Understanding key factors controlling the duration of river flow intermittency: Case of Burkina Faso in West Africa

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Understanding key factors controlling the duration of river flow intermittency: Case of Burkina Faso in West Africa

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A R T I C L E I N F O

Keywords:
Intermittent streams
Ephemeral streams
Aquifer permeability
Catchment area
Flow regime
Principal component analysis

A B S T R A C T

Study region: This study focused mainly on Burkina Faso in West Africa.
Study focus: This study aims to identify environmental variables that best explain the geographic variations of the flow intermittency regime, focusing on intermittency duration. Discharge data from 49 gauging stations were considered, mostly over large rivers. The mean number of dry months ($\overline{Ndry}$) was used as a predictor to define four classes of flow intermittency, for which the potential explanatory environmental variables were assessed based on correlation analysis and principal component analysis (PCA).
New hydrological insights for the region: The first two components (PCs) account for 82 % of the total variance with PC1 (52 %), and most of the catchments with similar flow intermittency are ordered according to PC2 (30 %), predominantly related to catchment permeability. Moreover, permeability was highly correlated with $\overline{Ndry}$ (r = - 0.75). Results suggest that catchment permeability and catchment areas are the most critical variables in determining flow intermittency classes in Burkina Faso, as the effect of precipitation can be overruled by the ones of permeability, catchment area, and Strahler order. This study is a first step in understanding the controls of river intermittency in data-scarce and poorly gauged regions of West Africa. The identified variables could be used as input in statistical models to predict and map river intermittency and provide valuable information for stream conservation.

1. Introduction

Intermittent rivers are rivers that stop flowing or go dry at some points in space and time, while perennial rivers, under normal conditions, sustain a continuous flow throughout the year (Acuna et al., 2014; González-Ferreras and Barquín, 2017). Most hydrological studies have long focused on perennial rivers rather than intermittent rivers (Meerveld et al., 2020). Still, the latter also play an important role and deserve the same attention (Leigh et al., 2016). Intermittent rivers may account for more than 50 % of all the world's rivers (Skoulikidis et al., 2017) and make up a large proportion of headwater rivers (Ward et al., 2020). In recent years, they

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have been the subject of growing interest, especially in their ecological functioning (Datry et al., 2011; Wilding et al., 2018). They are involved in the upstream-to-downstream transport of sediment and organic matter required for feeding fish and other aquatic species (Reid and Ziemer, 1994; Stubbington et al., 2019), regulation of floods (Morin et al., 2009), water quality processes (Dodds and Oakes, 2008), and in the share of greenhouse gas emissions (Datry et al., 2018).

Faced with climate change challenges, many studies predict an increase in the number of intermittent rivers in many parts of the world for the coming years (De Wit and Stankiewicz, 2006; Jaeger et al., 2014). In West Africa, Senegal and Mauritania may experience an increase in intermittency, while intermittency may be relieved further east (Döll and Schmied, 2012), as a result of contrasting precipitation changes between the western and eastern parts of Sahel over the 21st century (Gaetani et al., 2020). These climatic trends could be modified by intense anthropogenic pressure on water resources, especially in arid and semi-arid environments of West Africa, leading to an increased threat to biodiversity and water supply.

In arid and semi-arid regions, most rivers are intermittent and are often the only significant water source for consumptive use (Jacobson and Jacobson, 2013; Wekesa et al., 2020). In these regions, they are considered the primary groundwater recharge sources (Koïta et al., 2017; Shanafield and Cook, 2014). People heavily depend on them, for instance for local irrigation (Acuna et al., 2014; Haile Ghebremariam and van Steenbergen, 2006). The hydrological classification of rivers or catchments according to the characteristics of their flow regime is therefore critical, especially in these regions where the well-being of populations depends on the ability to manage water scarcity for food production (Castelli et al., 2018; Gebrehiwot et al., 2011; Zouré et al., 2019).

In Africa and West Africa in particular, hydrological studies are hampered by data scarcity and poor gauging, especially about streamflow discharge (Rabba et al., 2018). This is a serious methodological challenge and may explain the low number of studies (Berhanu et al., 2015; Brousseau et al., 2010; Gebrehiwot et al., 2011; Perez-Saez et al., 2017; Rivers-Moore et al., 2020; Schacht, 2019), which focused on the classification of the hydrological regime of catchments in Africa.

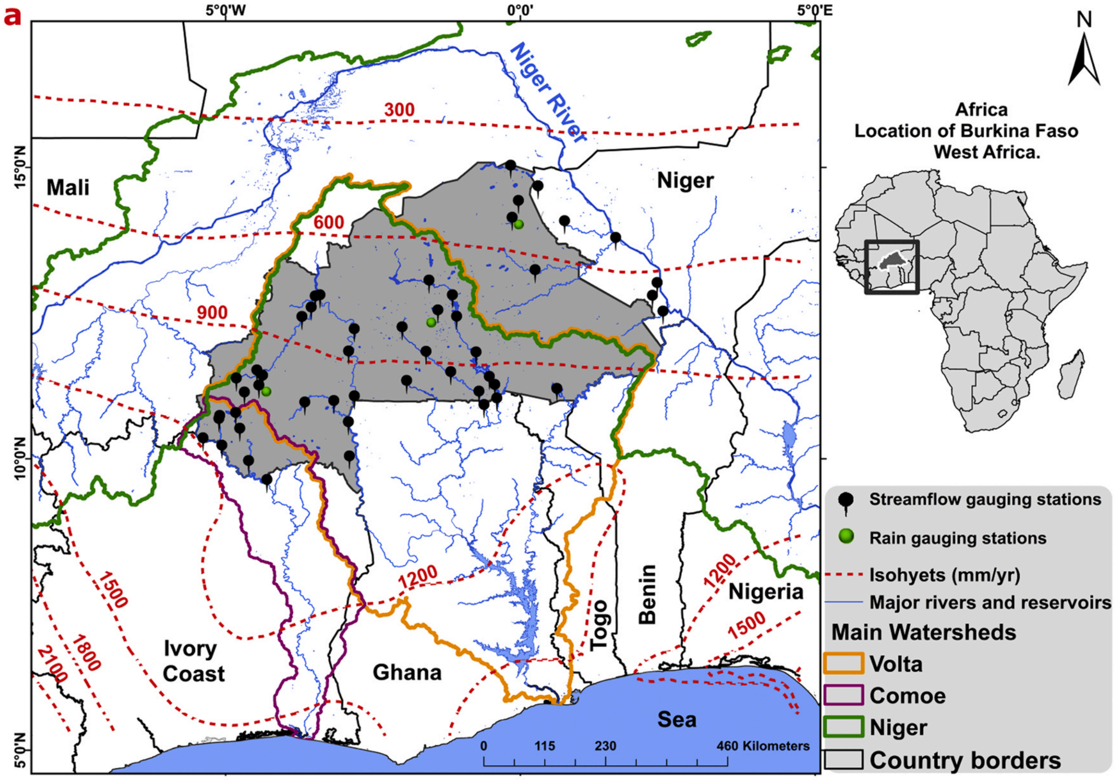
A range of hydrological indices has been used to classify catchments according to their flow regimes. The main components described by these indices are the magnitude, timing, duration, rate-of-change, and frequency of flow events (Poff and Ward, 1989; Richter et al., 1996). As Smakhtin (2001) described, intermittent and ephemeral streams are characterized by naturally extended periods of zero flow, which may generally be perceived as the 'lower bound' of low-flow in hydrology. The indices related to the duration and frequency of flow (e.g., mean, median, percent, and frequency of the number of days/months with flow or zero flow per year/season) are the most important to assess flow intermittency and are commonly used in the literature (Costigan et al., 2017; Larned et al., 2010).

Among these indices, the duration of zero-flow is of particular relevance as an indicator of water availability. It is also an essential characteristic for river ecosystems; and is considered a significant indicator of the potential aquatic species distribution and persistence that may inhabit a given environment (Datry et al., 2012; Leigh and Datry, 2017; Vardakas et al., 2017). For example, Snelder et al. (2013) used hydrological indices to assess flow intermittency in France based solely on the mean annual frequency of zero-flow periods and the mean duration of zero-flow periods.

In the literature, intermittent streams are referred to by various names such as temporary, ephemeral, irregular, non-permanent, non-perennial, episodic, seasonal, interrupted; Such profusion of terms can be confusing, as noted by Uys and O'Keeffe (1997). In this way, Busch et al. (2020) suggest using only the terms "non-perennial, intermittent, and ephemeral" to characterize these streams. The classification of streamflow intermittency in databases such as the NHD (National Hydrography Dataset) in the USA mainly focuses on field surveys and interviews with residents, but *in situ* flow observations often disagree with this classification (Hafen et al., 2020). The quantitative criteria used to classify the streams vary among authors. Hedman and Osterkamp (1982), for example, classified streams as perennial, intermittent, and ephemeral when flowing water is present annually more than 80 %, 10–80 %, and less than 10 % respectively. Reynolds et al. (2015) categorized rivers as strongly intermittent when the mean number of zero-flow days/year >20, weakly intermittent when the mean number of zero-flow days/year < 20, and perennial when the mean number of zero-flow days/year equals zero. Yu et al. (2018) defined perennial streams as those that ceased flowing < 10 % of the year (0–1 month), weakly intermittent as those that ceased flowing 10–70 % of the year (2–8 months), and strongly intermittent as those that ceased flowing >70 % of the year (>8 months).

Despite a handful of studies conducted in several regions regarding the identification and classification of intermittent rivers, an adequate understanding of the drivers controlling intermittency is still lacking (Costigan et al., 2015; Tooth, 2000). We can cite several studies throughout the world that focused on identifying flow indices and potential environmental variables that best explain the different aspects of the flow regime (Alcázar and Palau, 2010; Assani et al., 2006; Bejarano et al., 2010; D'Ambrosio et al., 2017; Gallart Gallego et al., 2012; Gebrehiwot et al., 2011; Kennard et al., 2010; Lane et al., 2017; Moliere et al., 2009; Oueslati et al., 2015). However, few studies have focused on assessing the main drivers of flow intermittency (Godsey and Kirchner, 2014). In their study, Assani et al. (2006) assessed the factors influencing the spatial variability of annual minimum flow characteristics in the southern part of the St. Lawrence River watershed in Quebec. They showed that the spatial difference of annual minimum flow characteristics between the north and south shore is mainly due to climatic factors, particularly annual precipitation. Reynolds et al. (2015) found that the most influential landscape drivers of flow intermittency and low flows are precipitation, snowfall, potential evapotranspiration, soil type, and drainage area. According to Trancoso et al. (2017), the controlling factors of zero flow ratio (proportion of zero flows in the full flow record) across different regions were aridity index and precipitation. However, they also pointed out that precipitation does not seem to impact the zero-flow ratio in some tropical areas, which are more sensitive to groundwater recharge and baseflow processes. Overall, it appears that the spatial and temporal variation of streamflow intermittency results from the interaction between several environmental variables.

