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RESEARCH ARTICLE

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Improving calibration of groundwater flow models using headwater streamflow intermittence

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Abstract

Non-perennial streams play a crucial role in ecological communities and the hydrological cycle. However, the key parameters and processes involved in stream intermittency remain poorly understood. While climatic conditions, geology and land use are well identified, the assessment and modelling of groundwater controls on streamflow intermittence remain a challenge. In this study, we explore new opportunities to calibrate process-based 3D groundwater flow models designed to simulate hydrographic network dynamics in groundwater-fed headwaters. Streamflow measurements and stream network maps are considered together to constrain the effective hydraulic properties of the aquifer in hydrogeological models. The simulations were then validated using visual observations of water presence/absence, provided by a national monitoring network in France (ONDE). We tested the methodology on two pilot unconfined shallow crystalline aquifer catchments, the Canut and Nançon catchments (Brittany, France). We found that both streamflow and stream network expansion/contraction dynamics are required to calibrate models that simultaneously estimate hydraulic conductivity K and porosity ϕ with low uncertainties. The calibration allowed good prediction of stream intermittency, both in terms of flow and spatial extent. For the two catchments studied, Canut and Nançon, the hydraulic conductivity is close reaching 1.5×10^{-5} m/s and 4.5×10^{-5} m/s, respectively. However, they differ more in their storage capacity, with porosity estimated at 0.1% and 2.2%, respectively. Lower storage capacity leads to higher groundwater level fluctuations, shorter aquifer response times, an increase in the proportion of intermittent streams and a reduction in perennial flow. This new modelling framework for predicting headwater streamflow intermittence can be deployed to improve our understanding of groundwater controls in different geomorphological, geological and climatic contexts. It will benefit from advances in remote sensing and crowdsourcing approaches that generate new observational data products with high spatial and temporal resolution.

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KEYWORDS

calibration of hydraulic properties, groundwater flow modelling, headwaters, stream network, streamflow intermittence, subsurface-surface interactions

1 | INTRODUCTION

Recent research has highlighted the significant prevalence of non-perennial streams: over 50% of the world's rivers are non-perennial, that is, cease to flow and eventually dry for part of the year (Messenger et al., 2021). Numerous studies underline the crucial role of non-perennial streams for ecological communities (e.g., Acuña et al., 2014; Allen et al., 2020; Bertassello et al., 2022; Datry et al., 2014). As a result of global change, changes in flow intermittence regimes and increasingly longer droughts predicted for the future will affect freshwater ecosystems (Datry, Boulton, et al., 2023; Jaeger et al., 2007; Kløve et al., 2014; Sauquet, Beaufort, et al., 2021), as is already the case in some parts of the world (Reynolds et al., 2015; Trambly et al., 2021; Zipper et al., 2021). Headwater streams—representing a significant proportion of the hydrographic network—are particularly affected by intermittence due to their upstream location (Beaufort et al., 2018; Benstead & Leigh, 2012). However, the management of these ecosystems remains challenging (Acuña et al., 2014; Magand et al., 2020) because key driving processes are still poorly understood (Shanafield et al., 2021). The challenge is even greater for ungauged basins, which are affected by the lack of available data (Hrachowitz et al., 2013). The hydrological community emphasizes the need to improve the fundamental understanding of headwater dynamics (Blöschl et al., 2019; Fan et al., 2019; Sarremejane et al., 2022; Westwood et al., 2020), especially in the context of growing socio-environmental and global change issues (Fovet et al., 2021).

The main controls on streamflow intermittence integrate climatic conditions, that is, precipitation, evapotranspiration, recharge (Botter et al., 2021; Leibowitz et al., 2018; McDonough et al., 2011) and geomorphological properties—that is, topography, landscape geomorphology (Jencso & McGlynn, 2011; Prancevic & Kirchner, 2019; Snelder et al., 2013) and subsurface properties—that is, lithology, soil types (Carlier et al., 2018b; Costigan et al., 2017; Smakhtin, 2001) and anthropogenic activities—that is, land use and water management (Truchy, et al., 2023). The dynamics of intermittence depend on the processes occurring at different spatiotemporal scales (Costigan et al., 2016; Gómez-Gener et al., 2021). In arid regions, flow intermittence is generated by fast hydrological processes through the generation of an upstream flow that exceeds the downstream flow, such as flash floods or flows generated mainly by surface runoff from the direct interception of precipitation (Zimmermann et al., 2014).

In temperate and humid regions, and especially in areas with shallow basement aquifers (Warix et al., 2021), groundwater has a major influence on the ramification of the hydrographic network and the discharge dynamics (Devauchelle et al., 2012; Dunne, 1975; Freund et al., 2023). These systems are highly dependent on subsurface-surface interactions and mainly generate – gaining – streams fed by groundwater (Sophocleous, 2002; Winter, 1999). Following seasonal

fluctuations in groundwater levels, the hydrographic network expands during recharge periods and contracts during recession periods (Kløve et al., 2011). For a given topography and aquifer geometry, water table elevation and fluctuation are controlled by both the recharge dynamics and the hydraulic properties (Bresciani et al., 2016; Haitjema & Mitchell-Bruker, 2005). In the context of an unconfined aquifer with a defined thickness d [L], the hydraulic head h [L] is determined by the dimensionless ratio of hydraulic conductivity K [L/T] and recharge rate R [L/T], that is, K/R [–] (Goderniaux et al., 2013; Luijendijk, 2022). For a given recharge rate, the transmissivity T [L²/T], that is, the product of K and h , controls the drainage density and the spatial extent of the stream network (Abhervé et al., 2023; Stoll & Weiler, 2010). Low transmissive aquifers display high groundwater levels and consequently dense stream networks in the upper part of the catchment, and conversely. The storage capacity of the aquifer is defined by the porosity ϕ [–]. Several studies in the literature have aimed to establish correlations between observed stream intermittence, groundwater dynamics and lithology (Day, 1980; Kaplan et al., 2021; Lovill et al., 2018; Whiting & Godsey, 2016; Zimmer & McGlynn, 2017a). In addition to geomorphological controls (van Meerveld et al., 2019), studies have specifically shown that transmissive lithologies facilitate rapid expansion/contraction (Godsey & Kirchner, 2014; Prancevic & Kirchner, 2019). It is also well known that insufficient subsurface storage capacity reduces flow permanence (Smakhtin, 2001). However, although hydraulic conductivity and porosity are expected to have an influence on water table fluctuations and consequently streamflow intermittence, their specific control has been poorly assessed in the literature.

A wide range of approaches have been used to specifically model streamflow intermittence. Classically, analysis of streamflow data has allowed to classification streamflow intermittence from regional to continental scales (Hammond et al., 2021; Price et al., 2021; Sauquet, Shanafield, et al., 2021; Trambly et al., 2021). Machine learning methods such as logistic regression (Jensen et al., 2018; Kaplan et al., 2020; Russell et al., 2015) or random-forest approaches (Bond & Kennard, 2017; Eastman et al., 2021; González-Ferreras & Barquín, 2017; Messenger et al., 2021; Peterson et al., 2023; Sando & Blasch, 2015; Snelder et al., 2013) have been deployed on a large scale. Rainfall-runoff models can simulate the flow intermittence but may fail to adequately represent the role of groundwater (Ivkovic et al., 2014), although some improvements to the surface-subsurface exchange process have been proposed by Staudinger et al. (2021). Empirical models (Durigetto et al., 2020), empirical upscaling (e.g., GIS raster-based) (Jaeger et al., 2019; Senatore et al., 2021), lumped and reduced-complexity modelling (e.g., TOPMODEL) (Mahoney et al., 2023; Ward et al., 2018; Williamson et al., 2015) or water balance models (Nippgen et al., 2015; Payn et al., 2009; Yu et al., 2020) have been used to simulate hydrographic network

dynamics. In their stochastic simulation approach, Durigetto et al. (2022) only considered hydroclimatic parameters and recognized the inability to capture river dynamics in cases where the subsurface is the main driver of flow permanence along the hydrographic network. The above methods do not represent physically the hydrological processes. The Soil Water Assessment Tool (SWAT) model has proven to be an efficient way to model streamflow intermittence (Jaeger et al., 2014; Levick et al., 2018), but it is unable to resolve 3D groundwater flow patterns that may occur in complex landscape topography and geology as shown by Dohman et al. (2021). Some physically-based distributed hydrological models fill this gap by including the subsurface in their framework (Daneshmand et al., 2019; Gao et al., 2021; Mimeau et al., 2024; Niedda & Pirastru, 2014; Querner et al., 2016), but they are often limited to stream reaches and hyporheic zones (Frei et al., 2009; Wondzell et al., 2009) or provide only 2D conceptual simulations (Quichimbo et al., 2020). Fully 3D integrated surface–subsurface hydrological models have been developed to better understand the factors triggering streamflow intermittence with HydroGeoSphere (Gutierrez-Jurado et al., 2021; Gutiérrez-Jurado et al., 2019) or CATHY (CATchment HYdrology) (Azarnivand et al., 2020; Weill et al., 2013; Zanetti et al., 2024) models. These approaches are particularly suitable for assessing the influence of subsurface properties on the saturated areas dynamics, but have limitations in terms of model deployment and computational time.

