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OVERVIEW

Intermittent rivers and ephemeral streams: Perspectives for critical zone science and research on socio-ecosystems

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Abstract

Intermittent rivers and ephemeral streams (IRES) are now recognized to support specific freshwater biodiversity and ecosystem services and represent approximately half of the global river network, a fraction that is likely to increase in the context of global changes. Despite large research efforts on IRES during the past few decades, there is a need for developing a systemic approach to IRES that considers their hydrological, hydrogeological, hydraulic, ecological, and biogeochemical properties and processes, as well as their interactions with human societies. Thus, we assert that the interdisciplinary approach to ecosystem research promoted by critical zone sciences and socio-ecology is relevant. These approaches rely on infrastructure—Critical Zone Observatories (CZO) and Long-Term Socio-Ecological Research (LTSER) platforms—that are representative of the diversity of IRES (e.g., among climates or types of geology). We illustrate this within the French CZO and LTSER, including their diversity as socio-ecosystems, and detail human interactions with IRES. These networks are also specialized in the long-term observations required to detect and measure ecosystem responses of IRES to climate and human forcings despite the delay and buffering effects within ecosystems. The CZO and LTSER platforms also support development of innovative techniques and data analysis methods that can improve characterization of IRES, in particular for monitoring flow regimes, groundwater-surface water flow, or water biogeochemistry during rewetting. We provide scientific and methodological perspectives for which this interdisciplinary approach and its associated infrastructure would provide relevant and original insights that would help fill knowledge gaps about IRES.

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critical zone observatories, long-term socio-ecosystem research, nonperennial, systemic approach, temporary waterways

1 | INTRODUCTION

Intermittent rivers and ephemeral streams (commonly referred to as “IRES”) represent half of the global river network (Datry, Larned, & Tockner, 2014; Schneider et al., 2017) and span all climates and biomes. IRES are more frequent in arid and semi-arid areas but are also present in temperate, tropical humid, boreal, and alpine areas, where they are mainly located in headwaters (Costigan et al., 2017). Their abundance is increasing due to climate change and water withdrawals for human activities (de Graaf, Gleeson, van Beek, Sutanudjaja, & Bierkens, 2019; Döll & Schmied, 2012), which has implications for freshwater biodiversity and the ecosystem services that rivers provide to societies. These systems contribute to the local and regional biodiversity of river networks, as well as to their functional and biogeochemical integrity, and they provide many ecosystem services, such as flood regulation, aquifer recharge, and wood and food supply (Acuña et al., 2014; Addy et al., 2019; Datry et al., 2018; Kaletova et al., 2019).

1.1 | A multitude of definitions among disciplines which calls for a systemic approach

Many disciplines have attempted to assign names and define classes of streams and rivers whose flows cease for varying periods and with variable predictability (Busch et al., ; Gallart et al., 2012; Uys & O’Keeffe, 1997; Williams, 2006). The large diversity of names and definitions to refer to IRES is not surprising given their occurrence and variety across the world (Datry, Bonada, & Boulton, 2017). The fact that many local names and terms exist (e.g., Steward, von Schiller, Tockner, Marshall, & Bunn, 2012) indicates that these systems are recognized by local residents as unique parts of the landscape that deserve unique names. Although commendable, global consensus remains elusive, especially since many intermittent waterways dry up during different periods in different years, leading to different names. In addition, a single specific definition would likely not be relevant for all disciplines. For instance, the presence of pools without flow may be incidental for fitting a hydrological model, but it may be crucial for understanding how biotic communities and processes are influenced by intermittent flow. Thus, rather than entering a semantic minefield, many authors have referred to “temporary rivers” or “nonperennial rivers” or “intermittent rivers and ephemeral streams” as a short-hand term for all flowing water that ceases to flow or that dries up completely at some point in time and/or space (Busch et al., ; Datry, Bonada, & Boulton, 2017; Larned, Datry, Arscott, & Tockner, 2010). Nonetheless, in recent years, several collaborative groups have emerged for interdisciplinary work to understand IRES, with the awareness that a systemic approach was needed to bridge knowledge gaps related to them (Shanafield et al., 2020).