At the global and regional scale, climatic variables, especially the aridity index, are likely to be the first-order control of river flow intermittency (Costigan et al., 2017; Trancoso et al., 2017). However, river flow intermittency is also controlled by processes acting at



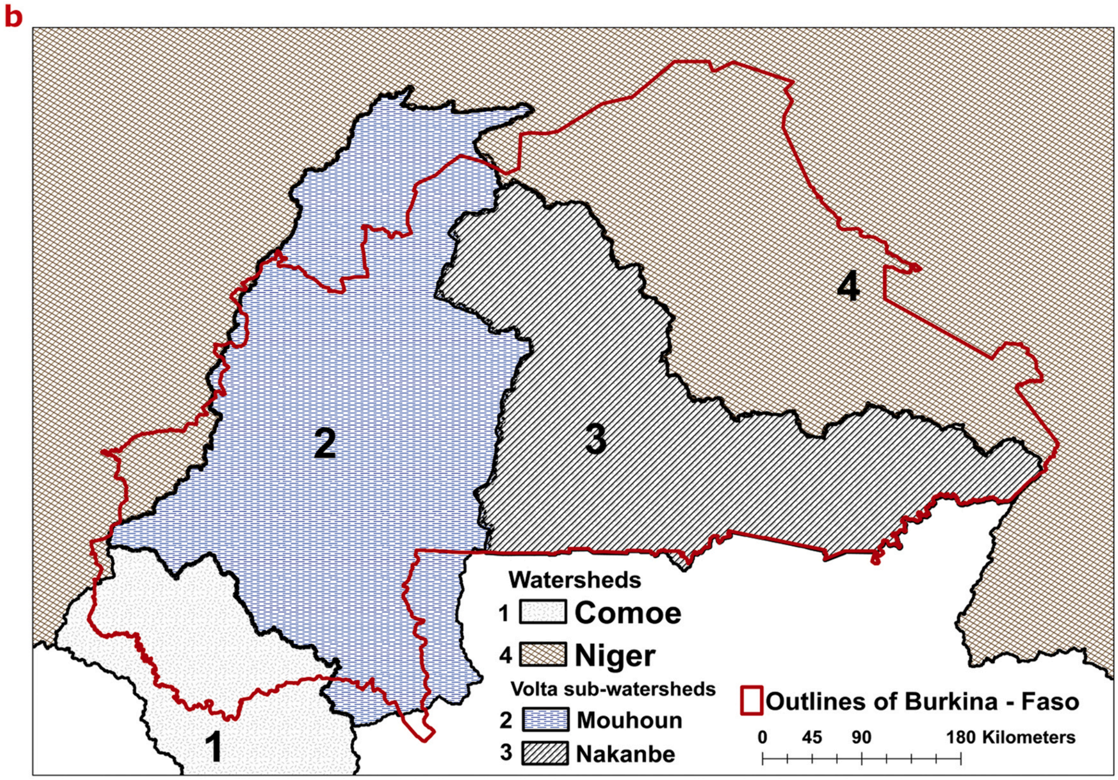


Fig. 1. a) Hydroclimatic characteristics of the study area. Burkina Faso is shown in dark grey. The main catchments' boundaries are derived from the HydroSHEDS database (Lehner et al., 2008). The main rivers and water reservoirs (light blue lines) are derived from the Digital Chart of the World (DCW) (ESRI, 1993). Isohyets (red dashed lines) represent average annual rainfall (mm/yr) calculated from Climatic Research

Unit (Harris et al., 2020) data at 0.5° spatial resolution over the period 1950-2018. The black and green dots give respectively the location of 49 streamflow gauges and 3 rain gauge stations provided by the hydrological and meteorological services; some gauges are superimposed in the representation due to their spatial proximity. **b) Focus on the different watersheds and sub-watersheds of Volta (Mouhoun and Nakanbe) in Burkina Faso**. (For interpretation of the references to colour in this Figure legend, the reader is referred to the web version of this article).

smaller scales than climate drivers (Snelder et al., 2013). Local factors such as geology, topography, and land use/land cover are important variables that also control the river intermittency and operate at different spatial and temporal scales (Buttle et al., 2012; Costigan et al., 2016; Kennard et al., 2010; Williams, 2006).

In West-Africa, there have been very few studies specifically dedicated to assessing the controlling factors of flow intermittency. Understanding the potential drivers of river intermittency should lead to better water resources management through effective water allocations following climate induced pressures on the intermittent flow regime.

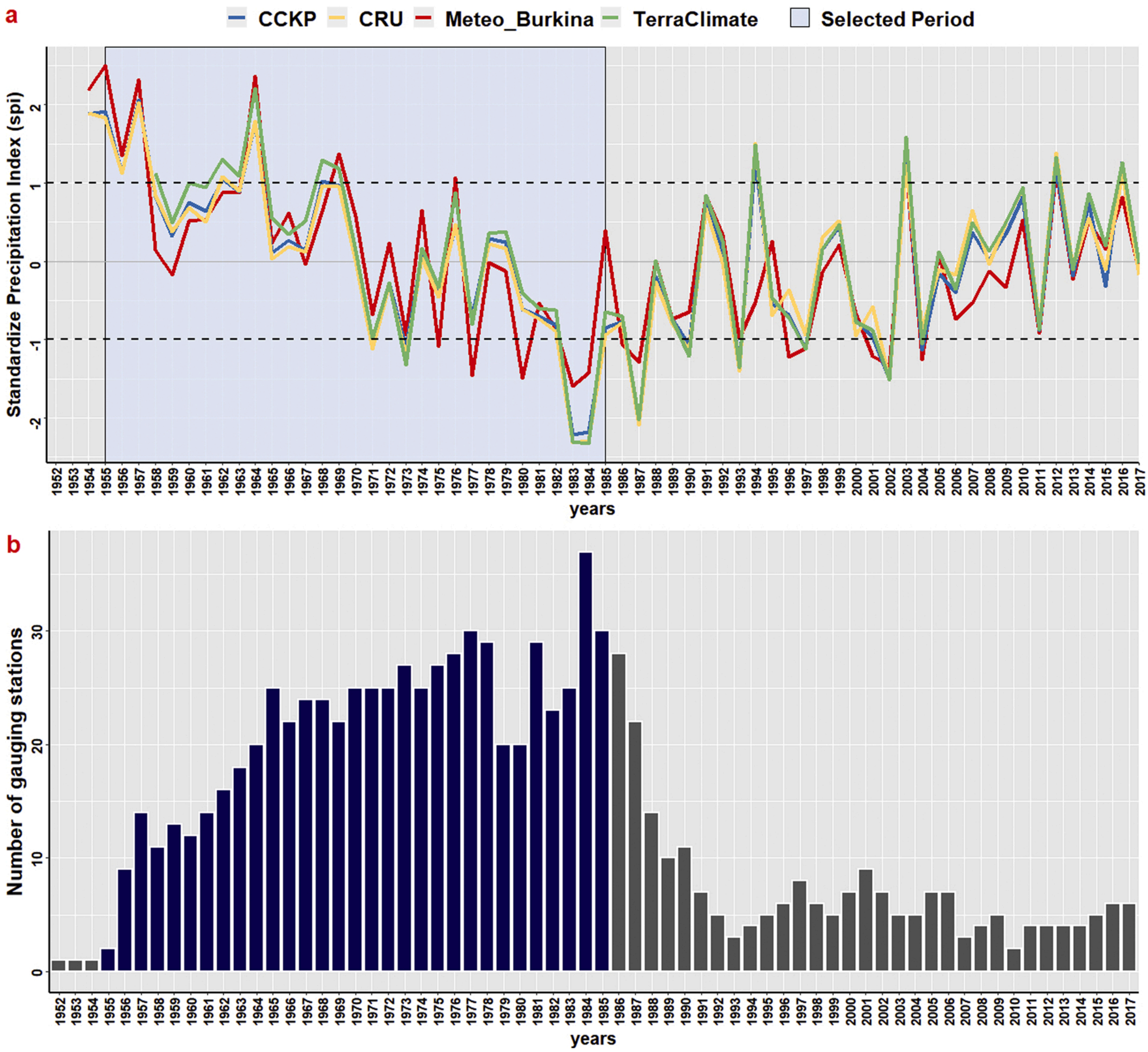


Fig. 2. a) Normal and drought period from 1954 to 2017. The Standardized Precipitation Index (SPI) was calculated considering three rain gauge stations located on the country's different climatic zones. The Dori rain gauge station (World Meteorological Organization Code: 1200010000) is located in the Sahelian zone; the Ouagadougou rain gauge station (WMO Code: 1200000100) is located in the Sudano-Sahelian zone; and the Bobo-Dioulasso rain gauge station (WMO Code: 1200004000) in the Sudanian zone. The SPI is calculated using the average annual precipitation of the three selected stations. The National Meteorology Agency (ANAM-BF) provided the meteorological data (Météo_Burkina) in Burkina Faso. Other databases are considered, and precipitation values are extracted at the locations of the synoptic stations. CCKP data are taken from the Climate Change Knowledge Platform, http://sdwebx.worldbank.org/climateportal/; Climatic Research Unit (CRU) (Harris et al., 2020); TerraClimate (Abatzoglou et al., 2018). **b) Distribution of the number of gauging stations available per year.**

This study aimed to investigate the role of climate, lithology, and topographic controls on geographical variations in the hydrological regime of rivers in Burkina Faso, with a particular focus on the duration of intermittency (periods with zero flow). To achieve this objective, the following research goals were carried out: (i) define a classification framework applied to river gauging observations in order to identify patterns in flow intermittency classes; (ii) evaluate the role of lithology, topography, and climate on flow intermittency classes through multivariate analysis; (iii) discuss their interactions and understand the spatial variability of flow intermittency.