Highlighting groundwater's control over the expansion/contraction of the headwater stream network, Shanfield et al. (2012) and Zimmer and McGlynn (2017b) recommend further process-based modelling studies to better understand the distinct role of the aquifer hydraulic properties on streamflow intermittence mechanisms. To fill this gap, the subsurface and more specifically the hydraulic properties of the aquifer, that is, hydraulic conductivity K and porosity ϕ , need to be better constrained, notably with new surface information, often more available than sparse subsurface data. Stream intermittence information has already been useful in the calibration of hydrological models (Mimeau et al., 2024; Seibert & Vis, 2016; Truchy et al., 2023), for example using the dataset from the french low-water observatory ONDE (Beaufort et al., 2018; Messenger et al., 2021; Sauquet, et al., 2021; Scheller et al., 2024).

We propose a new calibration framework to constrain the hydraulic properties of the aquifer by capturing the spatio-temporal dynamics of streamflow intermittence. We focus on contexts where the spatio-temporal variation in water table depth drives the dynamics of the surface seepage areas. We use a spatially distributed catchment-scale and process-based groundwater flow modelling framework to specifically simulate head variations, hydrographic network expansion/contraction dynamics and streamflow. We develop models with parsimonious parameterization by applying catchment-scale effective hydraulic properties of the aquifer. We calibrate the hydraulic properties on two crystalline catchments where sufficient surface hydrological observations are available, such as continuous streamflow measurements, stream network mapping inventories and discrete visual observations of water presence. We successively (1) simulate streamflow intermittence at the catchment scale using a

distributed 3D process-based groundwater flow model, (2) calibrate and validate the model using surface information only and (3) discuss the role of aquifer hydraulic properties on the spatiotemporal dynamics of the hydrographic network.

2 | MATERIALS AND METHODS

2.1 | Studied catchments

We selected two headwater catchments, the “Canut” catchment (25 km²) and the “Nançon” catchment (57 km²), located in the eastern part of the Brittany region, in north-west France (Figure 1). Both contribute to the supply of drinking water to local communities. The Strahler order (Strahler, 1964) of their main stream does not exceed three, with an average annual temperature of 11°C and precipitation of 800 mm/year for the period 1960–2020 from the SAFRAN meteorological reanalysis (Vidal et al., 2010). For this period, the average recharge simulated by the land model SURFEX (Le Moigne et al., 2020) forced by SAFRAN is about 260 mm/year for Canut and 340 mm/year for Nançon. The historical temperate climate with warm summers without dry season (Cfb in the Köppen–Geiger classification [Peel et al., 2007]) tends to evolve towards dry summers (Csb) in recent decades (Dubreuil, 2022). Using the CORINE Land Cover 2018 data (European Environment Agency, 2018), the land is covered by 78% of agricultural land, 20% of semi-natural and forest environment and 2% of artificial land for both catchments. Their morphologies are similar, with a minimum to maximum variation in topography of about 100 m and average slopes of 3%–4% (Crave & Davy, 1997; Lague et al., 2000). They are both located in the bedrock area known as the Armorican Massif (Ballèvre et al., 2009). Canut is composed of sedimentary rocks (Palaeozoic sandstone and schist) and Nançon of plutonic rocks, according to the 1:1000000 map (BRGM, 1998). Both shallow unconfined aquifers are composed, from bottom to top, of a low-permeability basement—except for fractures—and a weathered/fractured/fissured transmissive horizon a few dozen meters below the surface (Lachassagne et al., 2021; Mougin et al., 2008).

2.2 | Groundwater flow model

For both catchments consisting of a single dominant lithology, the aquifers are assumed to have a uniform and isotropic hydraulic conductivity K and porosity ϕ . In this study, we consider homogeneous effective hydraulic properties of the aquifer at the catchment-scale. Effective properties integrate the impact of heterogeneous subsurface features such as fractures, which are not explicitly represented in the model. The aquifer thickness d [m] are set at a constant value of 30 m, which defines the typical depth of the interface between the weathered/fissured/fractured zone and the fresh bedrock. This geometry of the aquifer represents the shallow active layer, commonly used in similar contexts and specifically for the region studied (Cornette et al., 2022; Dewandel et al., 2012; Mougin et al., 2008; Roques

