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Groundwater recharge and associated uncertainty estimation combining multi-method and multi-scale approaches

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Abstract

Groundwater resource assessment is a major concern for water managers who have to balance water demands and resources at a basin or territory scale. One operational way to address this question is often to estimate only the part of recharge which is linked to precipitation. Many methods to estimate groundwater recharge are described in the literature, varying in terms of time scale and the nature of the data they treat. They do not always provide a suitable estimate of uncertainty. To obtain both a realistic estimation of groundwater recharge and a confidence interval at the hydrogeological basin scale, we propose a multi-method approach combined to a gridded water budget approach at the system scale. Firstly, ESPERE a recharge estimation tool combining several analytical methods has been developed and then applied to nine French hydrogeological case studies. The methods implemented in ESPERE are based either on climate data, discharges or piezometric levels time-series processing. This first approach addresses uncertainties linked to the estimation methods themselves. It also highlights the variability of recharge due to the interannual variability of meteorological data. Then, a spatialized approach was applied, in order to address spatial variability of meteorological data and parameters that control the water infiltration toward the aquifer. It relies on numerical treatments chaining cartographic data processing and water budget calculation with a resolution of 8 km. The combination of both approaches allows providing recharge time series at the systems scale, homogeneous recharge maps at the regional scale and uncertainty estimation associated to the calculation methods.

Keywords*: G*roundwater recharge; estimation; uncertainty; ESPERE

1 INTRODUCTION

Groundwater recharge can be defined as the downward flow of water through the unsaturated zone to the water table, increasing the quantity of water stored in the aquifer formation (De Vries and Simmers, 2002). In other words, it is the proportion of rainfall that infiltrates and replenishes the groundwater reservoir. It depends not only on the meteorological context, but also on geomorphological characteristics (slope, hydraulic roughness, etc.), the surface of the catchment area, soil properties (vegetation, soil type, available water capacity), and the hydrodynamic properties of the subsurface formations.

Many methods to estimate groundwater recharge are described in the literature (e.g. Scanlon et al., 2002 and Xu and Beekman, 2003). They vary depending on both the time scale (from a daily step to a yearly step) and the type of data used (meteorological or hydrologic). According to the type of data used and the way recharge is computed, these methods deal with different types of recharge (direct recharge only or total recharge including indirect recharge). Several studies have attempted to compare the results of different methods, notably in the United States in the 2000s (e.g. Flint et al., 2002 and Coes et al., 2007) and have shown that the accuracy of these methods varies depending on the type of aquifer being studied. Actually, a part of the accuracy of groundwater recharge estimates depends on the accuracy and relevance of the inherent assumptions of the underlying models used to estimate groundwater recharge (Halford and Mayer, 2000).

Therefore, to obtain both a realistic estimation of groundwater recharge and a confidence interval for the result at the hydrogeological basin scale, one solution can be to apply various commonly-used methods relying on different hypotheses and combine their results. Following that idea, we ran the numerical tool ESPERE that allows applying rapidly and simultaneously up to ten different methods to estimate the aquifer recharge (Lanini et al., 2016). Then, in order to evaluate the spatial distribution of recharge, we spatialized one of the previously applied water budget method on a 64 km^2 grid. This two-steps process was performed on 9 case studies located in France with various hydrogeological and meteorological context. The combination of results obtained with various methods at two different spatial scales allows providing water managers with operational data on aquifer recharge.