2. Data and methods

2.1. Study area

Located in central West Africa, Burkina Faso is a landlocked country covering an area of 274,200 km^2. The altitude over half of the country ranges between 250 and 350 m above the sea level, whereas the highest values do not exceed 750 m, making the topography relatively flat. The country area is divided into three principal watersheds: Comoe (17,590 km^2), Niger (83,642 km^2), and Volta (172,968 km^2) (Fig.1.a). The Volta in Burkina Faso is subdivided into two sub-watersheds (Mouhoun and Nakanbe) (Fig.1.b). The study area is characterized by two alternating and contrasting seasons influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ), where the humid wind coming from the Atlantic Ocean in the South (Monsoon) meets the warm, dry wind coming from the Sahara in the North (Harmattan) (Ibrahim, 2012). Of the two seasons, there is a long dry season with almost no rainfall from October to May and a short rainy season from June to September. Rainfall is consequently highly seasonal, with a peak generally occurring in August (PANA, 2007).

There is a climatic South-North gradient of decreasing precipitation and increasing temperature and aridity across the country. Three climatic zones are commonly identified in the country based on the average annual precipitation (Jalloh et al., 2013; PANA, 2007): the Sahelian zone in the north (average annual rainfall less than 600 mm), the Sudano-Sahelian zone in the central region (average annual rainfall between 600 and 900 mm), and the Sudanian zone in the south (average annual rainfall between 900 and 1200 mm) (Fig.1a). These various climatic settings make the country a representative regional case study to investigate and understand the factors that control flow intermittency.

2.2. Hydrological and environmental data

Discharge data from 36-gauged stations, 16 stations with daily data, and 19 stations with monthly data were provided by the DGRE (*Direction Générale des Ressources en Eau*) in Burkina Faso over the period (1955–2017). In order to have more gauges, some global and regional hydrological databases were used to supplement the gauging stations obtained from DGRE and then provide additional information on gauging stations located in neighboring countries: Niger, Ghana, and Ivory Coast. To this end, we used monthly data from the Global Runoff Data Center (GRDC, 2019) for 45 gauged stations over the period (1951–1991), as well as daily data from the SIEREM (*Système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation*) database (Boyer et al., 2006) for 80 gauging stations over the period (1952–2006).

The complete dataset was checked and processed according to the following four criteria: (i) gauged stations with less than 5 daily missing discharge records values per month were considered and averaged to monthly values; (ii) for each gauge station, only the years with complete data (12 months) were considered; (iii) for duplicate gauged stations featured in different databases, only the one with the most extended record period was retained; (iv) finally, gauged stations with at least four years of complete monthly data were considered. Monthly time steps are often used to characterize river flow regimes (Gallart Gallego et al., 2012; Yu et al., 2018), particularly in data-scarce areas (Perez-Saez et al., 2017). A set of 58 gauged stations over the period 1952–2017 was finally constituted for further analysis.

A period of drought and desertification strongly affected West Africa in the 1970s and 1980s (Fig. 2a). Thus, many studies pointed out a change in rainfall patterns from the year 1970 with a recovery around the 1990s (Barbé and Lebel, 1997; Ouedraogo et al., 2002). Over the 58 gauges stations, the maximum number of available gauging stations per year is observed between 1955 and 1990 (Fig.2b). From 1985, the number of available gauging stations had sharply decreased, mostly restricted to large rivers. To avoid the anthropic influence of numerous dams constructed since the 1980s (Cecchi et al., 2007), a pre-development period (1955–1985) was considered

Table 1
Flow intermittency classes and their description.

Flow intermittency classes	Description	$\overline{Ndry}$(month/year)	Proportion of flow intermittency classes (%)
Perennial (P)	Sustaining a flow more than 90 % of the time.	(0–1)	26.53
Weakly intermittent (WI)	Characterized by stagnant and isolated pools of water during the dry season[a].	(2–4)	16.33
Highly intermittent (HI)	Marked by a lack of surface water during the dry season.	(5–7)	26.53
Ephemeral (E)	Usually, small headwater streams that flow in direct response to precipitation events.	(8–12)	30.61

[a] The dry season is characterized by very little or no rain from October to May.

so that the river regimes are considered weakly altered. The period 1955–1985 can be subdivided into two sub-periods: a normal period (1955–1969) followed by a drought period (1970−1985). Over the period 1955–1985, 49 gauging stations with at least four years of complete monthly data were considered for this study. Discharge data have an average availability of 14 years, and the majority of gauges (61.22 %) have at least ten years of data Fig. 1a of supplemental material (SM).

The river network used in this study was derived from the BNDT database in Burkina Faso (IGB, 2012) at a scale of 1:200 000. The Strahler's order of the river network (Strahler, 1957) was determined using the RivEx tool (Hornby, 2020) under ESRI ArcGIS software (version 10.6.1). Catchments delineated from each gauging station were derived from HydroSHEDS (Lehner et al., 2008) digital elevation model (DEM) with 3″ (approximately 90 m) resolution. The process was implemented in the R language (R Core Team, 2019) with an interface to GRASS GIS . The delineated catchment areas were compared with the information of catchment areas provided in the GRDC and DGRE databases. Thus, 43 catchments are compared and showed similar areas ($R^2 = 0.99$, p-value < 0.001 SM Fig. 1b). The catchments studied cover 87 % of the country's surface area, of which more than 50 % have a surface area between 1000−10000 km^2 (SM Fig. 2).

The permeability estimate in the study area was derived from lithological information (rock type). In Burkina Faso, the information on the main lithological formations, an updated version (2018) of Castaing et al. (2003) map, was acquired from the BUMIGEB service (*Bureau des Mines et de la Géologie du Burkina Faso*) at a scale of 1:1000000. To take into account the lithological information of some catchments that have a part of their area outside Burkina Faso, we used the GLiM lithological layer (Hartmann and Moosdorf, 2012), which is the most recent global layer available at the scale of 1:3750000. However, to ensure the nomenclature compatibility between the two databases, for each lithology type defined at the country scale in the BUMIGEB database, correspondence and reclassification criteria with the GLiM database were defined. This allowed taking advantage of the lithological precision of the geological map of BUMIGEB (scale 1: 1,000,000) compared to those of the global GLiM database (scale 1: 3750000) (SM Fig. 3). Then, a permeability map was derived from the lithological map by assigning a single permeability value for each lithology type. As detailed in the supplementary material (SM Section 2), the value of each lithology type is based from the permeability range by sediment or rock type (Chapter 6) of Maidment (1993) and on the fact that for a given climate and slope, prior research has found higher drainage densities in areas with lower permeability (Schneider et al., 2017). For each catchment, the average permeability is obtained by weighting the permeabilities obtained for each lithology type by the area occupied by each lithology type in the catchment.

To investigate the impact of dams on river intermittency, we used information on available dams from 1947 to 1985 (SM Section 3), as extracted from the GRanD database (Lehner et al., 2011). Over the period 1947–1985, the two most important dams are: the Lery dam (250 Mm^3), built in 1976 for agricultural purposes in the Mouhoun watershed, with 4 studied gauges downstream of the dam; and the Kompienga dam (2000 Mm^3) in the Nakanbe watershed, built in 1984 for hydroelectric purposes, with only one studied station on the river, far upstream of the dam (SM Fig. 7). A significant proportion of small dams (< 1 Mm^3) are not listed in the GRanD database. However, all small dams together account for less than 4 % of national storage capacity (Cecchi et al., 2009) and represent about 60.7 % of all dams in 1986 (Piquemal, 1991).

2.3. *Flow index and intermittency classification*

Generally, the flow duration is the primary descriptor of different stream classification (Fritz et al., 2020; Kaplan et al., 2019). Given the monthly time step chosen and for the sake of parsimony, the mean number of dry months per year ($\overline{Ndry}$) which represents the duration of intermittency is the flow index selected in this study to assess intermittency and is widely used in the literature. A dry month is defined as a month for which all flows are equal to zero. $\overline{Ndry}$ is a key metric relevant to river ecology (Vadher et al., 2018) and is calculated according to Eq.(1):

$$\overline{Ndry} = \frac{\sum_{i}^{n} Ndry(i)}{n} \tag{1}$$

where *Ndry (i)* is the number of dry months in a given year ***i*** and ***n*** is the number of considered years.

In this study, based on terminologies established by Uys and O'Keeffe (1997), rivers were categorized into four classes according to their mean number of dry months per year ($\overline{Ndry}$) (Table 1).

To get a long enough data record to characterize the spatial patterns of river flow intermittency in the study area, with a consistent number of gauges throughout the period, the monthly time step was preferred to the daily time step, and the flow intermittency classes obtained when comparing the common gauges (5) with daily and monthly time step data over the study period are similar (SM Section 4, SM Table 2).

2.4. *Assessment of the potential factors of intermittency*

A range of variables describing environmental attributes (Table 2) was considered as potential explanatory factors of intermittency. These variables were selected from the literature for their possible relevance in assessing the perennial or intermittent behavior of river streams (D'Ambrosio et al., 2017; Kennard et al., 2010; Moliere et al., 2009; Snelder et al., 2013) and also based on the availability and temporal resolution of the data. These include topography (5 variables), climate (5 variables), and lithology/bedrock permeability (1 variable). Land use/land cover (LULC) data were not included because no dataset could be found over the studied period (1955–1985). The oldest dataset of the national land use database, called BDOT (Base de Données d'Occupation des Terres), corresponds to the year

Table 2
Set of environmental variables considered in this study as potential flow intermittency controls. In bold, the independent variables selected for further analyses.