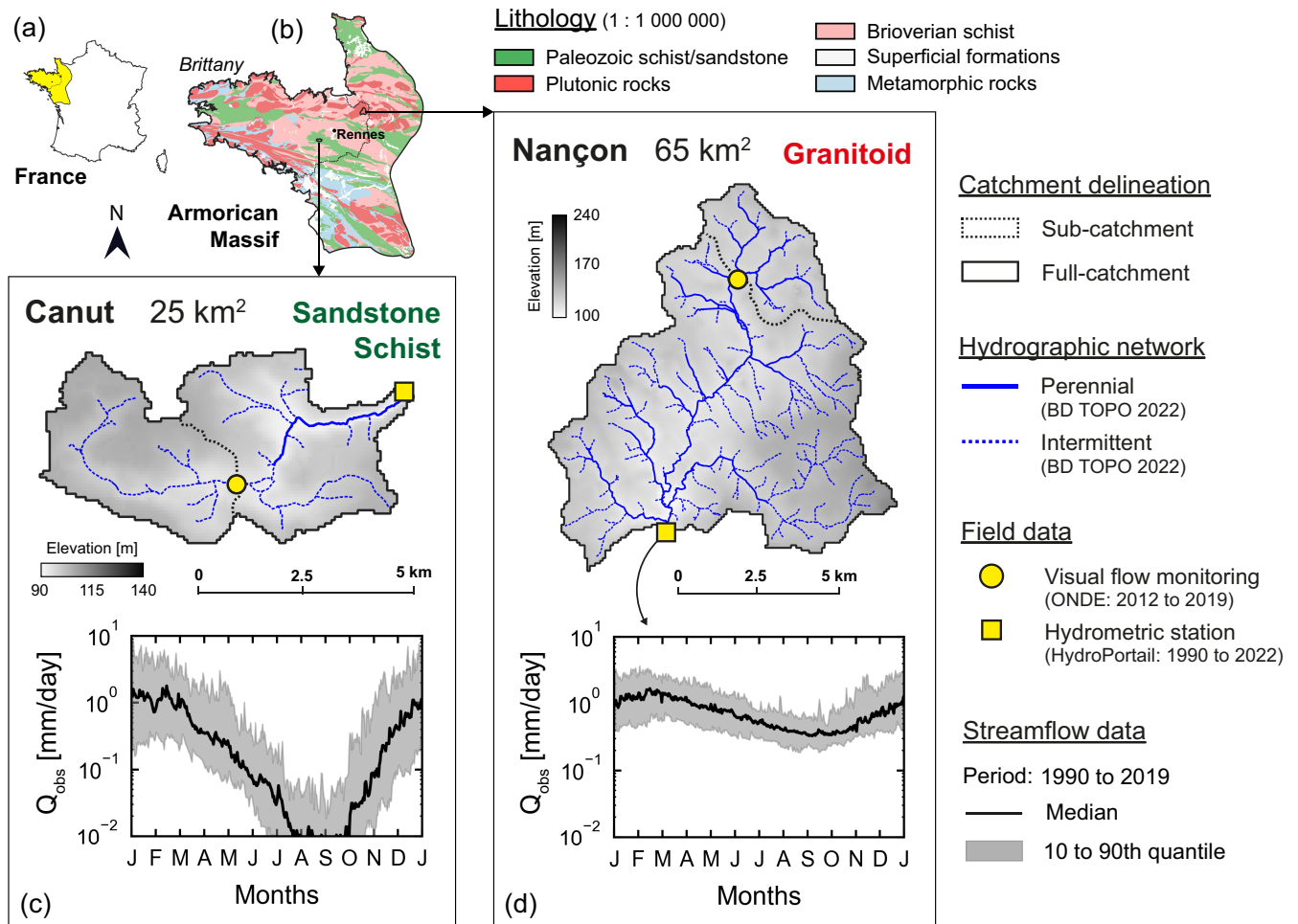


FIGURE 1 (a) Location of the two study catchments in north-western France, more precisely in the eastern part of Brittany, (b) with the geological map (scale 1:1000000) in the background. Zoom on the catchments of (c) Canut and (d) Nançon with the topography in the background and the hydrological data monitoring stations used in this study.

et al., 2016). A sensitivity analysis of this aquifer thickness parameter on the simulation of the hydrographic network was carried out in Abhervé et al. (2023). This study has already demonstrated the consistency and validity of using this 30 m thickness for both catchments studied. The topography is given by the $75 \times 75 \text{ m}^2$ Digital Elevation Model (DEM) generated by photogrammetric restitution and provided by BD ALTI (IGN, 2021). Geospatial processing is performed using the WhiteBoxTools software available in Python (Lindsay, 2016).

The MODFLOW software suite is used to solve the unconfined groundwater flow equation using a three-dimensional finite difference approach (Harbaugh, 2005; Niswonger et al., 2011). The Python package FloPy (Bakker et al., 2016) is used to set up and handle the simulations at a monthly time step. The modelled domain is discretized using the regular DEM mesh horizontally and in six layers vertically. To reduce uncertainties associated with potential flow across topographic boundaries, a buffer zone is added to the topographical catchment boundaries, increasing the modelled domain by 10%, where the no-flow boundary condition is applied. The discretization results in a total of about 10 000 elements for the Canut catchment and 20 000 for the Nançon catchment. At the surface, the drain package (DRN) of

MODFLOW (Harbaugh, 2005) handles the seepage that occurs when the groundwater table reaches the surface. We calculate the specific (divided by the catchment area) seepage flow $Q_{\text{seep}} [\text{L/T}]$ by summing the groundwater exfiltrated in seepage areas over the entire catchment area. By focusing on the saturated subsurface, our approach does not explicitly simulate surface processes such as infiltration—not dominant in our context of gaining streams. Nevertheless, we trace the downslope flowpaths from each seepage pixel to the catchment outlet. Thus transforms the discontinuous spatial pattern of seepage areas into a simulated continuous hydrographic network.

Recharge and runoff are obtained from the land surface model SURFEX (EXTERNALIZED SURFACE) version 8.1 developed by Météo-France (Le Moigne et al., 2020; Noilhan & Mahfouf, 1996) (for more detailed information, the reader is referred to <https://www.umr-cnrm.fr/surfex/>). Supplied with meteorological variables, SURFEX computes the energy and water fluxes at the soil-vegetation-atmosphere interface (Masson et al., 2003). Precipitation is partitioned into evapotranspiration, surface runoff and soil drainage. Surface runoff occurs as saturation excess and infiltration excess flows (Vergnes et al., 2020) and the deep soil infiltration constitutes the groundwater

recharge in this study. SURFEX was driven by the SAFRAN meteorological reanalysis (Quintana-Seguí et al., 2008; Vidal et al., 2010), available for the French metropolitan area at a resolution of $8 \times 8 \text{ km}^2$, with a daily time step from 1 August 1958 to 31 July 2020. The time series are converted to a monthly time step in order to focus on inter-annual and seasonal variations. As the two neighbouring catchments are very close and the climate variability between them is very low, we extract the mean climate forcing from the SAFRAN-SURFEX grid intersecting the two model domains (eight grid cells in total). Recharge and runoff are rescaled so that their sum is on average equal to the streamflow data independently measured at the gauging stations located at the outlet of the two catchments. The rescaling factors are equal to 0.87 for Canut and 1.04 for Nançon. Close to 1, the rescaling factors show limited corrections. The rescaled recharge R [L/T] is applied uniformly over the groundwater flow model domain. In post-processing, the rescaled runoff r [L/T] is added to the seepage flow Q_{seep} simulated by the groundwater flow model over the whole catchment area within the same time step without any delay. The sum of both constitutes the simulated specific (divided by the catchment area) streamflow Q_{sim} [L/T].

2.3 | Observed surface hydrological data

2.3.1 | Hydrographic network maps

We used the most accurate stream network available for France: the BD TOPO national database at 1:10000 updated in December 2022 (IGN, 2022), compiled from historical photogrammetric reconstructions with a spatial accuracy of a few meters. The stream segments classification provides information on the intermittent and perennial stream segments, that is, filled and/or continuous-flow segments throughout the year (IGN and OFB, 2019) (Figure 1). The investigated catchments do not have lakes, dams or other obstacles in the stream network that would alter the dynamics. We updated the structure of the perennial segments of the stream network based on field investigations. The segments had been shortened for the Canut catchment. Indeed, the BD TOPO vector initially indicates the main stream as perennial upstream of the ONDE station (more details in Section 2.3.3), while frequent non-flows are observed at this location. Additional punctual observations made along the stream network between 2018 and 2024 support these observations, and delineate the start of the perennial network approximately 1 km downstream of the Observatoire National Des Etiages (ONDE) station, as shown in Figure 1. For Nançon, the national hydrographic network BD TOPO is consistent with ONDE data and additional monitoring carried out by the French Biodiversity Agency (OFB).

The drainage density of the vector layers for perennial and fully (perennial + intermittent) expanded stream network is 0.17 and 1.24 km/km^2 , for Canut and 0.71 and 2 km/km^2 for Nançon, respectively. The observed vector layers were rasterized at the 75 m grid resolution of the DEM used for the groundwater flow model. We calculate the observed water-saturated density $D_{\text{d obs}}$ [%], that is, the drainage density, as the percentage of grid cells occupied by a stream

segment. Based on the layers provided by the database. We define three stream network densities: perennial $D_{\text{d obs,per}}$ [%], intermittent $D_{\text{d obs,int}}$ [%] and fully $D_{\text{d obs,ful}}$ [%] with:

$$D_{\text{d obs,ful}} = D_{\text{d obs,per}} + D_{\text{d obs,int}}. \quad (1)$$

Calculated values for these stream network densities are available in supplementary material (S6). $D_{\text{d obs,per}}$ and $D_{\text{d obs,ful}}$ correspond, respectively, to low-flow and high-flow conditions.

2.3.2 | Streamflow measurements

The outlets of the study catchments correspond to hydrometric stations where daily specific streamflows Q_{obs} [L/T] are measured by the French environmental services. The data are available on the Hydro-Portail hydrometric network (Leleu et al., 2014) (<https://hydro.eaufrance.fr/>, for detailed information). We initially extract daily time series available for both catchments from 1990 to 2019. Over this period, the average specific discharge of the Canut is 0.73 and 0.95 mm/d for the Nançon catchment (Figure 1). Both catchments have the same average peak specific discharge around 1 mm/d. Canut has more pronounced low flows, with frequent zero flows and a 10th quantile close to zero, compared to Nançon where low flows remain higher than 0.2 mm/d. These stations are designated as not significantly influenced by anthropogenic disturbances.