2 MATERIAL & METHODS

2.1 Recharge estimation methods

The procedures included in ESPERE and applied in this study can be split up into four categories: empirical, soil water budget, water-table fluctuation, and discharge filtering methods. They operate with at a daily or yearly time step.
The empirical method is the Turc method (1954) which is based solely on climate data (precipitation and temperature) and which has been successfully applied within various hydro-climatic contexts throughout the world. The second group of methods is based on the calculation of the water budget. At the aquifer scale, effective rainfall defined as the total precipitation minus actual evapotranspiration and water stock variation in the unsaturated zone, is equal to the sum of runoff and infiltration.
The three soil water budget methods implemented in ESPERE derived from the Thornthwaite model (1948). Thornthwaite's equations calculate the daily effective rainfall based on precipitation, potential evapotranspiration and a single parameter related to the nature of the soil and representing its maximum storage capacity. Successive improvements have been proposed in the literature, notably to take into account snowfall or to introduce a progressive emptying of soil water reserves. ESPERE includes Thornthwaite's method and two refined formulations (derived from Dingman, 2002): one using PET values input by the user (usually Penman-Montheih PET) and another calculating daily PET using the Hamon equation. In order to transform the effective rainfall calculated using these methods into groundwater recharge, a coefficient called “effective rainfall infiltration” (ERI) is used.
The third type of method used to calculate recharge in ESPERE is the water table fluctuation method (WTF) based on the treatment of groundwater level time series. This method relies on the hypothesis that variations in the water table are mostly linked to infiltrated water that arrives at the water table during a given laps of time (Healy and Cook, 2002). The water budget of the aquifer can therefore be written as $R=s.\Delta H/\Delta t$ where R is the recharge and ΔH is the water-table height variation during Δt. *s* is the specific yield (i.e. the drainage porosity of the unconfined aquifer). The WTF procedure implemented in ESPERE at the annual time step was suggested by Delin et al. (2007) and implies summing up all the water level rises over the year.
The last category of methods are signal treatment procedures applied to analyze time series of river streamflow. These methods separate the part of streamflow that comes from surface and subsurface runoff from the part related to base flow. Baseflow is the part of streamflow that originates from stored sources. Over a long period (basically over a year), it can be equated to groundwater recharge. They are often associated with a base flow index (BFI), which is the ratio of base flow to total flow for a given period (month, season, or year). The Institute of Hydrology in Wallingford (UK) developed a commonly-used procedure to calculate base flow and the BFI (e.g. Gustard and Demuth, 2008). The Visual Basic code in ESPERE for BFI calculation is adapted from the code developed by the European Drought Centre (Tallaksen & Van Lanen, 2004). Two other numerical filters of streamflow time series, proposed by Chapman and Maxwell (1996) and Eckhardt (2005) are used in ESPERE. They are based on the assumption that the pure recession sequences can be modeled by a decreasing exponential.

2.2 Spatialized Thornthwaite Water budget Method

All methods included in the ESPERE tool provide global recharge estimations at the scale of the studied hydrogeological basin. We attempted to describe its spatial variability within the basin using one of the methods of the single group of those allowing it: water budgets. The Thornthwaite soil water budget method was applied for each 8x8 km cell of a mesh covering the studied catchment. Groundwater recharge is assumed to be equal to infiltration calculated by this soil water budget. The methodology, summarized on figure 1, implies that spatial distribution of soil water storage capacity is known, and that daily meteorological data (precipitation, potential evaporation, and temperature) are available for each cell. We run all the procedure combining the use of ArcGIS and Matlab software. Meteorological data was taken from the Météo-France SAFRAN reanalysis (Vidal et al., 2010) and soil storage capacity from the DoneSol INRA (2014) national soil database.