1.2 | State of the art

The past few decades have experienced a sharp increase in the interest for IRES, primarily in the fields of biodiversity and ecology. This is illustrated by a variety of special issues on IRES (Arthington, Bernardo, & Ilhéu, 2014; Datry, Arscott, & Sabater, 2011; Datry, Fritz, & Leigh, 2016; and another SI in *Water 2020*, Vol. 12) and the release of the first book compiling knowledge about IRES (Datry, Bonada, & Boulton, 2017). The ecology of IRES has attracted much attention, although it still lags behind that of the ecology of perennial rivers and streams (Datry

et al., 2014). IRES consist of mosaic of habitats (terrestrial, lotic, and lentic) inhabited by a rich biodiversity that is determined by the resistance and resilience of its associated taxa (Datry et al., 2017; Rodríguez-Lozano, Leidy, & Carlson, 2019). Associated research challenges have been described, such as characterization of dry-phase and terrestrial communities (Allen et al., 2020; Datry, Fritz, & Leigh, 2016; Legal et al., 2020; Ruhi, Datry, & Sabo, 2017; Stubbington et al., 2019) and the influence of the flowing phase on dispersal and recolonization (Leigh & Datry, 2017; Vinatier et al., 2018).

Some biogeochemical characteristics of IRES are also fairly well emphasized, and recent results suggest that IRES may play a large role in global biogeochemical cycles (Benstead & Leigh, 2012; Datry et al., 2018; von Schiller et al., 2019). Dry or lentic phases can modify the nature (Ylla, Sanpera-Calbet, Muñoz, Romani, & Sabater, 2011) and the biodegradability (Datry, Corti, Claret, & Philippe, 2011; Dieter et al., 2011) of organic matter, and they are followed by rapid mobilization during rewetting (Corti & Datry, 2012; Guarch-Ribot & Butturini, 2016; Harjung, Sabater, & Butturini, 2018; Shumilova et al., 2019). Transfer of suspended solids and associated substances (e.g., pesticides, heavy or trace metals, phosphorus, pharmaceuticals) involves surface runoff events, which are frequently associated with the onset of flow in intermittent upstream networks via ditches, drains, and headwater streams (Carluer & Marsily, 2004; Dollinger, Dagès, Bailly, Lagacherie, & Voltz, 2015; Jordan-Meille, Dorioz, & Mathieu, 1998). The changes in IRES width, length, and surface also influence efflux of gases from inland waters (Barefoot, Pavelsky, Allen, Zimmer, & McGlynn, 2019; Butman & Raymond, 2011).

In hydrological studies, intermittency is not always explicit if the focus of the analysis relates to the flowing phase or the water budget, even if the study system is intermittent. Hydrological studies of IRES focus mostly on how to classify nonperennial hydrological systems (Beaufort, Carreau, & Sauquet, 2019; Fritz et al., 2013; Gallart et al., 2012; González-Ferreras & Barquín, 2017; Kaplan, Sohr, Blume, & Weiler, 2019; Kennard et al., 2010; Moliere, Lowry, & Humphrey, 2009; Perez-Saez, Mande, Larsen, Ceperley, & Rinaldo, 2017; Rinderer, Ali, & Larsen, 2018; Sefton, Parry, England, & Angell, 2019; Yu, Bond, Bunn, Xu, & Kennard, 2018) or on how to describe the intermittence of flow/network using which metrics (Botter & Durighetto, 2020; Costigan et al., 2017; Eng, Grantham, Carlisle, & Wolock, 2017; Fritz, Johnson, & Walters, 2008; Gallart et al., 2012; Jensen, McGuire, McLaughlin, & Scott, 2019; Jensen, McGuire, & Prince, 2017; Jensen, McGuire, Shao, & Andrew Dolloff, 2018; Reynolds, Shafroth, & LeRoy Poff, 2015; Sauquet et al., 2020). There is fewer literature which rather investigates the processes that are expressed by intermittence or that caused intermittence (Costigan, Daniels, & Dodds, 2015; Lovill, Hahm, & Dietrich, 2018; Perrin & Tournoud, 2009; Schilling, Cook, Grierson, Dogramaci, & Simmons, 2020; Ward, Schmadel, & Wondzell, 2018; Whiting & Godsey, 2016; Zimmer & McGlynn, 2017a; Zimmer & McGlynn, 2017b). Recent reviews on the hydrology of IRES explain this situation by the lack of quantitative data to describe and characterize these systems (Borg Galea, Sadler, Hannah, Datry, & Dugdale, 2019; Costigan et al., 2017; Sauquet et al., 2020) and the difficulty in identifying and interpreting zero flow (Zimmer et al., 2020).