2.3.3 | Visual observations of intermittence

We used field observations from the ONDE network (Nowak & Durozoi, 2012) (for more detailed information, the reader is referred to <https://onde.eaufrance.fr/>). The French Biodiversity Agency (OFB) has set up this long-term monitoring network, which records summer low water flows on headwater streams in order to anticipate and manage water crises during severe droughts. These stations are mainly located on headwater streams with a Strahler order of less than five. The stations are located in the middle of the main stream for Canut and at the upstream part for Nançon (Figure 1). Since 2012 (except for 2013), the stream has been visually inspected annually by trained personnel from May to September, at least 4 out of 5 months, between the 23rd and 26th of the month. A total of 32 observations are used for each of the 2 catchments. For this work, we focus on the three flow conditions: 'dry'—when the channel is empty—and 'ponded'—when there is still water in the riverbed but no visible flow—while the other classes are classified as 'flow' state. This type of qualitative—but spatially defined—data complements the hydrometric gauging station by providing upstream information on the flow intermittence.

2.4 | Model calibration and validation approaches

The hydraulic properties (hydraulic conductivity K and porosity ϕ) of the groundwater flow models for the Canut and Nançon catchments

are estimated using both (1) the continuously measured streamflow at the catchment outlet and (2) the most accurate observed stream network layers available at the national scale.

By combining the objective functions for streamflow F_Q (Equation 3) and saturation F_A (Equation 6), we aimed to minimize the convoluted objective function F_{QA} [–] (Equation 2).

$$F_{QA} = F_Q + F_A. \quad (2)$$

The closer F_{QA} is to zero, the better is the ability to model both the streamflow and the hydrographic network. Calibration is performed by systematically exploring a wide range of 400 models: 20 values of K ranging from 10^{-8} to 10^{-2} m/s and 20 values of ϕ ranging from 0.1% to 10%. These ranges are typically found in classic textbooks for the lithologies studied (Domenico & Schwartz, 1990; Freeze & Cherry, 1979). Simulations were performed with a monthly time step over the period 1960–2020.

Simulated Q_{sim} and observed Q_{obs} streamflow are compared using the Nash Sutcliffe Efficiency applied to the logarithm (NSE_{log}) to ensure that low and high flows have comparable weights in the comparison (Nash & Sutcliffe, 1970). NSE_{log} equals 1 for a perfect match. The streamflow objective function tends to zero for the best models with F_Q [–] according to Equation (3). Models are considered good for $NSE_{log} > 0.65$ (Ritter & Muñoz-Carpena, 2013) corresponding to $F_Q < 0.35$.

$$F_Q = |1 - NSE_{log}|. \quad (3)$$

Simulated and observed hydrographic networks are compared at the catchment-scale. For each model explored, we compute the 5-quantile and the 95-quantile of the total simulated hydrographic network density, $A_{sim,tot}$ [%]. These quantiles are used to avoid capturing potential extreme events (minimum and maximum). They respectively represent two simulated hydrographic network densities: perennial $D_{d, sim, per}$ [%] and fully $D_{d, sim, ful}$ [%]. Comparing these results with the observations, we obtain two ratios Ω [–] as follows:

$$\Omega_{per} = \left(\frac{D_{d, sim, per} - D_{d, obs, per}}{D_{d, obs, per}} \right)^2. \quad (4)$$

$$\Omega_{ful} = \left(\frac{D_{d, sim, ful} - D_{d, obs, ful}}{D_{d, obs, ful}} \right)^2. \quad (5)$$

According to Equation (6), by averaging these ratios in the objective function for saturation F_A [–], we give equal weight to both. Following the threshold defined for streamflow, saturation models are considered acceptable for $F_A < 0.35$. The best models for saturation are obtained when F_A tends to zero.

$$F_A = \frac{\Omega_{per} + \Omega_{ful}}{2}. \quad (6)$$

Finally, the best model is validated by comparing the simulated hydrographic network density for the sub-catchment upstream of the

ONDE station $A_{sim, onde}$ [%] with visual observation data of water absence/presence. In addition, we visually check that the spatial distribution of the simulated stream network is consistent with observed one. For quantitative validation, we also calculate the mismatch distance between simulated and observed stream networks based on the methodology of Abhervé et al. (2023). From the pixels of the simulated stream network, we calculated the nearest downslope flowpath to the observed stream network D_{so} [L], averaged as $\overline{D_{so}}$ [L]. Conversely, the same operation is performed from the pixels of the observed stream network to the simulated one $\overline{D_{os}}$ [L], averaged as $\overline{D_{os}}$ [L]. The average D_{mean} [L] of $\overline{D_{so}}$ [L] and $\overline{D_{os}}$ [L] provides information on the mismatch distance between the simulated and the observed stream networks (supplementary material (S8)).

2.5 | Quantifying spatiotemporal stream dynamics

In this study, we define an intermittent stream based on the definition of Busch et al. (2020) as ‘a non-perennial river or stream with a considerable connection to the groundwater table, having variable cycles of wetting and flow cessation, and with flow that is sustained longer than a single storm event’. For each simulated year, we distinguish flowing year-round streams and seasonal streams. From the total simulated stream network $A_{sim,tot}$ [%], we therefore classify sections of the stream network as seasonal $A_{sim, sea}$ [%] (intermittent during the year), if they cease to flow for at least 1 month per year, and otherwise as year-round streams $A_{sim, year}$ [%] (perennial during the year). The monthly time step is consistent with the frequency of the observations and the time step of the model.

The persistency index (P_i) (Botter et al., 2021; Durigetto et al., 2020; Jensen et al., 2017) is used to quantify stream intermittency across the catchments. For each pixel of the catchment, we compute the number of times $n_{(x,y)}$ water appeared divided by the total number of time steps of the simulated period N (Equation 7):

$$P_{i(x,y)} = \frac{\sum_{i=1}^N n_{(x,y)}}{N}. \quad (7)$$

Over the whole simulated period and from equation (7), pixels with a $P_i = 1$ are classified as perennial, those with $0 < P_i < 1$ as intermittent and finally those with $P_i = 0$ as no flow.

The subsurface flowpath lengths L_{gw} [m] were calculated for each pixel and time step, from the simulated water table to the downslope nearest simulated stream. The average $\overline{L_{gw}}$ is computed over the catchment. They are then compared with the proportion of seasonal streams $A_{sim, sea}/A_{sim, tot}$ [–] for the two catchments.

The impact of temporal changes in hydrogeological conditions to streams dynamics is evaluated by comparing the aquifer response time t_r [T] and the saturated surface. t_r represents the time required of a change in water level induced by recharge to propagate through the hydrogeological system and induce a change in streamflow. t_r is computed over the catchment by dividing the change in total groundwater storage dS_{gw} [L^3] by the change in total seepage flow dQ_{seep} [L^3/T]:

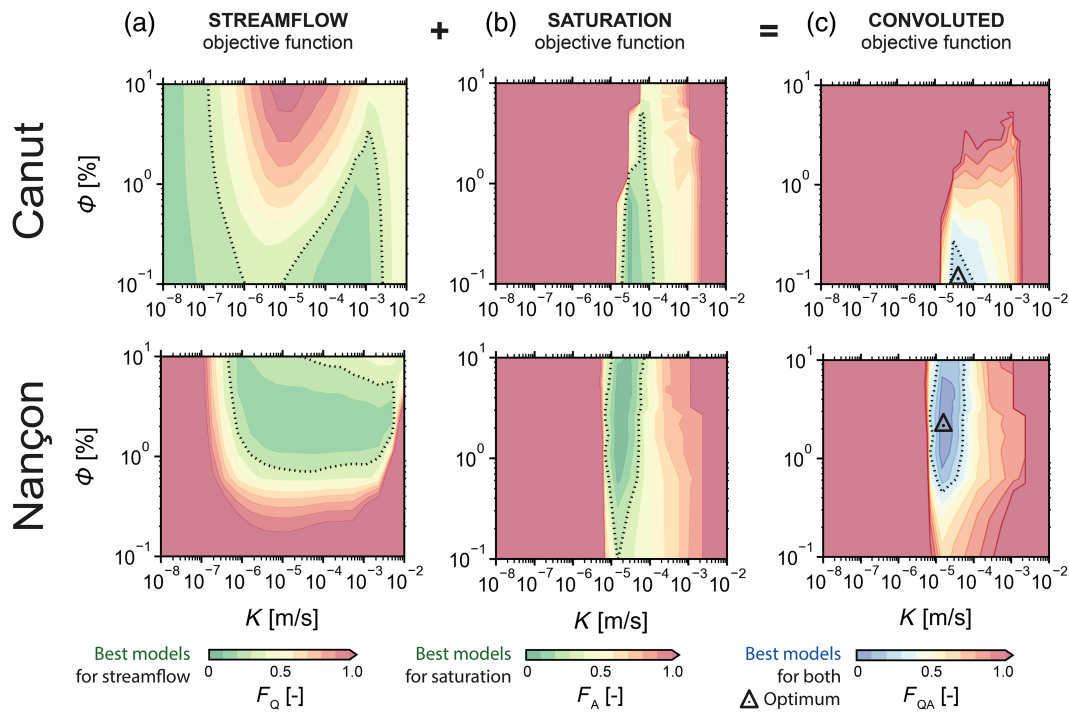


FIGURE 2 Performance criteria according to K and ϕ for the Canut and Nançon catchments. (a) F_Q assessing the agreement of the simulated and observed streamflow with Nash Sutcliffe Efficiency applied to the logarithm (Equation 3). (b) F_A assessing the agreement of the simulated and observed hydrographic network densities (Equation 6). (c) Combination of both criteria F_{QA} (Equation 2). All criteria lead to optimal models when reaching values of 0. The dotted black lines refer to the objective function value of 0.35, which delimits the range of the relevant models.

$$t_r = \left| \frac{dS_{gw}}{dQ_{seep}} \right|. \tag{8}$$

In calculating the absolute value of the ratio in Equation (8), both the characteristic drainage (discharge) and recharge time scales are considered. The resulting aquifer response times are calculated at each time step and converted into days.

3 | RESULTS

3.1 | Calibration results and validation of the groundwater flow model

Figure 2a shows the value of F_Q (Equation 3) calculated and mapped in the K vs. ϕ domain from the 400 simulations covering the parameter space. The range of models relevant to streamflow data—shown in green in the figure, is more precisely delimited by a dotted contour. For Canut, the corresponding parameter sets display a ‘U’ shape. Models with hydraulic conductivities K less than 10^{-5} m/s have limited sensitivity in ϕ and are globally quite saturated. Recharge is rapidly transferred to the catchment outlet by saturation excess overland flow, which is characterized by very low aquifer diffusivity (more details in the supplementary material (S2)). For cases with hydraulic conductivities K higher than 10^{-5} m/s, porosity ϕ should remain

below 1%. The diffusivity is relatively high and the catchment response to recharge remains rapid. For the Nançon catchment, the optimal space is quite different and large, with K ranging from 10^{-6} to 10^{-3} m/s and ϕ between 0.8% and 10%. The differences in behaviour are consistent with the general knowledge of catchments. The Canut catchment, like other catchments in the region (Cornette et al., 2022), is a fast-responding catchment that requires either low hydraulic conductivity or high diffusivity to induce large surface overland flows or fast subsurface transfers, respectively. The Nançon catchment is known to be a less reactive catchment with higher low flows (Dewandel et al., 2021), requiring intermediate hydraulic conductivity values.

Additional constraints are provided by fitting the hydrographic network densities according to the F_A criterion (Equation 6). As shown in Figure 2b and additional information provided in the supplementary material (S3), the pattern of the relevant models is quite similar for both catchments. The models should be sufficiently conductive to limit oversaturation leading to excessively high hydrographic network densities. K ranges between 1.5×10^{-5} and 2×10^{-4} m/s for the Canut catchment and from 6×10^{-6} to 8×10^{-5} m/s for Nançon. Further details on the role of hydraulic properties on saturation variations are given in supplementary material (S4).

By combining F_Q and F_A into F_{QA} (Equation 2), the ensemble of solutions is reduced to a limited set of models that respect both the streamflow and the hydrographic network, represented by the blue

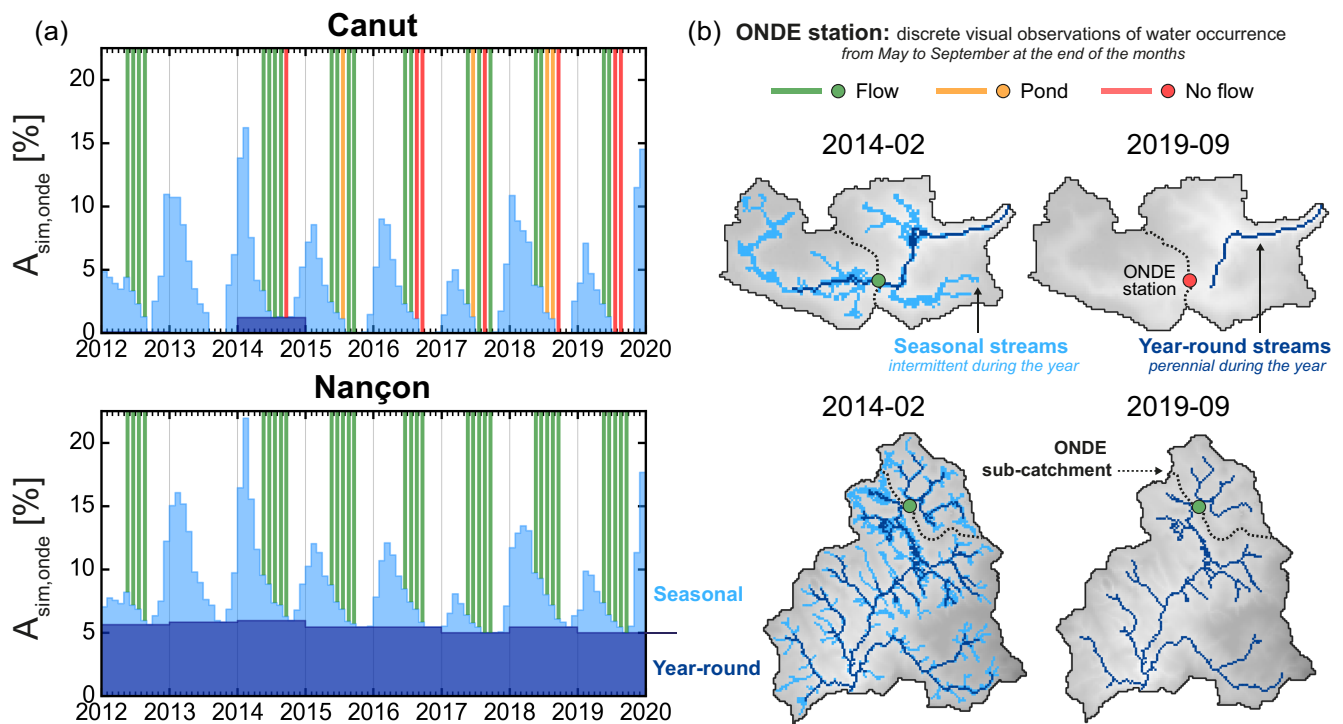


FIGURE 3 (a) Evolution of the simulated hydrographic network densities upstream of the Observatoire National Des Etiages (ONDE) station $A_{sim,onde}$ [%], distinguishing the seasonal (intermittent during the year) and year-round (perennial during the year) parts. In the background, the vertical stripes represent the flow types observed at the ONDE station (once a month from May to October between 2012 and 2020, with one missing year in 2013). (b) Maps of the simulated stream network for two representative times, that is, February 2014 for high recharge and September 2019 for baseflow. The dashed line represents the sub-catchments for the ONDE stations.

area in Figure 2c. For Canut, the best model is obtained with $F_{QA} = 0.2$ for $K = 4.5 \times 10^{-5}$ m/s and $\phi = 0.1\%$, resulting in a high diffusivity of 5.3×10^{-1} m²/s. For Nançon the best model is obtained with a three times lower conductivity $K = 1.5 \times 10^{-5}$ m/s and a more than 20 times higher porosity $\phi = 2.2\%$ leading to a more than 30 times lower diffusivity of 1.5×10^{-2} m²/s, with $F_{QA} = 0.01$. Note that both models lead to high NSE_{log} values of 0.86 for Canut and 0.88 for Nançon (supplementary material (S5)). The spatial distribution of the stream network is quantitatively validated by low values of the mismatch criterion distance D_{mean} (lower than 125 m), showing very good spatial match between the simulated and observed stream networks (supplementary material (S8)).