Type	Environmental variable	Description (units)	Data source, reference, and time scale
Topography	**Area**	**Catchment area (km^2)**	**3" Digital Elevation Model (DEM) from hydroSHEDS** (Lehner et al., 2008)
	Slope	Catchment average slope (°)	3" Digital Elevation Model
	Elevation	Catchment average elevation (m)	3" Digital Elevation Model
	Topo_wi	Catchment average of Topography wetness index (-)	Global DEM derivatives at 1 km based on the MERIT DEM (Hengl, 2018)
	Strahler	**River Strahler order of gauging station location (-)**	**Derived from national hydrographic database IGB (BNDT)**
Climate	**P**	**Catchment average annual precipitation (mm)**	**TerraClimate** (Abatzoglou et al., 2018) **at the resolution of 4km*4km and 1958−1985 period.**
	PET	Catchment average annual potential evapotranspiration (mm)	TerraClimate (Abatzoglou et al., 2018) at the resolution of 4km*4km and 1958−1985 period.
	AET	Catchment average annual actual evapotranspiration (mm)	TerraClimate (Abatzoglou et al., 2018) at the resolution of 4km*4km and 1958−1985 period.
	Aridity (PET/P)	Catchment average of aridity index (-)	TerraClimate (Abatzoglou et al., 2018) at the resolution of 4km*4km and 1958−1985 period.
	Tmoy	Catchment monthly average of mean air temperature (°C)	TerraClimate (Abatzoglou et al., 2018) at the resolution of 4km*4km and 1958−1985 period.
Lithology	**K**	**Catchment average permeability (m^2)**	**Estimated from the lithological map (see SM Fig. 6)**

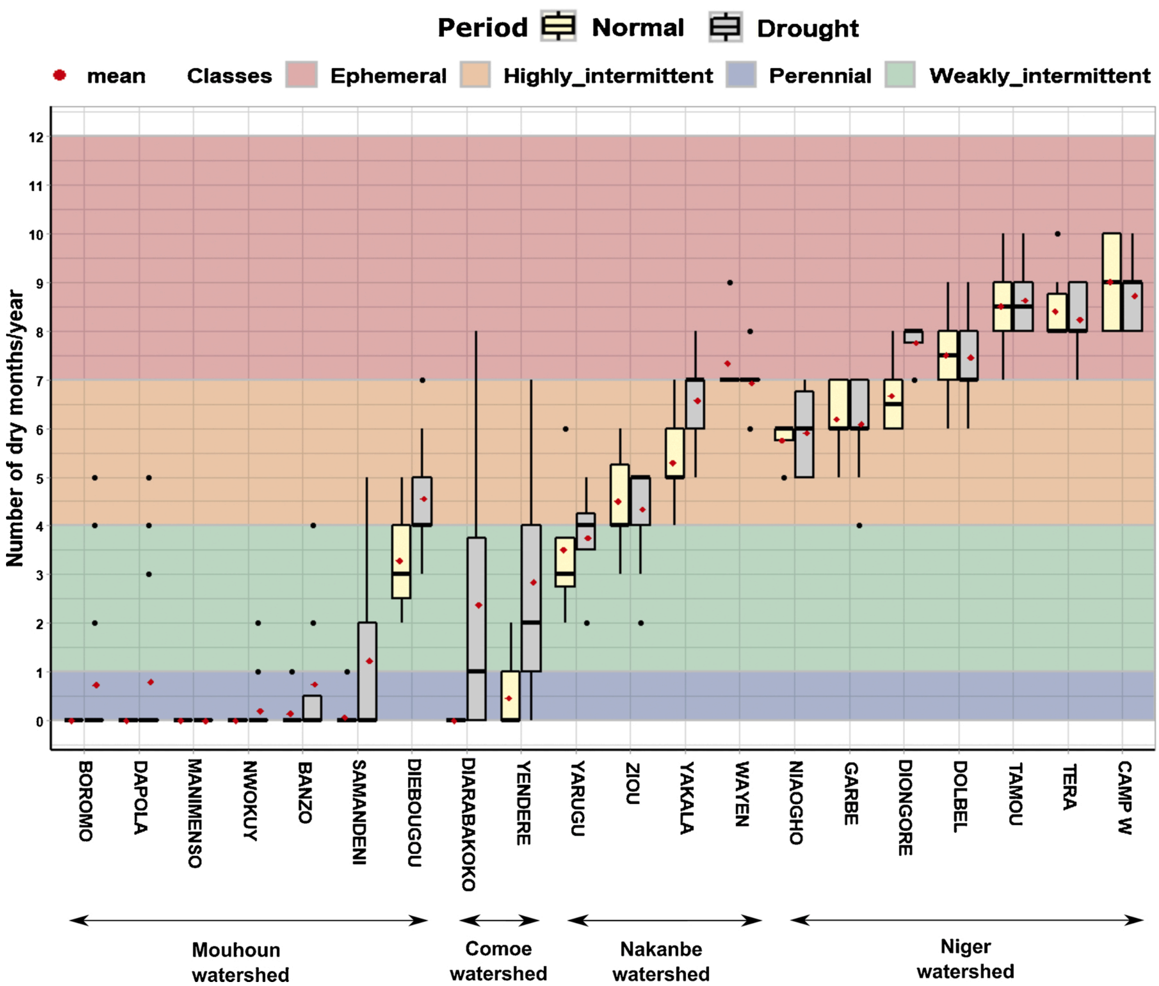


Fig. 3. Boxplot of the number of dry months per year during the normal and drought periods (1955-1969 and 1970–1985, respectively) at the 20 common gauging stations. The outliers of the boxplots are displayed in black dots and the gauges are ordered by watershed.

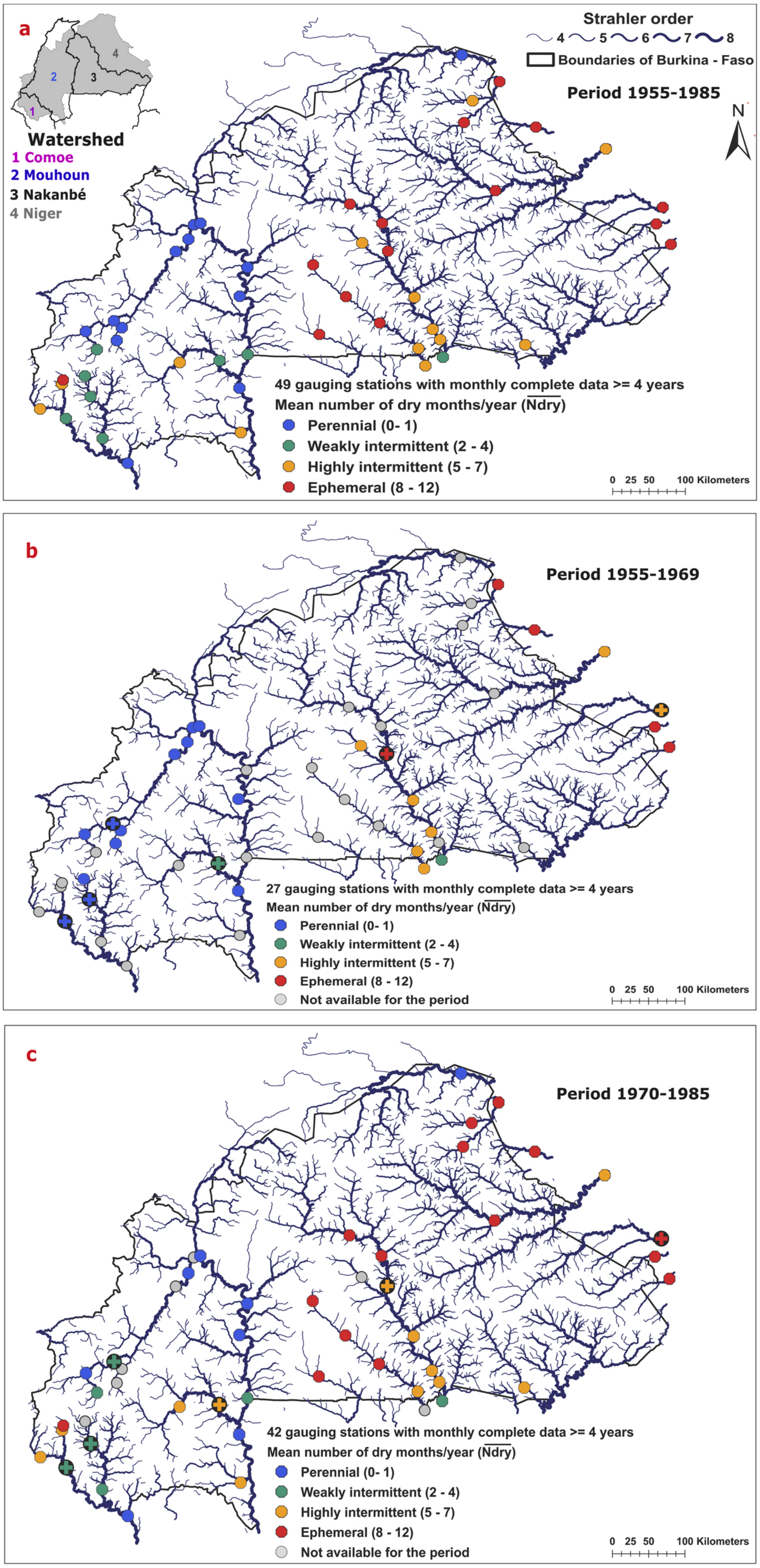


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Fig. 4. Geographical variation of flow intermittency classes based on the mean number of dry months per year: a) over 1955–1985; b) over 1955-1969 (normal sub-period); c) over 1970-1985 (drought sub-period). In b and c, gauging stations that have a different intermittency class between both sub-periods are evidenced by crosses inside the circles. River line thickness is proportional to Strahler's order.

1992, and was shown to be of poor quality by Cecchi et al. (2009).

Anthropogenic factors might also influence the timing, magnitude, and duration of river flow (Hughes, 2005; Skoulikidis, 2009). The evolution of flow intermittency classes for the 20 gauge stations common to the normal (1955–1969) and drought (1970−1985) sub-periods shows that only 30 % of these gauges exhibit a shift of flow class from the normal to the drought period. Besides, this shift is modest as it consists of only one intermittency class (Fig. 3, SM. Section 3). This analysis indicates a weak influence of both dams and drought on the evolution of intermittency classes, and led us to neglect dams as potential explanatory factors.

All environmental variables were averaged for the catchments upstream of the gauging stations except for Strahler order, which is estimated at the gauging station location. The set of environmental variables was further reduced to avoid multicollinearity (by minimizing statistical redundancy among variables) through a Pearson correlation matrix. At this stage, for pairs of variables with a correlation above the threshold $|r| > 0.75$ (considered to indicate a high level of correlation), only one was retained (SM Fig. 8). The retained variable is the one that is also correlated with multiple others (i.e., the variable with the highest absolute mean correlation with the other variables) and therefore allows a set of highly correlated variables to be reduced. It must be noted that evaporation related variables, including the aridity index, although often considered in similar studies, were not kept in this process since they show a strong correlation with precipitation (SM Section 5). A final reduced set of four significant environmental variables (independent variables) included in further analyses are presented in Table 2 (in bold).