Lastly, from a socio-economic perspective, there are still few attempts to quantify the goods and services that IRES provide or to explore social perceptions of IRES (Armstrong, Stedman, Bishop, & Sullivan, 2012; Leigh, Boersma, Galatowitsch, Milner, & Stubbington, 2019; Rodríguez-Lozano, Woelfle-Erskine, Bogan, & Carlson, 2020). These perceptions strongly influence the level of care and the management rules applied to IRES, although the lower value attributed to IRES makes them frequently exposed to multiple stressors and less protected than perennial rivers.

1.3 | Remaining research challenges

Major challenges remain for developing a holistic understanding of IRES. Low regional synchronization of zero flows reveals unknown processes that control intermittence (Snelder et al., 2013), especially the relative influence of natural drivers like climate (Borg Galea et al., 2019; Skoulikidis et al., 2017; Ward, Wondzell, Schmadel, & Herzog, 2020), geology (Lovill et al., 2018; Ward et al., 2018; Whiting & Godsey, 2016), topography (Jensen et al., 2018; Jensen et al., 2019; Prancevic & Kirchner, 2019), and of human factors such as land use and water withdrawals (de Graaf et al., 2019; Dresel et al., 2018; Skoulikidis et al., 2017). It is also unclear how drying alters the estimation of water balance (Cuthbert et al., 2016) and water travel times (Bansah & Ali, 2019; van Meerveld, Kirchner, Vis, Assendelft, & Seibert, 2019). Mechanisms behind extension/contraction dynamics of hydrographic networks (e.g., Durighetto, Vingiani, Bertassello, Camporese, & Botter, 2020; Godsey & Kirchner, 2014; Prancevic & Kirchner, 2019) are poorly

understood (Lovill et al., 2018; Zimmer & McGlynn, 2017b) and their consequences for ecology (Boulton, Rolls, Jaeger, & Datry, 2017) and biogeochemistry (Hale & Godsey, 2019; Zimmer, Bailey, McGuire, & Bullen, 2013) also need more investigation. In particular, knowledge about the importance and functions of drying-phase populations and rewetting-phase biogeochemistry must be refined. These challenges require a systemic approach that combines hydrological, hydrogeological, hydraulic, ecological, and biogeochemical properties and processes. Indeed, all these processes involve environmental interfaces (sediments/stream, groundwater/surface water, terrestrial/aquatic ecosystems) where disciplinary approaches of the different compartments complement each other (Datry, Fritz, & Leigh, 2016; National Research Council, 2001; Shanafield et al., 2020). Such a systemic approach should also include interactions of these processes with humans (Datry, Boulton, et al., 2018; Haberl et al., 2006; Koundouri, Boulton, Datry, & Souliotis, 2017), whose activities directly influence the hydrological regimes, while human management of aquatic ecosystems affects biogeochemical and ecological functioning.