We evaluate the models qualitatively by comparing their results with the observations from the national monitoring network ONDE. For the best models, Figure 3a illustrates the simulated hydrographic network density at the sub-catchment extracted from the ONDE station $A_{sim,onde}$ [%] (Figure 3b), distinguishing the intermittent from the perennial part calculated on an annual basis. The ONDE observations are shown as vertical stripes in the background of the figure (red for the absence of water, i.e., no-flow, orange for pond, i.e., presence of water but not flowing and green for flowing). For Canut, the model simulates the presence of water in 84% of the ONDE observations showing flow or pond (21 out of 25) and the absence of water in 71% of observations without flow (5 out of 7). For Nançon, the model successfully simulates continuous perennial flow, even though the ONDE

station is located in the upstream part of the catchment. In Figure 3b, the maps showing the maximum and minimum extent of the hydrographic network illustrate the consistency of the model with the ONDE station observations. The stream is intermittent for Canut, as shown by the alternating green dot in February and red dot in September, indicating that the stream dries up at the station. For Nançon, the stream is predominantly perennial, with two green dots in February and in September.

3.2 | Analysis of groundwater controls on intermittency using the best model

The groundwater storage and streamflow regimes for both catchments, simulated using 3D groundwater flow models, are illustrated by the groundwater levels shown in cross-sections at the highest and lowest flow conditions (Figure 4a). The amplitude of the groundwater table variations is higher for the Canut compared with the Nançon catchment. In the Canut catchment, the combination of high K and low ϕ values suggests that groundwater may be disconnected from the main stream during low-flow periods, resulting in a persistence index of less than 1 at the ONDE station (Figure 4b). The same figure for the discontinuous pattern of simulated seepage areas without the downslope flowpath function generating a continuous hydrographic network is available in the supplementary material (S7). In contrast, in

FIGURE 4 (a) Cross section of the maximum (high water flow period) and minimum (low water flow period) simulated groundwater levels. (b) Maps of the persistency index for both catchments calculated for the period 1960 to 2020. The dashed line represents the sub-catchments for the Observatoire National Des Etiages stations.

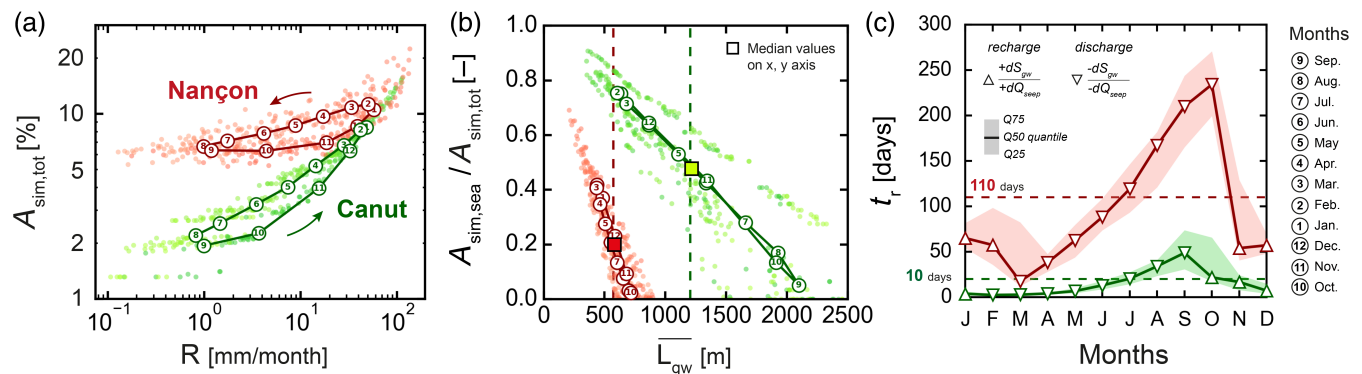
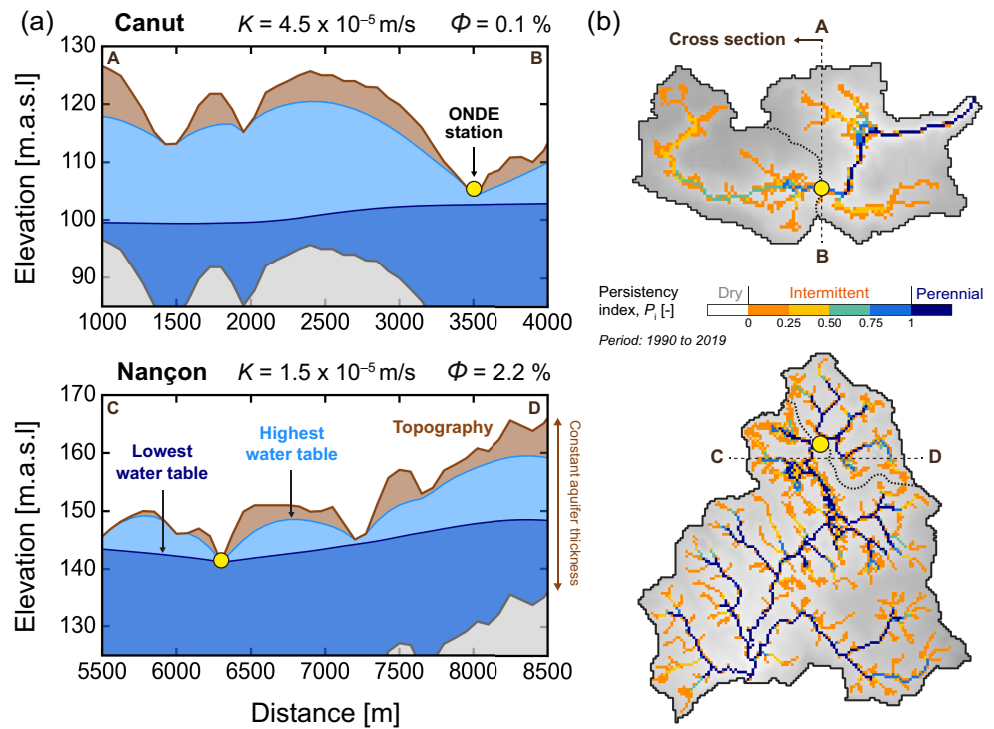


FIGURE 5 (a) Simulated catchment-scale hydrographic network density A_{sim} , [%] as a function of recharge R applied to the model for each monthly time step. (b) Proportion of seasonal (intermittent during the year) streams $A_{sim,sea}/A_{sim,tot} [-]$ as a function of the subsurface flowpath lengths $\bar{L}_{gw}[m]$. The solid line loop connecting the numbers 1–12 represents the intermonthly averages calculated over the simulated period from 1960 to 2020. (c) Intermonthly variations in aquifer response times t_r [days], calculated as the change in total groundwater storage $dS_{gw} [L^3]$ normalized by the change in total seepage flow $dQ_{seep} [L^3/T]$ at the catchment scale.

the Nançon catchment the groundwater table continuously feeds the river in the upstream part of the catchment, leading to a higher proportion of perennial streams compared with Canut. In both catchments, intermittent flow, indicated by low persistency index values, was mainly located in the headwaters of first-order streams (Figure 4b), while perennial streams were mainly found in the valley bottoms downstream of the catchment. An animated version of Figure 4, depicting the spatio-temporal evolution from 2012 to 2020, is available in the supplementary material (S1).