The principal component analysis (PCA) is a multivariate statistical method for reducing large dataset dimensionality, increasing interpretability while minimizing information loss (Jolliffe and Cadima, 2016). In this study, it was used to: (i) explore the relationship between significant environmental variables (to show how they correlated to or deviated from each other); (ii) identify patterns in

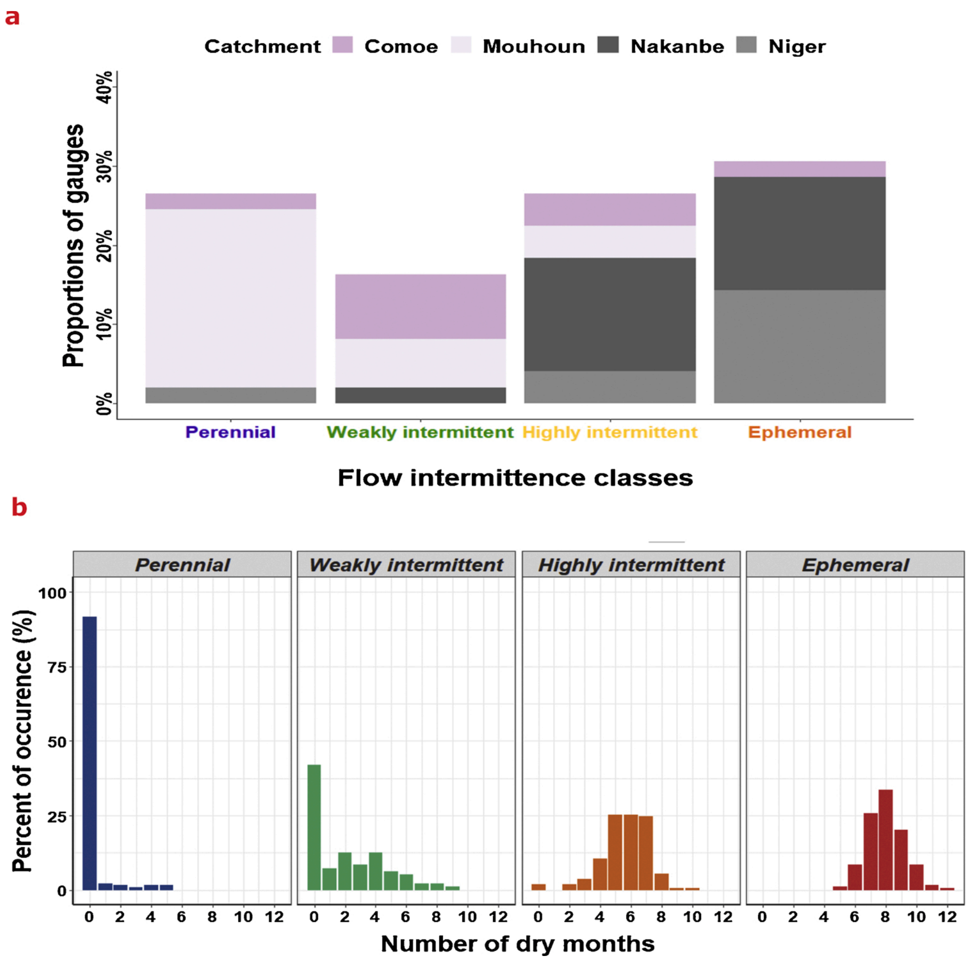


Fig. 5. a) Proportion of gauging stations within large basins and flow intermittency classes over 1955–1985. b) Distribution of the number of dry months for each individual year of each station belonging to an intermittency class over 1955–1985.

catchments with similar flow intermittency classes; (iii) analyze the relationship between the duration of intermittency ($\overline{Ndry}$) and significant environmental variable. PCA was performed using XLSTAT (Addinsoft, 2015) based on the set of 49 catchments and four (4) environmental variables (in bold in Table 2). Before performing the PCA, the input variables were standardized to z-score values so that all variables have the same weight (van den Berg et al., 2006). The number of meaningful Principal Components (PCs) was determined using Kaiser's criterion (Kaiser, 1960) by selecting all components with eigenvalues greater than 1 (Assani et al., 2006). The contribution of environmental variables to the explanation of a PC was considered significant if their loading value was at least 25 %.

The duration of intermittency $\overline{Ndry}$ was introduced as a supplementary quantitative variable once the PCA has been constructed. This supplementary quantitative variable is not included in the calculation of distances between individuals. It should facilitate the interpretation of the results and help detect the environmental variables that have the most significant impact on intermittency duration.

3. Results

3.1. Flow intermittency classes

All studied stations fall on medium to large rivers, with a Strahler order between 4 and 8 (Fig. 4a). Four flow intermittency classes were considered to categorize rivers in terms of intermittency (section 2.3). It appears that 26.5 % of gauge stations are perennial, 16 % are weakly intermittent, 26.5 % are highly intermittent, and 30 % are ephemeral (Table 1, Fig.4a). The perennial and weakly intermittent gauge stations are mostly located in the south-western part of the country (Mouhoun and Comoe basins, Fig.4a, Fig.5a), where intermittent gauges are only found in upstream reaches, with medium Strahler orders (4–5). In contrast, the eastern part of the country (Nakanbe and Niger basins) shows a huge majority of highly intermittent and ephemeral gauges, whichever the stream order

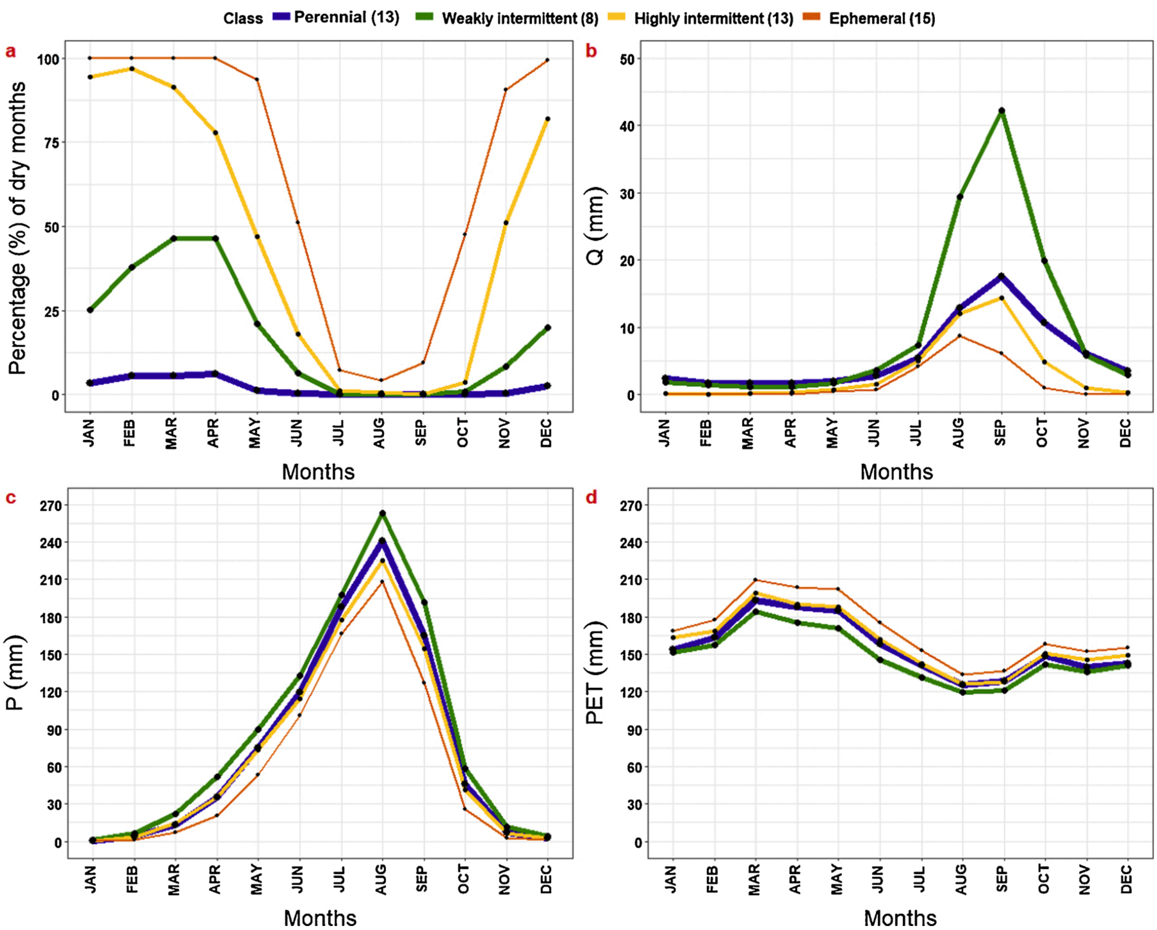


Fig. 6. Percentage of dry months per class (a), the long-term average of monthly discharge per class (b), average precipitation regime pattern (c), average potential evapotranspiration regime pattern (d). The width of the graphic lines is proportional to the mean catchment area per class. The considered period is 1955-1985.

(Fig.4a, Fig.5a). Fig. 5b shows that the classification based on the mean number of dry months per year remains effective at the annual timescale, since the number of dry months per individual year markedly increases from the perennial to the ephemeral class.

Among the 49 gauging stations studied over the period (1955–1985), 20 gauging stations are shared between the normal (1955–1969) and drought (1970−1985) periods. Among these 20 stations, only six have a different intermittency class over the two periods, with a shift of only one class towards the ephemeral side in response to the drought. In particular, three perennial gauges stations on medium rivers located in the south-west of the country become weakly intermittent (Fig.4b, c). Overall, the intermittency patterns depicted by the three sets of stations over the full, normal, and dry periods (Fig.4) are very similar, and we preferred to work on the full set (1955–1985) to better sample the spatial variability of the potential intermittency drivers.

The analysis of the percentage of dry months (Fig.6a), the average of monthly discharge (Fig.6b), and the average of monthly precipitation and potential evapotranspiration regime (Fig.6c, d) of the country shows a marked distinction of values between classes. A difference can be noted in the dry month percentage per-flow class timing, duration, and magnitude. The ephemeral class is characterized by a lower percentage of dry months and a peak discharge in August (Fig.6a, b), when the maximum monthly average precipitation is observed for all classes (Fig.6c). This synchronicity of peak flow and peak precipitation is suggestive of a strong dependence of the ephemeral rivers on the annual precipitation regime.

In contrast, for the three other classes, peak flow occurs in September, i.e., one month later than the maximum monthly precipitation. The highly intermittent, weakly intermittent, and perennial classes are also characterized throughout the year by a lower percentage of dry months than the ephemeral class. The lag time can be defined as the time between the center of mass of the precipitation excess and the peak discharge (Askew, 1970; Fang et al., 2005). This higher time lag between peak precipitation and peak flow than in the ephemeral class is probably explained by contrasting hydrological processes in the catchments of the different classes, especially given the large similarity of precipitation timing and intensity in all four classes.