1.4 | Critical zone observatories and Long-Term Socio-Ecological Research platforms

The Earth's critical zone (CZ) is the “heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources” (National Research Council, 2001). CZ Science has emerged as an interdisciplinary field of research that studies biotic and abiotic interactions within terrestrial environmental systems at different temporal and spatial scales and across anthropogenic gradients. It relies on observation and experimental data acquisition within Critical Zone Observatories (CZO) located across the world in different contexts and at small to regional scales, with some sites running for more than 50 years, (e.g., Brantley et al., 2017; Gaillardet et al., 2018). In ecology, the concept of socio-ecosystems has been developed to acknowledge that natural and human systems are complex and co-evolve (Haberl et al., 2006). Dedicated Long-Term Socio-Ecological Research (LTSER) platforms started in the 1980s support this approach by conducting long-term monitoring of environmental and socio-economic factors (e.g., Dick et al., 2018). Both CZ and LTSER sciences rely on a systemic approach to analyze “ecosystem structure, function, and services in response to a wide range of environmental forcings using long-term, place-based research” (Mirtl et al., 2018) that targets the sustainability of socio-ecosystems (Bretagnolle et al., 2019). In overall, CZ fosters the disciplines in the geosciences and biosciences while LTSER links the biophysical processes to governance and communications with collaborations by natural and social sciences.

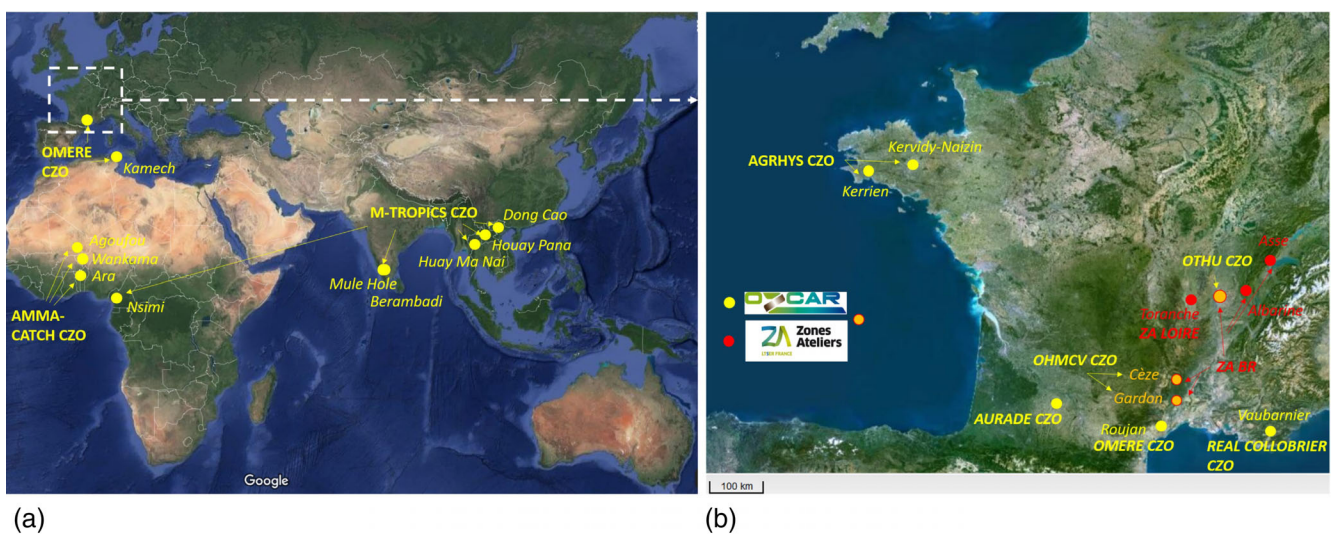


FIGURE 1 Location of French Critical Zone Observatories (CZO) of the OZCAR network (yellow) and Long-Term Socio-Ecological Research (LTSER) platforms of the RZA network (red) with flow intermittence along a variety of natural and human gradients in (a) the Eastern Hemisphere and (b) France. Catchment characteristics are listed in Table 2. Sites in orange belong to both networks