The relationship between recharge and the simulated hydrographic network density at the catchment scale $A_{sim,tot} [\%]$ is depicted in Figure 5. In particular, it shows a distinct hysteretic behaviour for

both catchments. The hysteresis loop follows a counter-clockwise direction in both catchments, although the shape and position of the loop differ between them. In both cases, the hydrographic network expands increasing recharge from October to January and with contracts with decreasing recharge from February to August. Despite an increase in recharge from August to October, the hydrographic network continues to contract or stabilize. This phenomenon is attributed to the time lag between groundwater recharge, the rise of the water table and its gradual reconnection with the surface. During this period, the hysteretic relationship for the Nançon catchment appears flatter, a characteristic influenced by its higher storage capacity compared with the Canut catchment. Similarly, when the recharge decreases

from January to February, the hydrographic network continues to expand for Nançon, whereas it immediately contracts for Canut. The wider range of saturation variations for the Canut catchment, ranging from 16% down to 1%, is influenced by its higher transmissivity—compared with 22% down to 5% for Nançon. The high diffusivity for Canut leads to rapid aquifer drainage and consequently to significant fluctuations in the expansion and contraction of the hydrographic network.

In addition, the Figure 5b shows a negative relationship between the proportion of seasonal (intermittent during the year) streams $A_{\text{sim,sea}}/A_{\text{sim,tot}}$ and the subsurface flowpath lengths. For both catchments, the subsurface flowpath length \overline{L}_{gw} increases as the stream network contracts and intermittent streams disappear. The calculated aquifer response times t_r vary from one to several hundred days (Figure 5c). They decrease during the recharge period and then increase as the aquifer empties during the discharge period. During droughts, when the water table is low, groundwater flows slowly due to a lower hydraulic gradient and longer subsurface flowpaths (Figure 5b). The opposite occurs during the recharge period. The aquifer response times are on average 1 order of magnitude higher for Nançon than for Canut, with averages of 10 and 110 days, respectively. The higher t_r of Nançon result in a less dynamic expansion/contraction of the hydrographic network than Canut.

4 | DISCUSSION AND CONCLUSIONS

This study contributes to improving the modelling of streamflow intermittence with the underlying processes at the groundwater-surface water interface. The groundwater compartment is often overlooked or oversimplified in hydrological models used to study the dynamics of stream network expansion/contraction. Neglecting these controls can lead to inaccurate predictions, especially during baseflow when groundwater is the main contributor. We propose a novel approach to overcome this challenge through a new model calibration scheme designed to improve the representation of the 3D groundwater flow and its key role in headwater streamflow intermittence.

4.1 | Use of streamflow intermittence information to estimate aquifer hydraulic properties

We demonstrate that the use of hydrographic network observations offers opportunities to improve estimation in hydraulic properties that properly capture the dynamics of streamflow intermittence. We show that only the combination of streamflow and stream network maps in the calibration leads to good estimates of both the hydraulic conductivity (K) and the porosity (ϕ) of the aquifers. In fact, we found that a non-unique solution exists when only streamflow is considered, which poses a challenge in selecting a representative set of parameters. As already shown in Abhervé et al. (2023), the extent of the stream network provides a constraint on groundwater level, allowing us to estimate the T/R ratio, and hence K by making assumptions on d and R .

Here, the approach is developed/extended in transient where the estimation of porosity relies on both the streamflow and the expansion/contraction of the hydrographic network. Indeed, the amplitude of water table fluctuations, and hence the spatio-temporal dynamics of the stream network, is closely related to the available storage in the catchment.

The transmissivities and associated hydraulic conductivities estimated in this study are consistent with values obtained from hydraulic tests or numerical groundwater models carried out in the similar region and lithological context (BRGM, 2018; Jiménez-Martínez et al., 2013; Kolbe et al., 2016; Le Borgne et al., 2006). More precisely, we find the same order of magnitude of K at 10^{-5} m/s as in other studies carried-out on the Nançon catchment (Abhervé et al., 2023; Cornette et al., 2022; Dewandel et al., 2021) and the Canut catchment (Abhervé et al., 2023). The low porosity values estimated are consistent with the values found in the literature in crystalline bedrock contexts (Leray et al., 2012; Roques, 2013; Singhal & Gupta, 2010; Wyns et al., 2004). Indeed, the porosity of the fissured or weathered layer in the lithological contexts of the region is mainly about 1% (Dewandel et al., 2006). More specifically for Nançon, studies by Cornette et al. (2022) and Dewandel et al. (2021) also estimated an average porosity of less than 4% for aquifers at 30 m depth, which is consistent with our results.

4.2 | Applicability, limitations and potential improvements of the approach

By using data from a public monitoring network database (ONDE) in this study, it has been shown that these data are very useful for validating model results. However, their interpretation requires certain assumptions, especially regarding the extrapolation of observations upstream and downstream of the station. For example, we assume that the entire stream upstream of the station is considered as dry if no flow is observed, or flowing if flow is observed. We focus on the simulated spatially continuous hydrographic network, generated from the initially simulated discontinuous pattern of seepage areas. (supplementary material S7). This assumption is valid in humid regions and shallow aquifers, where streams are mainly gaining. This may not be the case in other regions, especially where discontinuities in groundwater seepage result in high infiltration into stream losing sections. Also, our current methodology does not allow us to simulate surface water infiltration processes or ephemeral flows, which by definition are generated by storm rainfall.

In contexts where unsaturated processes dominate, it would be crucial to use a coupled land-surface model to represent soil layers that could play an important role in subsurface-surface interactions. For example, using fully integrated models, adding complexity and heterogeneity to the model could enable us to better simulate the spatio-temporal dynamics of observations more accurately. For example, a refining DEM around streams is often used to better represent local groundwater-surface interactions. Although they effectively simulate more hydrological processes, these approaches require more

data and are often much more difficult to set up, with limitations in terms of computational time (Thornton et al., 2022).

The parsimonious approach proposed here, that is, considering a homogeneous aquifer with effective properties, allows us to valid predictions for the two pilot catchments presented. The modelling approach is applicable in contexts of strong subsurface–surface interactions, where the water table is close to the surface, in direct interaction with the surface hydrographic network. As it requires only surface hydrological data, its large-scale deployment will help us to better predict streamflow intermittence in other regions with different geomorphological, geological and climatic contexts.

4.3 | Hydrogeological processes controlling the spatio-temporal dynamics of the stream network

We find differences in the hydraulic properties of the aquifers between the two studied catchments, which explain the different observed spatio-temporal streamflow dynamics. More reactive hydrological dynamics are observed for Canut, which is explained by relatively low porosity. Conversely, the more buffered hydrological dynamics in Nançon required a relatively high porosity—about 20 times higher than in Canut. The lower storage capacity of the Canut catchment results in a lower proportion of perennial streams than in the Nançon catchment, which has higher aquifer storage capacity.

These results follow previous studies showing the role of modelled groundwater dynamics on streamflow (Carlier et al., 2018a; Gascuel-Oudoux et al., 2010). Although the literature emphasizes that stream networks are dynamic in a wide range of topographic, geologic and climatic contexts, our findings support the hypothesis derived from field surveys that specifically highlight the influence of the subsurface (Ackerer et al., 2023; Belemtougri et al., 2021; Durigetto & Botter, 2022; Godsey & Kirchner, 2014; Hatley et al., 2023; Lapidès et al., 2021; Prancevic & Kirchner, 2019; Warix et al., 2023; Zimmer & McGlynn, 2017b). Authors generally identify transmissivity and subsurface storage capacity, as key factors in streamflow intermittence processes. However, the specific role of each of these parameters is rarely discussed. Our investigation of K and Φ provides new insights into the combined effect of these subsurface parameters. The sensitivity analysis (Figure A1 and supplementary material S4) shows that K mainly controls the average extent of the hydrographic network, while Φ drives its spatio-temporal dynamics. The lower the transmissivity, the higher the average drainage density, and conversely. High aquifer storage capacity favours the prevalence of perennial streams over intermittent ones, and conversely.