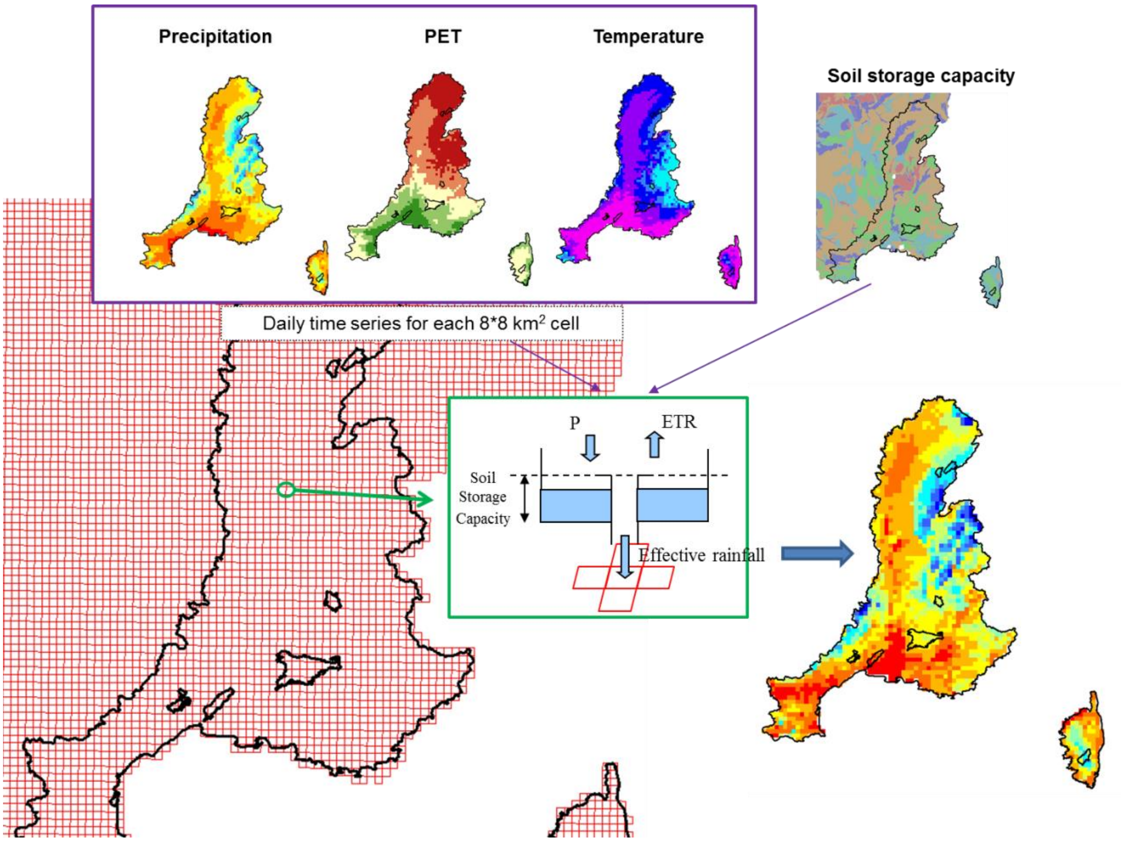


Figure 1: Methodological sketch of the gridded water budget method for effective rainfall computation (here applied over the whole Rhône-Mediterranean & Corsica basin, see figure 2).

2.3 Case studies presentation

The nine case studies are located in France in the Rhone-Mediterranean & Corsica basin (figure 2), and were chosen as they are representative of various hydrogeological and meteorological contexts. The characteristics of these hydrogeological basins are summarized in table 1.

Table 1: Physical, geological and meteorological characteristics of the nine case studies

	Impluvium area	Geological formation	Annual precipitation (1996 -2011)	Average daily temperature (1996 -2011)	Average soil storage capacity
Dijon	45.8 km^2	Alluvial	793.6 mm	11°C	170 mm
Fontaine de Vaucluse	1317.5 km^2	Karstic	987.8 mm	9.9 °C	20 mm
Galaure	225 km^2	Sandstone	973.1 mm	11.6 °C	149 mm
Gillardes	200 km^2	Karstic	1175.3 mm	5.6 °C	30 mm
Lez	177 km^2	Karstic	978.4 mm	13.7 °C	48 mm
Lison	137.7 km^2	Karstic	1514 mm	8°C	30 mm
Loue	247.6 km^2	Karstic	1514.1 mm	7.5°C	30 mm
Taravo	331 km^2	Granitic	1297.9 mm	11.3°C	47 mm
Vistrenque	265 km^2	Alluvial	760.9 mm	14.8°C	82 mm

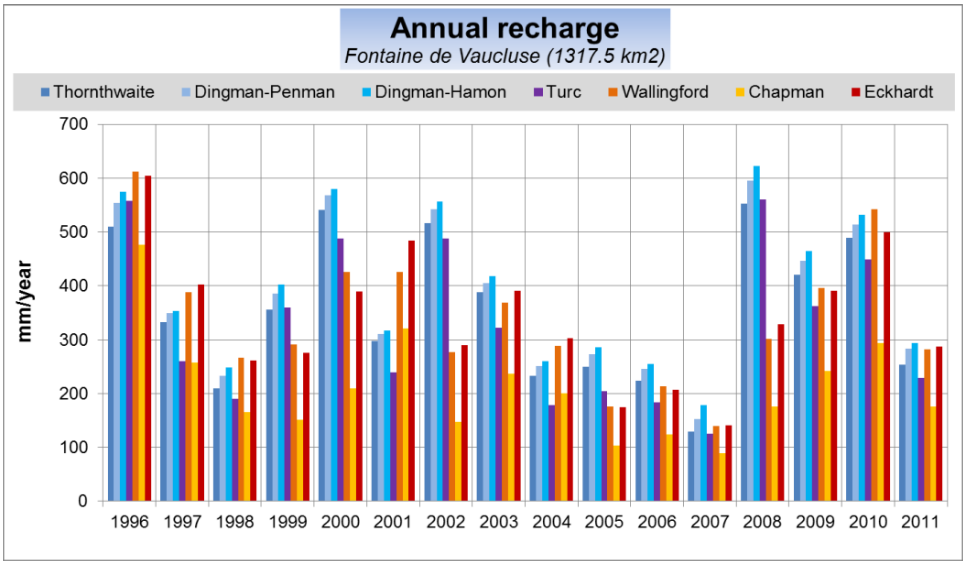
Figure 2: Location of the nine case studies

3 RESULTS

In the two following sub-sections, detailed results obtained for the Fontaine de Vaucluse system are presented. The last sub-section summarizes results for the nine case-studies.