The lag time depends on the catchment properties such as catchment surface area, land use/land cover, geology, soil type, and slope (Dingman, 2015). Generally calculated with a finer time step than monthly, a lag time can be determined in each catchment by analyzing the cross-correlation between the monthly average precipitation and the monthly average discharge (Dettinger and Diaz, 2000). In this framework, the lag time is the time lag (here in months), maximizing the correlation coefficient between the lagged monthly precipitation and monthly discharge. Fig. 7 shows a decrease in the mean value of the lag time from the perennial class to the ephemeral class, and confirms that the most intermittent classes (highly intermittent and ephemeral) have shorter lag times than the other classes (weakly intermittent and perennial).

This shorter lag time for the ephemeral and highly intermittent class can be related to several catchment characteristics, such as catchment area and permeability. Indeed, the thickness of the plotted lines in Fig.6 is proportional to the average catchment area per class, revealing its decrease from the perennial class to the ephemeral class. Most ephemeral and highly intermittent rivers are located in catchments of low permeability (SM Fig. 4), which may result in lower storage of water and a high runoff coefficient in these catchments (Pfister et al., 2017).

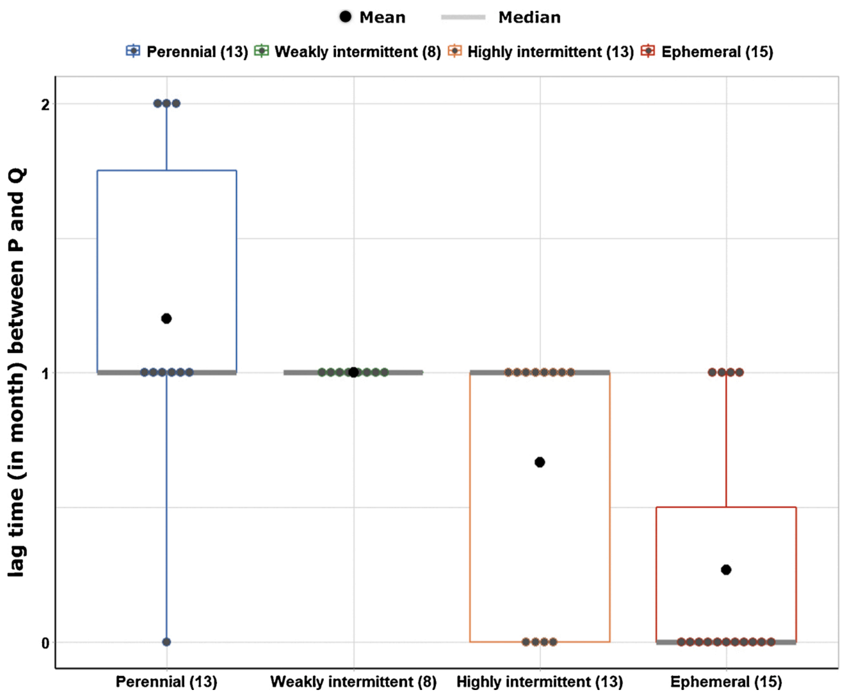


Fig. 7. Boxplot of estimated lag time value according to the intermittency classes over 1955–1985. The lag time (in month) is estimated for each catchment through a cross-correlation between the average monthly precipitation (P) and the average monthly discharge (Q).

Fig. 6b also shows that highly intermittent and ephemeral classes produce discharge from early May to late November (up to December for a highly intermittent class). However, the perennial and weakly intermittent classes display a significant flow discharge throughout the year, probably due to groundwater contributions to streamflow (SM Fig. 4, SM Fig. 6). This is consistent with Buttle et al. (2012), who observe that the short duration response of ephemeral streamflow to precipitation inputs can be expected to produce relatively steep falling limbs of the hydrograph compared to perennial basins where groundwater inputs support flow. Differences in storage properties (permeability), contributing area, Strahler order, between catchment drained by perennial versus ephemeral streams, may also manifest in catchment response. The maximum periods of potential evapotranspiration (Fig.6.d) coincide with low precipitation periods (Fig.6.c), especially from December to May. The highest values of the percentage of dry months and the lowest discharge values are also observed from December to May. This period is favorable for the intermittency of rivers.

3.2. Principal Component Analysis (PCA)

The PCA carried out with the most significant environmental variables (P, K, Area, and Strahler order) showed that only the first two components have an eigenvalue greater than 1 (SM Table 3). These first two components account for 82 % of the total variance (Fig.8). The first component (PC1) accounts for 52 % of the total variance and is related to catchment topography and climate variables. PC1 axis is mainly explained by Strahler order (37 %), followed by precipitation (28 %) and catchment surface area (27 %) (SM Fig. 10). The second component (PC2) accounts for 30 % of the total variance and is dominated by catchment permeability and catchment surface area, which contribute to the variance of the PC2 axis at 55 % and 27 %, respectively (SM Fig. 10).

The flow index $\overline{Ndry}$ added to PCA as a supplementary variable shows a high and negative correlation with permeability (r = -0.75) (Fig.8, SM Fig. 8), PC2 (r = -0.85) and PC1 (r = 0.08) (Fig.8, SM Table 4). The PC2 axis is more related to flow intermittency classes than the PC1 axis, suggesting that permeability and catchment area are the most critical environmental variables in discriminating flow intermittency classes in Burkina Faso. Fig.8 also shows the positioning of the 49 catchments with their intermittency classes in the plane formed by the first two components (PC1, PC2). Catchments with higher values of Strahler order, surface area, permeability, or annual precipitation values are more likely to be classified into the perennial or weakly intermittent classes (Fig.8, SM Figure 11). On the other hand, highly intermittent and ephemeral classes correlate with lower values of Strahler order, surface area, permeability, or

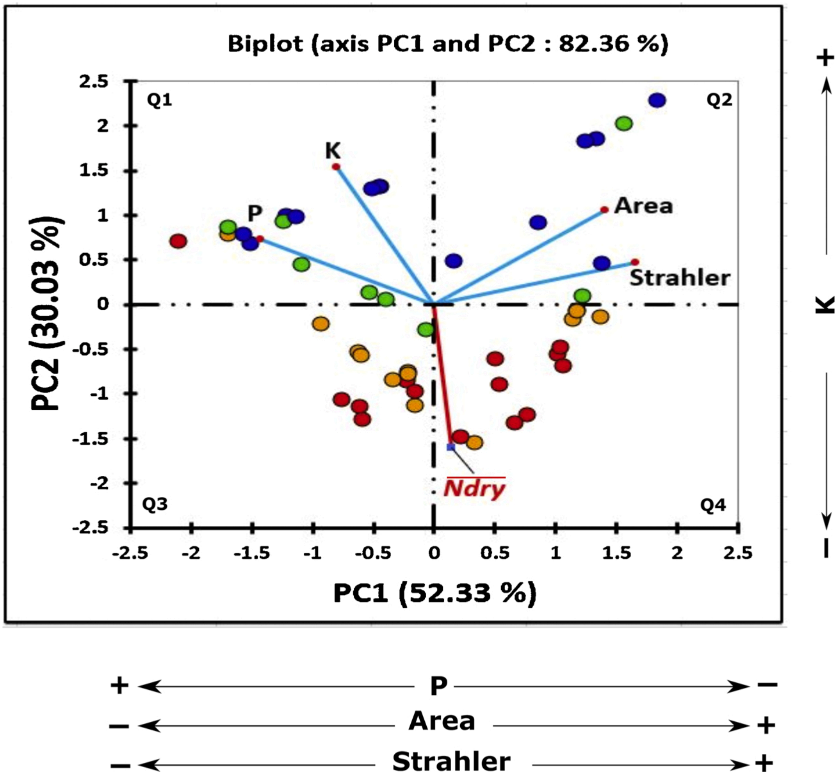
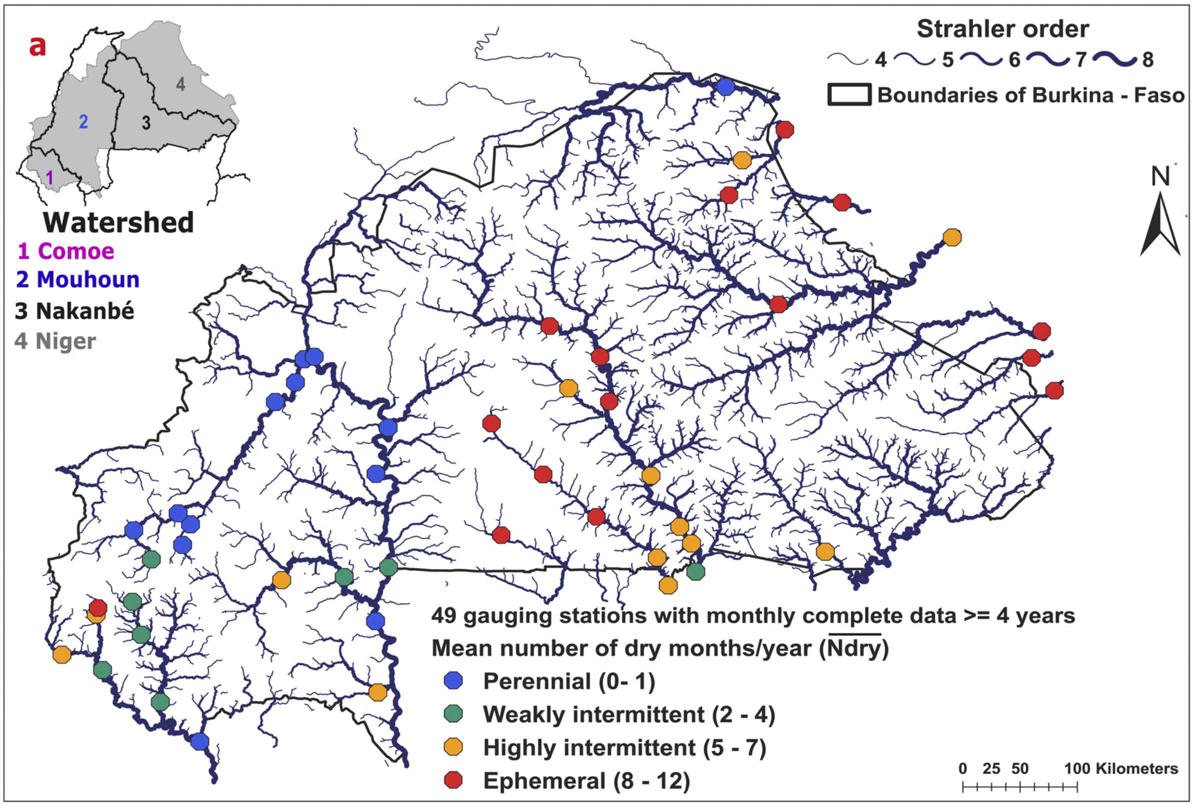


Fig. 8. Biplot of the first two axes resulting from the PCA (n = 49 catchments, over 1955–1985) for significant environmental variables and the flow index ($\overline{Ndry}$) introduced as a supplementary variable. Q1 to Q4 designates quadrants 1 to 4. The catchments are classified as perennial (blue dots), weakly intermittent classes (green dots), strongly intermittent classes (orange dots), and ephemeral classes (red dots). Legend: P - average precipitation (mm/yr), Area - catchment area (km^2), K – permeability (m^2), Strahler – Strahler order (-). Some catchments are superimposed in the representation due to their spatial proximity. (For interpretation of the references to colour in this Figure legend, the reader is referred to the web version of this article).