TABLE 1 Summary of the possible contributions of the CZO and LTSER networks to the major research challenges identified for IRES described in the overview (with reference to the corresponding sections)

Major challenges (Section 1.3)	Associated gaps	Why CZ science and socio-ecology can meet these requirements or what they should improve to progress in this direction	
		Interfaces studied through an interdisciplinary approach of particular relevance for IRES (Section 5.1)	Observation facilities, and methodological advances generated via CZO and LTSER platforms (Section 5.2)
Hydrological processes of intermittence and river network expansion/contraction	<ul style="list-style-type: none"> Fine-scale process studies Dynamic mapping of IRES at fine resolution over large areas 	<ul style="list-style-type: none"> Groundwater-surface water exchanges Influence of vegetation cover on water fluxes 	<ul style="list-style-type: none"> New satellite sensors Storage measurement techniques Distributed low cost or proxies sensors Hydrological signatures
Quantifying respective roles of natural factors (Section 2) versus human actions (Section 3)	<ul style="list-style-type: none"> Multi-site approach, covering the diversity of natural and human contexts Long-term records to include progressive evolution/responses 	<ul style="list-style-type: none"> Influence of vegetation cover on water fluxes Groundwater-surface water exchanges 	<ul style="list-style-type: none"> Multi-site and long-term observation and experimental data from CZO and LTSER CZ models and virtual experiments New techniques to explore these multi-site and long-term data from data sciences
Consequences for ecology	<ul style="list-style-type: none"> Dry phases and terrestrial communities Multi-site approach to test for transferability and generality of identified processes and patterns 	<ul style="list-style-type: none"> Influence of vegetation cover on element fluxes Bio-physico-geochemical behavior of streambeds 	<ul style="list-style-type: none"> Co-located hydrological, biogeochemical, ecological, and sociological data and common protocols More data to be collected: Ecological in CZO and sociological (perception and management) everywhere
Consequences for stream and river biogeochemistry	<ul style="list-style-type: none"> Stream metabolism in rewetting phase Effect of drying on the geogenic (weathering), anthropogenic (wastewater and diffuse) contributions 	<ul style="list-style-type: none"> Influence of vegetation cover on element fluxes Bio-physico-geochemical behavior of streambeds Hydrological, biogeochemical, and isotopic tracers 	<ul style="list-style-type: none"> High-frequency chemical data: To catch fast rewetting and to deconvolute hetero-autotrophy from diurnal variations of concentrations) Tracers to deconvolute hydrological (mixing), geochemical (weathering) and biological processes

The CZO and LTSER networks are in good position to address some of the remaining challenges for research on IRES because:

1. They can study the wide variety of IRES because their observatories (CZO) and platforms (LTSER) are widely distributed (Mirtl et al., 2018; Figure 1). It is relevant to cover the IRES diversity to build a general and unified theory, also including monsoon systems poorly taken into account due to a dearth of data from tropical region (e.g., Knoben, Woods, & Freer, 2018).
2. They conduct long-term in-situ or remote observations that are relevant for understanding and predicting dynamics of IRES as climate and human forcings can evolve slowly or compensate each other locally, and because the ecosystem responses to these forcings can be buffered or delayed (Allen et al., 2019; Eng, Wolock, & Dettinger, 2016).
3. They promote a holistic and interdisciplinary approach to terrestrial environments (including inland waters) that is fully suitable for complex socio-ecosystems such as IRES (Datry, Boulton, et al., 2018; Shanafield et al., 2020).