3.1 Fontaine de Vaucluse multi-method recharge estimation with ESPERE

The Fontaine de Vaucluse spring is the largest karstic outlet in France, with a mean flow rate of 16.7 m^3/s (1996-2011). The karstic network is developed in the lower Cretaceous limestone series, of which the thickness can reach 1500 meters. More details on the functioning of this system are given in Fleury et al. (2007).
Regarding the available data, seven different methods could be applied to evaluate the recharge of the Fontaine de Vaucluse karstic aquifer: three water budget methods (blue bars on figure 3), three streamflow filters (orange & red bars) and Turc empirical method (purple bars). The ERI coefficient value was set to 64% and the soil storage capacity to 20 mm (see §3.2). The flow rate mean recession curve constant was determined using the very convenient Excel tool provided by Posavec (2010). Over 16 years (1996-2011), the recharge estimated using the seven methods for the Fontaine de Vaucluse aquifer ranges between 89 and 623 mm/year, with a mean value of 335 mm/year and a median value of **299 mm/year.**



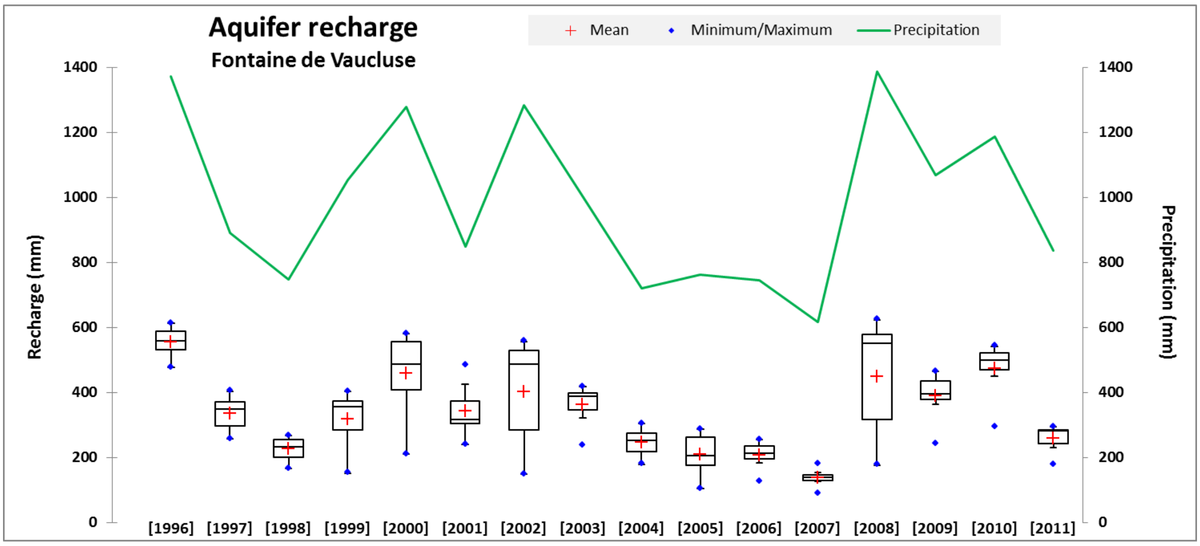


Figure 3: Annual recharge multi-method estimation for the Fontaine de Vaucluse karstic aquifer