These findings are also highlighted by the hysteretic behaviour between the recharge and streamflow dynamics already described in the literature (Beven, 2006; Gharari & Razavi, 2018; Kirchner, 2009; Zuecco et al., 2016). As in previous studies (Andermann et al., 2012; Aubert et al., 2013; Davies & Beven, 2015; Fovet et al., 2015; Pfister et al., 2017; Schmidt et al., 2020), we relate the difference in degree

and shape of the simulated hysteresis loop to the subsurface storage capacity of the studied catchments. Furthermore, our modelling approach is particularly well suited to quantify the spatio-temporal evolution of aquifer response times. The values estimated for a dozen days are consistent with those observed for similar lithological contexts in the same region (Guillaumot et al., 2022; Jiménez-Martínez et al., 2013; Molénat et al., 1999). In agreement with the synthetic model study by Shanafield et al. (2012), aquifer response times are greater for the Nançon due to its higher storage capacity in comparison to the Canut catchment with low porosity. We have shown that response times increase as the aquifer empties and the hydrographic network contracts. In addition to the diffusivity of the aquifer, this dynamics is mainly due to the increase in the lengths of the subsurface flowpaths during the contraction of the stream network, as highlighted by van Meerveld et al. (2019) and recently discussed in Kirchner et al. (2023). Our results are consistent with these previous works showing, that the expansion/contraction of the flowing stream network translates into changes of subsurface flowpath lengths. In addition to being able to distinguish the role of hydraulic conductivity and porosity in streamflow intermittence, our findings confirm the need to consider hydrogeological processes when assessing and understanding stream intermittency.

4.4 | Future perspectives and deployment across multiple sites and issues

The availability of spatio-temporal observations detailing streamflow intermittence is critical for the calibration of hydrological models (Ijja Van Meerveld et al., 2017). Indeed, the use of these new unconventional data in the calibration of groundwater models provides interesting information that significantly reduces the number of possibilities (Schilling et al., 2019). Although new methods are emerging such as camera surveys (Noto et al., 2024) and electrical conductivity sensors (Gallo et al., 2020; Jensen et al., 2019; Kaplan et al., 2019; Paillex et al., 2020), historical data rely heavily on labour-intensive manual mapping and observation (Barefoot et al., 2019; Bujak-Ozga et al., 2023; Zanetti et al., 2021), making them sparse and time-consuming to produce. By enabling widely distributed observations, participatory science initiatives are expected to play a key role in improving calibration and validation approaches in the near future (Truchy et al., 2023; Etter et al., 2020; Truchy et al., 2023). These observations are of particular interest when the monitoring stations span multiple locations along the network, with different degrees of flow persistence. At the same time, advances in drone surveys and remote sensing are providing increasingly accurate and high-resolution data to assess intermittence dynamics (Cavallo et al., 2022; Dralle, Lapidès, et al., 2023). For example, the Surface Water and Ocean Topography (SWOT) mission is collecting detailed measurements of the spatial evolution of surface waters over time for mapping with a centimetric precision (Altenau et al., 2021; Biancamaria et al., 2016). Although maps of the global hydrographic network are

becoming increasingly accurate (Allen & Pavelsky, 2018; Amatulli et al., 2022; Lehner & Grill, 2013; Tootchi et al., 2019; Yamazaki et al., 2019), future surface water mapping products at fine spatial and temporal scales including persistence information (Gallart et al., 2016; Huang et al., 2018; Pekel et al., 2016; Rapinel et al., 2023) will be essential to refine the model calibration/validation framework presented in this study and for deploying this approach in ungauged basins.

In addition to numerical developments, this study addresses a significant knowledge gap identified by the hydrological community regarding the role of key hydrogeological processes in headwater flow dynamics. Further research is needed to accurately quantify the coupled groundwater–surface water processes involved in different contexts. We are confident that such a groundwater modelling approach can be readily applied to other areas characterized by strong groundwater–surface water interactions. In particular, we believe this would help the community to better understand the links between the lithology that control the critical zone properties and its architecture on ecosystems (Datry, Boulton, et al., 2023; Dralle, Rossi, et al., 2023; Hahm et al., 2019; Sánchez-Montoya et al., 2023). In a predictive framework, such models will be essential to anticipate changes in streamflow intermittence under future climatic conditions. These insights will be crucial for local stakeholders involved in water and land management, and invaluable for the protection of water-dependent ecosystems.

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CONFLICT OF INTEREST STATEMENT

None of the authors have any competing interests to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A

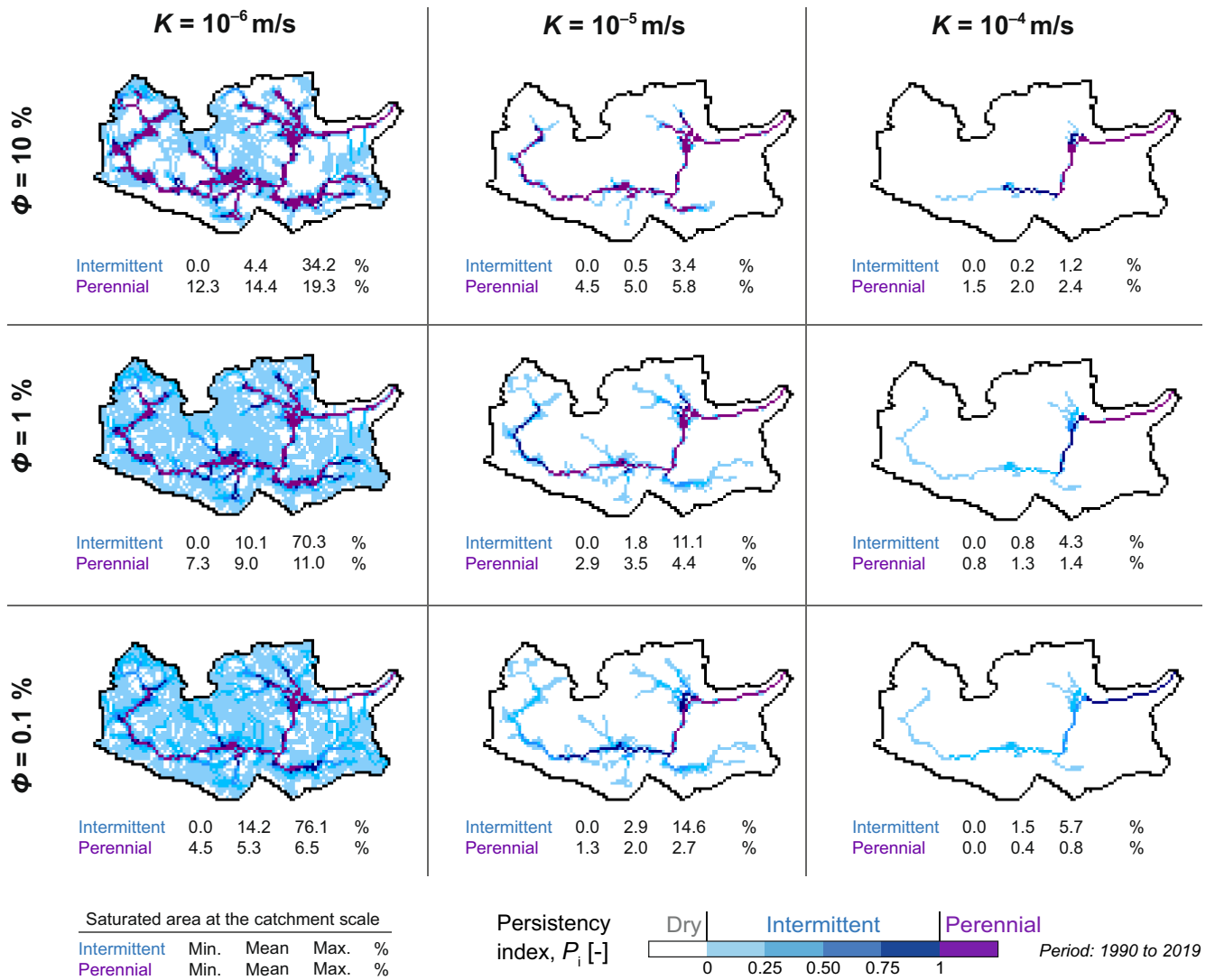


FIGURE A1 Maps of the persistency index P_i obtained for nine pairs of K and ϕ tested for the Canut catchment (simulation period 1960–2020). Below each map, the minimum, average and maximum water-saturated area, that is, drainage density at the catchment scale displayed for the intermittent and perennial part.