In this overview, we illustrate why CZ and socio-ecology approaches can be relevant for filling knowledge gaps about IRES (Table 1). First, we show that IRES have diverse flow regimes, origins and evolutions, and that French CZO and LTSER networks (OZCAR, RZA) represent this diversity well (Section 2). Second, we detail human actions and feedbacks on intermittence that make IRES complex socio-ecosystems, since a greater integration of the human component

of environments is an explicit objective of CZ and socio-ecology sciences (Section 3). Third, we review current and emerging data and tools for characterizing IRES (Section 4). Finally, we address some perspectives to illustrate in practice how CZO and LTSER can provide original contributions to the understanding and prediction of intermittence processes. These perspectives involve studying processes at environmental interfaces that are of particular relevance for IRES and using CZO and LTSER facilities to monitor and model them (Section 5).

2 | REPRESENTATION OF DIVERSITY OF OCCURRENCES, ORIGINS, AND EVOLUTIONS OF IRES WITHIN CZO AND LTSER AND THE NEED FOR INTEGRATED APPROACHES

2.1 | The diversity of IRES represented within CZO and LTSER

IRES exhibit wide diversity across the world (Datry, Bonada, & Boulton, 2017), as illustrated by some of the catchments drained by IRES and monitored by CZO and LTSER networks in the world (Figure 1, Table 2). They range in size from a few hectares to more than 10,000 km², and while they occur most frequently in tropical and Mediterranean regions, they also occur in temperate and oceanic regions. IRES are not associated with a specific geology or land use, since intermittence occurs in pristine, less intensive, and more intensive agricultural catchments, as well as urbanized ones. As for perennial waterways, IRES also have diverse flow regimes, as for instance illustrated by the relative durations of flowing/dry phases (Table 2). Flow can stop for short seasonal period (Figure 2a–c) or for most of the year (Figure 2d–f), and may sometimes be nearly limited to storm-flow events during the wet season. However, many aspects of the flow regimes of IRES have yet to be quantified, such as the predictability or rates of change of IRES flow over time. The diversity of IRES studied by CZO and LTSER networks in France and elsewhere in the world will help to do so in the near future.

2.2 | Natural origin and drivers of intermittence

The origin of intermittence can be natural (this section) or anthropogenic (Section 3). Regional and local factors such as climate, geology, soils, topography, and land use are important drivers of the intermittence of streams and rivers (Boulton et al., 2017; Costigan, Jaeger, Goss, Fritz, & Goebel, 2016; Pate, Segura, & Bladon, 2020; Williams, 2006). IRES usually dominate upstream sections of hydrographic networks in temperate regions that have high precipitation throughout the year (Fritz et al., 2013). They represent most streams and rivers, of a variety of Strahler orders, in arid and semi-arid regions that have lower or less frequent precipitations, and in regions in which precipitation falls only within one or two seasons (Kennard et al., 2010). Snow and glaciers may cause local intermittence when precipitation is temporarily stored in the snow pack in winter (e.g., Paillex, Siebers, Ebi, Mesman, & Robinson, 2020). On the contrary, they can also reduce seasonal intermittence downstream by providing meltwater.

Bedrock permeability exerts a main control on flow regime (Carrier, Wirth, Cochand, Hunkeler, & Brunner, 2018). Summer streamflows and timing of response to winter recharge is correlated to geology (Tague & Grant, 2004). A permeable bedrock is recognized to cause a strong attenuation of baseflow component (Le Mesnil, Charlier, Moussa, Caballero, & Dörfliger, 2020), while bedrock and weathering profiles with low permeability and/or low porosity limit this process (Séguis et al., 2011). When the water table lies below the river network, groundwater is recharged mainly by infiltration from the IRES (Dages et al., 2009; Maréchal et al., 2009; Scanlon et al., 2006). In this case, the occurrence and duration of intermittent flows depend on the time required to redistribute infiltrated water within the underground material, itself controlled by the hydraulic properties of this material (Rau et al., 2017). Steep slopes, and small and elongated catchments may favor intermittence by rapidly transferring water to the hydrographic network at the catchment scale (Prancevic & Kirchner, 2019), making it difficult to regionalize patterns of flow intermittence (Snelder et al., 2013).