3.2 Spatialized recharge for the Fontaine de Vaucluse system

In order to describe the spatial distribution of the estimated recharge, the spatialized water budget method results were analyzed. This distribution may be mainly controlled by the meteorological and ERI coefficient variability, as the soil storage capacity over the Fontaine de Vaucluse system is spatially uniform and equal to 20 mm (DoneSol INRA, 2014). To include an assessment of the uncertainty associated to the value of the distributed ERI coefficient, two different computation methods were compared. The first is based on the use of the infiltration to the effective rainfall ratio simulated by the SURFEX land-surface scheme (Masson et al., 2013) averaged over the 1996-2011 period. The second is based on the IDPR index (Mardhel et al., 2004) which characterizes the infiltration and runoff properties of landscape. The ERI coefficient was finally computed by averaging the values obtained using both methods over all the cells of the grid (see Caballero et al, 2016 – in French, for details). The resulting averaged value of infiltration over the overall Fontaine de Vaucluse system, represents 64% of the effective rainfall, with local values varying from 55 to 74% (figure 4).
The spatial distribution of the annual recharge at the basin scale, calculated with the spatialized Thornthwaite water budget method over the 1996-2011 period with 8x8 km resolution, is presented in figure 5. The mean recharge averaged over the entire surface of the basin, is equal to **344 mm/year.** The associated uncertainty is addressed in the next section.

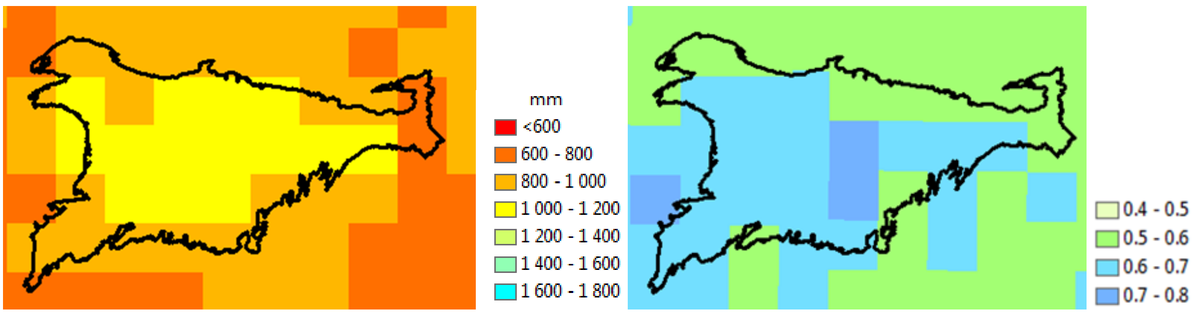


Figure 4: Annual precipitation (1996 – 2011) (left map) and spatialized ERI coefficient (right map), 8 km resolution, for the Fontaine de Vaucluse system.

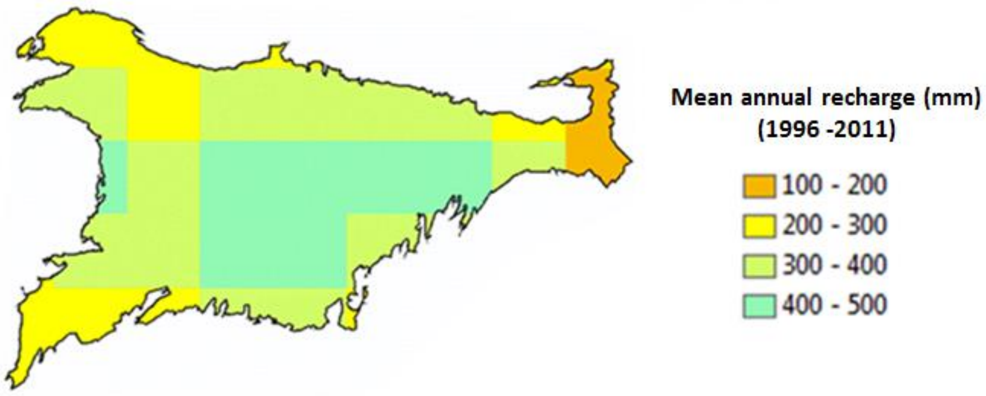


Figure 5: Annual groundwater recharge for the Fontaine de Vaucluse system.