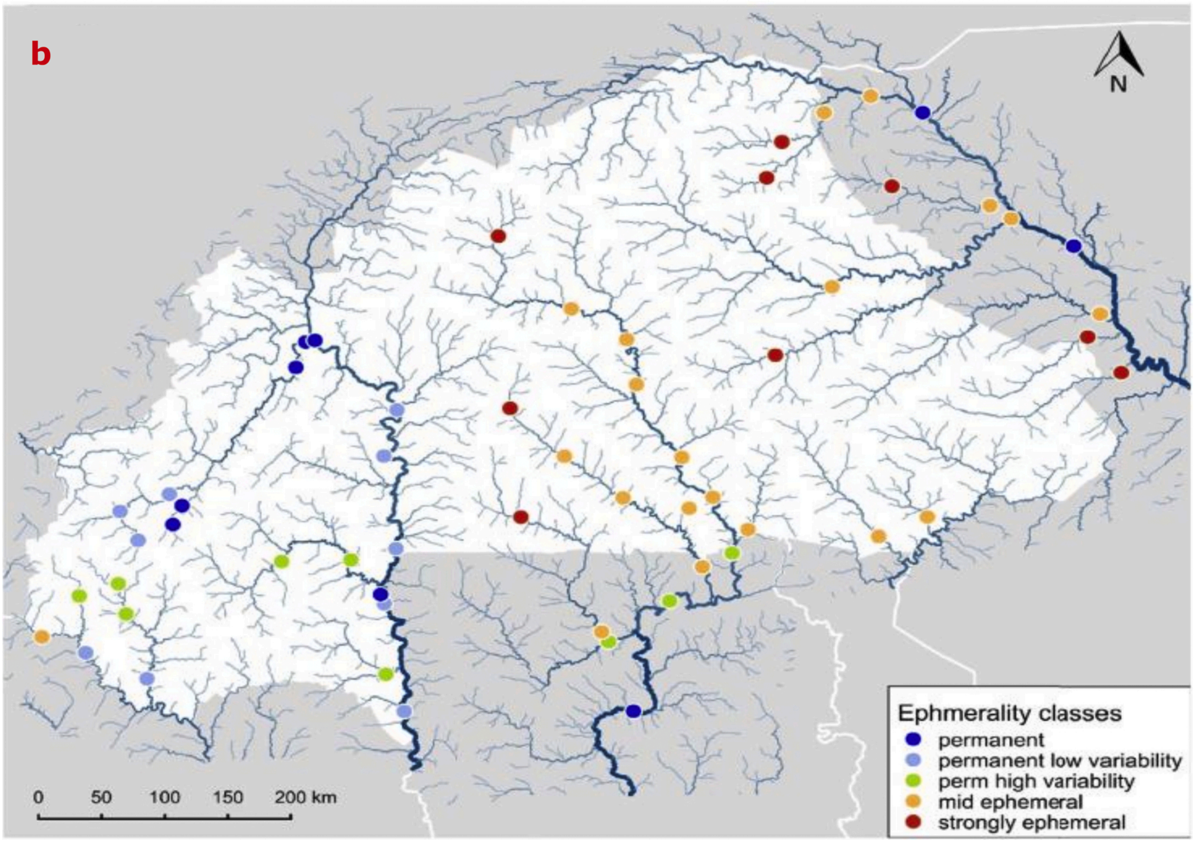


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Fig. 9. Comparisons of intermittency classes in Burkina Faso: a) The present study over 1955–1985, b) Adapted from (Perez-Saez et al., 2017).

annual precipitation. One interesting result is an apparent clustering of catchments located on the first two quadrants (above the first axis) compared to those located on the third and fourth quadrants (Fig.8). Thus, the catchments with positive PC2 values (thus high permeability) are more likely to be perennial or weakly intermittent. Two exceptions, the Douna and Niofila catchments, display high permeability and very high rainfall values (resp. 1163 and 1166 mm/yr) but belong to the highly intermittent and ephemeral classes. Some studies have shown that streams located upstream of the river network are likely to have flow intermittently due to their size (Beaufort et al., 2018; Wohl, 2017). Conversely, catchments with negative PC2 values (low permeability) are more likely to be highly intermittent or ephemeral.

4. Discussion

4.1. Comparison with previous studies

In the present study, there is a consistent geographical variation in the intermittency classes with stations that tend to be perennial, mostly located in the south-western part of the country. A previous study of Perez-Saez et al. (2017) focuses on modeling the dynamics of waterborne diseases in Burkina Faso based on hydrological classification and stream ephemerality prediction. An unsupervised clustering approach based on the number of zero flow months per year and for each gauge was used to determine the number of intermittency classes. Comparing the results obtained with those of Perez-Saez et al. (2017) on flow intermittency classes in Burkina Faso reveals a strong consistency, although the number of classes defined and classification methods remain different (Fig. 9). In

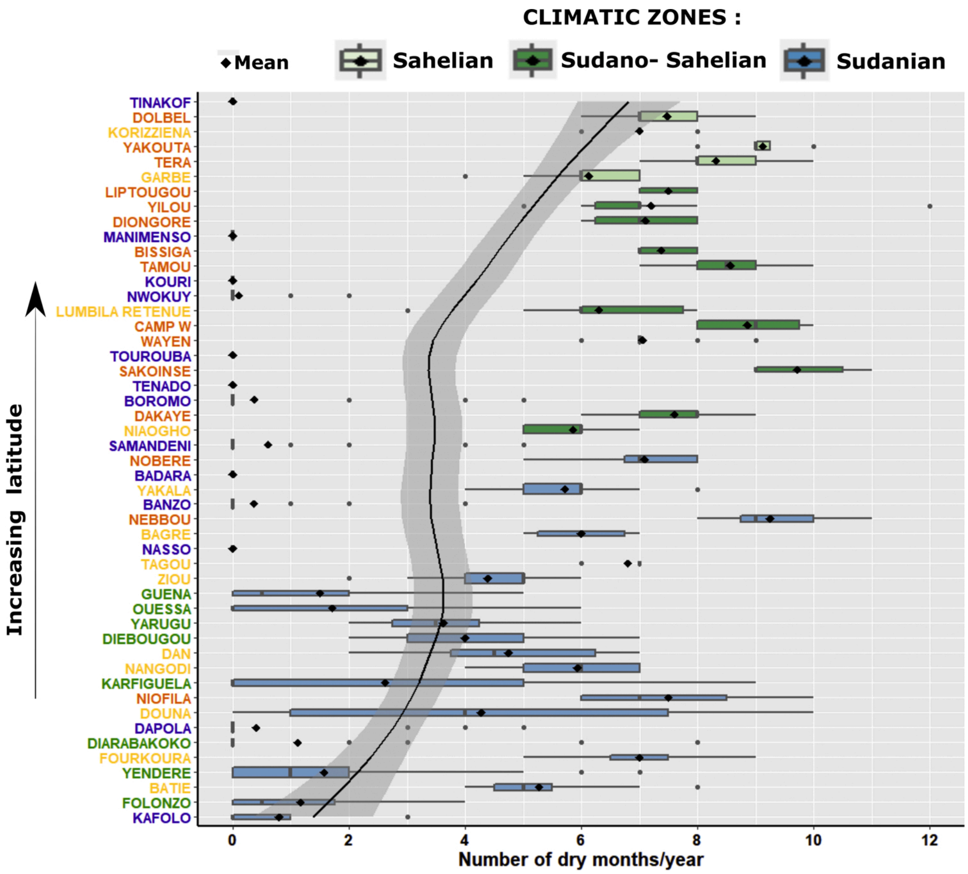

Fig. 10. The observed number of dry months per gauging stations over 1955–1985. The middle line represents the median in each boxplot, whereas the black dot represents the average value. The boxplot thickness is proportional to the number of observations. The gauged stations are ordered according to the increasing latitude. The trend curve (black line), with a 95 % confidence interval (grey zone), is obtained by local weighted least-squares smoothing of the raw counts of dry months. According to the climatic zones, the boxplots' color is defined from the Sudanian zone in blue to the Sahelian zone in light green. The color of gauging station names depends on their intermittency class: perennial (blue), weakly intermittent (green), highly intermittent (orange), ephemeral (red). (For interpretation of the references to colour in this Figure legend, the reader is referred to the web version of this article).

general, no more than one intermittency class difference is observed between the two maps (Fig. 9). The significant differences lie in the number of gauged stations taken into account. Perez-Saez et al. (2017) only consider gauges stations (58) with at least three years of data, whereas in the present study, the selected stations (49) have at least four years of data. The period investigated is also different: 1955–1985 in this study 1960−1990 in Perez-Saez et al. (2017). These numerous elements listed above are probably at the origin of the discrepancies between Fig. 9a and b.

In Perez-Saez et al. (2017) study, the variables selected as input for ephemerality controls in the statistical model (Gradient Boosting Tree) were limited to aridity index, annual discharge, and remote-sensing based vegetation characteristics. However, no hydrogeological variable was considered, which constrained the conclusion that the most important driving variable of ephemerality was mean annual discharge.

