Fig. A.15. Same as Fig. 5, but by season.

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