3.3 Results for the nine case studies

For the nine case studies (figure 2), the following methods were run with ESPERE over the 1996-2011 period: three water budget, three stream flow time series filter, Turc, and the Water Table Fluctuation method when piezometric data were available (Dijon, Lez and Vistrenque). The ERI coefficients needed for these simulations are calculated as described for the Fontaine de Vaucluse case study. They range from 0.59 (Gillardes system) to 0.8 (Loue karstic system).
The average recharge values estimated with ESPERE for the nine aquifers over the period 1996-2011 are presented in table 2 together with their mean absolute deviation (MAD). The latter illustrates the variability of both the different recharge estimation methods and the meteorological forcing over the 16 years period (wet/dry years). The uncertainty on recharge estimation, expressed by the ratio MAD / Mean, ranges between 19 and 42%. At the same time, the interannual variability of meteorological data, expressed by the same indicator, ranges from 9 to 22%.
The relative uncertainty of the mean annual spatialized recharge can be calculated as the sum of the relative uncertainty of effective rainfall and of the relative uncertainty of ERI coefficient. The daily effective rainfall is calculated for each 8*8 km² cell included in the hydrogeological catchment, with the Thornthwaite method, as described in §2.2. Its mean interannual value (period 1996-2011) presents a spatial variability that we characterized as the half of the difference between maximum and minimum values at the catchment scale. The uncertainty on the ERI coefficient includes both its spatial variability at the catchment scale, and the uncertainty on its evaluation (from IDPR and SURFEX results as explained in §3.2). The mean spatialized annual recharges and their associated uncertainty are presented in table 3.
For Fontaine de Vaucluse, the mean annual recharge at the basin scale over the 1996-2011 period, calculated with an 8km resolution, is equal to 344 mm/year ± 135 mm. This value has to be compared to the mean value of 335 mm/year with a mean absolute deviation of 118 mm obtained with the global multi-method calculation at the catchment scale.

Table 2: ESPERE recharge estimation (mean and uncertainty) for the nine case studies

	PRECIPITATION (mm)			RECHARGE (mm)		
	Mean	MAD	MAD/mean	Mean	MAD	MAD/mean
Dijon	794	75	9%	148	45	31%
Font. de Vaucluse	988	217	22%	335	118	35%
Galaure	973	131	13%	204	64	32%
Gillardes	1175	212	18%	455	114	25%
Lez	978	208	21%	260	89	34%
Lison	1514	188	12%	681	173	25%
Loue	1514	189	12%	750	141	19%
Taravo	1298	244	19%	479	147	31%
Vistrenque	761	150	20%	165	71	43%

Table 3: Mean spatialized recharge for the nine case studies

	Annual Effective rainfall (1996-2011)			ANNUAL RECHARGE (1996-2011)	
	Spatial average (mm)	Spatial variability	ERI precision	Spatial average (mm)	Precision +/- (mm)
Dijon	140.4	5.0%	2%	85	6.0
Font. de Vaucluse	538.9	29.2%	10%	344	134.7
Molasses	339.9	37.0%	12%	250	122.5
Gillardes	600.1	6.4%	14%	334	68.2
Lez	521.2	5.5%	7%	348	43.6
Lison	885.7	15.5%	11%	657	174.0
Loue	941.0	13.7%	11%	726	179.3
Taravo	836.9	40.0%	19%	480	283.1
Vistrenque	222.2	30.7%	8%	237	91.7

4 DISCUSSION – CONCLUSION

Using different methods to estimate recharge is recommended in order to integrate the uncertainties linked to the processes involved in direct and indirect recharge (Scanlon et al., 2006). The different methods included in the ESPERE tool allow calculating an averaged value of recharge for a given hydrogeological basin, with an estimation of the uncertainty associated to the data used and the hypothesis on which each method is built. Together with the mean value of the recharge over a given period provided by the approach, the temporal variability (monthly or annual) linked to the climate can be described and qualified.

Even if all methods are not always applicable to all kinds of hydrogeological contexts (for example the WTF method may not be applied for karstic and hard-rocks systems due to the poor significance of a piezometric signal in such an heterogeneous context), applying several methods to different basins and comparing their results allows illustrating their comparative renewable water resources and uncertainties. A simple spatialized computation of recharge procedure, based on the Thornthwaite water budget method and applied on 8x8 km grid cells, allows illustrating the spatial variability of the recharge and exploring its main components. This computation procedure, while including a single method for the recharge estimation, allows mapping the monthly and annual recharge on extended regions, provided the necessary data for meteorological forcing, the soil water storage and the effective rainfall infiltration coefficient. It can also be used to explore the impact of climate projections on future recharge. The accuracy of the results can then be tested by comparing them to those obtained using the ESPERE global and multiple method assessment on specific case studies. To date, there was no clear relation found between the hydrogeological context of a given case study and the differences between spatialized and global ESPERE recharge estimations. Applying the multiple method assessment to a higher number of basins may bring more insights and allow qualifying this source of uncertainty more thoroughly.

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