Outside of Burkina Faso, Hammond et al. (2021) showed that climate, particularly the aridity index, is the dominant controlling factor of stream intermittency at the continental scale of the USA for both human-impacted and non-impacted gauges stations. The effect of physiographic variables such as permeability and catchment area emerges more at a smaller scale. Similar conclusions can be drawn from the large-scale study of Sauquet et al. (2021), encompassing Australia, Europe, and the USA. The aridity index emerges as the climatic variable that best discriminates the different flow intermittency classes, although the control of physiographic variables on flow intermittency classes was not investigated. In the present study, we did not keep the aridity index as an explanatory factor, as it is strongly correlated to precipitation (SM Fig. 8), so we only kept the latter to reduce the number of autocorrelated variables (see Section 2.4).

4.2. Link between intermittency and catchment hydrology

One of the main results of the present study is that the geographical variation of intermittency classes in Burkina Faso shows a significant spatial coherence. The perennial and weakly intermittent classes are mostly located in the Comoe and Mouhoun catchments. In contrast, the highly intermittent and ephemeral classes are mainly located in the Nakanbe and Niger catchments (Fig.4a, Fig.5a). The upper Mouhoun catchment is entirely based on a sedimentary zone, and 86 water sources are identified; 77 sources are perennial (Dakoure, 2003), indicating a strong groundwater contribution to baseflows. Among these sources, there is a famous source called "*Nasso-Guinguette*", which is the most important water source in West Africa (Huneau et al., 2011). The Comoe catchment is partly sedimentary (about 20 % of its surface area), and more than 100 perennial sources were identified (Dakoure, 2003). Many other studies showed the importance of spring flow rates in the sedimentary zone as contributing to the Mouhoun and Comoe rivers' baseflow and their tributaries (Kouanda et al., 2018; Koussoube, 2010; Ouédraogo, 1994; Sauret, 2013; Tirogo et al., 2016). Kouanda et al. (2018) estimated at 45 % the contribution of the average groundwater discharges to the total flow of Samendeni river (a tributary of Mouhoun river) during the rainy season in 2017. During the dry season, the Mouhoun and Comoe rivers are essentially fed by substantial inflows of baseflow (Pavelic et al., 2012), explaining their high probability of being perennial or weakly intermittent.

Nakanbe and Niger catchments in Burkina Faso are mainly located on metamorphic rocks. Therefore, some studies (Mahe, 2009; Yameogo, 1988) have shown that the aquifer in the Nakanbe catchment is a fractured aquifer and very deep to be connected to the river. These distinct hydrogeological conditions between the Mouhoun and Comoe catchments compared to the Nakanbe and Niger catchments could explain this observed geographical variation in flow intermittency classes.

The distribution of intermittent and perennial streams among the gauged rivers is not strongly dependent on the average annual precipitation because, as shown by the large proportion of perennial streams found in arid and semi-arid climates (Sahelian and Sudano-Sahelian zones) (Fig.10). There, the precipitation effect is overruled by the mean catchment permeability, the catchment area, and Strahler order. This result is consistent with those obtained by Carlier et al. (2018) in the Swiss Plateau and Prealpes, who suggested that catchments with relatively permeable geological units have a high buffering potential on precipitation, and therefore, a significant water storage dynamic.

Our results also suggest that the catchments belonging to the ephemeral class have a shorter lag time than other classes, which may be due to their size (relatively small catchment area) and low permeability compared to other classes.

Among the non-anthropogenic variables identified in this study as intermittency controls, only precipitation is likely to change in the future, the other variables being relatively "static". The comparison between the normal and drought sub-periods shows little sensitivity of intermittency classes to substantial variations of mean annual precipitation (Fig.3). Fig. 10 also shows that mean annual precipitation is not the primary factor explaining the distribution of perennial streams in the country, which means that rivers display a certain resilience against persistent droughts, as also evidenced by the similar spatial distribution of intermittency between the normal and dry sub-periods (Figs. 3,4). The intermittency classes for 8 gauges stations common to the period 1955–1985 and the period 1986–2017 (with at least 4 years of data for each period) also shows little variation with 2 gauges stations that shift, one from weakly intermittent to perennial and the other from highly intermittent to weakly intermittent (SM Section 8), which can be explained by the recovery from the drought period (Lebel and Ali, 2009). This low sensitivity of rivers to annual rainfall amounts may be related to the very high seasonality of rainfall in the country: by default, river flow is seasonal too, whichever annual mean precipitation, unless particular catchment processes, here groundwater flow, make it perennial. This implies that the evolutions of the rainy season length and groundwater recharge processes may be more important for the evolution of intermittency in Burkina Faso than the ones of annual mean precipitation.

Future climate projections in West Africa suggest an increase of precipitation in the central and eastern parts, and a decrease in the western parts, with no clear indication about a possible shift in the length of the rainy season (Biasutti, 2019; Gaetani et al., 2020). Although uncertainties increase when we zoom in, the above studies may imply a significant increase of precipitation in the eastern part of Burkina Faso. In this area of low permeability, this may not affect a lot the evolution of intermittency, which does not depend strongly on total precipitation over the 1955–1985 period and also does not show significant changes at current gauges analyzed, but some changes may not be detectable at the monthly time step. Nevertheless, this contrasts with the results of Döll and Schmied. (2012), who predicted a shift of river flow regimes from intermittent to perennial in this eastern part of West Africa due to increasing precipitation under climate change. However, the increase of precipitation may lead to increased floods, as already observed in the Sahelian part of the Niger basin (Casse et al., 2016).

4.3. Limitation of the study and potential applications

In this present study, it is crucial to be aware that many shortcomings remain. Firstly, land use/land cover (LULC) were not considered as potential explanatory variables due to LULC data's unavailability over the study period. Other studies also neglected their potential influence (Beaufort et al., 2019; Snelder et al., 2013), while Kaplan et al. (2020) found they were not dominant explanatory variables of no-flow metrics in a small catchment of Luxembourg. Dams, which are a form of LULC alteration, were also overlooked in our study, as we have shown that their influence on flow intermittency classes seems to be weak during the 1955–1985 study period (SM. Section 3), but their effects may not necessarily be reflected at the monthly time scale. In Burkina Faso, the primary function of dams is to store water to make up for shortages during the dry season. Their effect might be felt at the beginning of the rainy season, when downstream flow is reduced, but once they are full, water flows through the spillway until the end of the rainy season. Only stations located downstream of huge dams could be influenced beyond the beginning of the rainy season, and become either more intermittent due to storage, or less intermittent if the dams are used for hydropower.

Additionally, the reclassification of geological information from the BUMIGEB database to the GliM's nomenclature has undoubtedly led to some loss of information because certain types of lithologies have been grouped into one. Nevertheless, the use in Burkina Faso of the BUMIGEB lithological map at the scale of 1:1,000,000 to the complement of the GliM map at the scale of 1:3750000 is a better alternative to the single-use of GliM map (Hartmann and Moosdorf, 2012), which has a very coarse scale and lacks precision compared to the local BUMIGEB map. The permeability map is derived from this final lithology map, using permeability values within a range depending on rock type and observed drainage density. These assumptions potentially introduce uncertainty to the estimation of permeability. Although the estimated permeability map shows some similarities with the British Geological Survey's (BGS) aquifer type/productivity map (SM Section 2), where areas mapped as having high aquifer productivity also generally exhibit high permeability, the estimated permeability remains uncertain because it is derived from coarse geologic maps.

In arid and semi-arid regions where intermittent streams are assumed to be predominant (Gallo et al., 2020), stations tend to be located on large streams (Zimmer et al., 2020), so our study is not representative of the majority of rivers in the country, smaller and assumed to be intermittent by the local authorities (Fovet et al., 2021). The lack of hydrological data makes it impossible to estimate intermittency indices in ungauged catchments. Data loggers with sensors are technologies to measure the absence or presence of water continuously and are less expensive than traditional gauging stations to survey flow intermittency (Bhamjee et al., 2016; Kaplan et al., 2019; Peirce and Lindsay, 2015). They can help to better monitor headwater streams in numerous ungauged areas of West Africa. These new data can make it possible to study river flow intermittency at much smaller scales.

As a perspective, the identified flow intermittency controls in this study can notably be used in flow regionalization processes or as predictive variables to produce intermittency maps as performed by Snelder et al. (2013). However, particular care should be taken when extrapolating these control factors outside the study area, where other factors may be dominant.

5. Conclusion

This study highlighted the control of several environmental variables on flow intermittency in Burkina Faso selected among the components that are climate, lithology, and topography. Significant differences are observed in the geographic variation of flow intermittency classes, with perennial and weakly intermittent gauges stations mostly located on Comoe, and Mouhoun catchments; meanwhile, highly intermittent and ephemeral stations are mostly located on Nakanbe and Niger catchment. The main feature discriminating these river catchments comes from their lithology and permeability. This is consistent with the finding that rivers classified as ephemeral in Burkina Faso have shorter lag times than other flow intermittency classes. Despite the importance of annual precipitation and Strahler order in discriminating intermittent rivers, this study suggests that catchment permeability and surface area explain the geographical variation of flow intermittency class in Burkina Faso. We also showed that, if the spatial variations of precipitation contribute to the patterns of flow intermittency, the long-term contrasts of precipitation between the normal and dry subperiods may have a weak influence on intermittency classes, which could indicate a substantial resilience of rivers in the country.

Further studies are needed to understand better the other factors and hydrological processes controlling intermittency in arid and semi-arid environments. In Sahel, since the 1990s, there is some evidence of recovery from the drought (Lebel and Ali, 2009), large dams have been built, and land conversion for agriculture has increased (Yonaba et al., 2021). With the increasing availability of data, notably from remote-sensing, the influence of these anthropogenic factors could now be considered, although the number of river gauging stations has decreased. Other environmental variables could be also investigated, such as the dry season length or the Standardized Precipitation-Evapotranspiration Index (Vicente-Serrano et al., 2010), which was strongly related to the annual and seasonal zero-flow day occurrence in many stations of Europe and Mediterranean countries outside Europe (Tramblay et al., 2020). Eventually, the identified control variables could be used to develop predictive models, to provide a comprehensive spatial distribution of river intermittency throughout the country, retrospectively and in the future.

Author statement

Axel Patindé Belemtougri: Conceptualization, Methodology, Formal analysis, Writing - original draft; **Agnès Ducharne:** Conceptualization, Methodology, Writing - review & editing, Supervision; **Fowe Tazen:** Formal analysis, Writing - review & editing; **Ludovic Oudin**: Formal analysis, Writing - review & editing; **Harouna Karambiri**: Conceptualization, Methodology, Writing - review & editing, Supervision.

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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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100908.

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