Natural vegetation exerts a fundamental control on evapotranspiration and thus on catchment water balance at all scales (Gribovszki, Kalicz, Szilágyi, & Kucsara, 2008; Lupon, Ledesma, & Bernal, 2018), but also on soil infiltration capacity. Riparian vegetation may host specific processes that control flow intermittence. For instance, in the sub-humid Sudanian zone of western Africa (AMMA-CATCH sites in Benin), trees in riparian fringes may control the

TABLE 2 Characteristics of catchments that drain intermittent rivers and ephemeral streams that are intensively monitored within OZCAR (French Critical Zone Observatories) and RZA (French Long-Term Socio-Ecological Research) networks

Observatory/ plateform	Country	Site name	Catchment area (km ²)	Climate	Precipitation (mm/year)	Reference ET (mm/year)	Geology	Land use	Flow restricted to precipitation event	Dry season > flowing season	Flowing season > dry season
AMMA-CATCH (Galle et al., 2018)	Mali	Agoufou	245	Semi-arid	375	1,915	Sandstone	Grasslands	X		
AMMA-CATCH	Benin	Nalohou	0.16	Tropical sub- humid	1,200–1,300	1,600	Gneiss and micashists	Forest, savanna, and crops		X	
AMMA-CATCH	Benin	Ara	12	Tropical sub- humid	1,200–1,300	1,600	Gneiss and micashists	Forest, savanna, and crops		X	
AMMA-CATCH	Benin	Donga	600	Tropical sub- humid	1,200–1,300	1,600	Gneiss and micashists	Forest, savanna, and crops		X	
AMMA-CATCH	Bénin	Ouémé Supérieur	10,400	Tropical sub- humid		1,600	Gneiss and micashists	Forest, savanna, and crops		X	
AMMA-CATCH	Niger	Tondikiboro	0.11	Semi-arid	450–600	2,500	Sandstone	Crops, fallows, and bare soils	X		
AMMA-CATCH	Niger	Wankama	1	Semi-arid	450–600	2,500	Sandstone	Crops and fallows	X		
M-TROPICS (Sekhar, Riotte, Ruiz, Jouquet, & Braun, 2016)	India	Mule hole	4.1	Tropical dry	1,120	930	Gneiss	Forest	X		X
M-TROPICS	India	Maddur	7	Tropical dry	900	1,250	Gneiss	1/2 crops and 1/2 forest	X ^a		X ^b
M-TROPICS	India	Berambadi	80	Tropical dry	700–900	1,250	Gneiss	2/3 crops and 1/3 forest	X		
M-TROPICS (Valentin et al., 2008)	Laos	Houay Pano	0.007	Tropical humid	1,305–1,738	840–1,000	Shale and schist	From bush fallow and crops to tree plantations	X		
M-TROPICS	Vietnam	Dong Cao	0.077	Tropical humid	1,048–2,506		Schist	From natural vegetation to fodder and tree plantations	X		

(Continues)

TABLE 2 (Continued)

Observatory/ plateform	Country	Site name	Catchment area (km ²)	Climate	Precipitation (mm/year)	Reference ET (mm/year)	Geology	Land use	Flow restricted to precipitation event	Dry season > flowing season	Flowing season > dry season
M-TROPICS	Thailand	Huay Ma Nai	0.93	Tropical humid	1,028–1,493		Siltstone and sandstone	Crops	X		
M-TROPICS	Cameroon	Nsimi	0.60	Tropical humid	1,700	1,300	Granito- gneiss	Mixed humid forest and crops			X
OMERE (Molénat et al., 2018)	Tunisia	Kamech	2.63	Mediterranean	645	1,366	Marls and sandstone	Crops	X		
OMERE	France	Roujan	0.91	Mediterranean	628	1,109	Marl, sandstone, and limestone	Vineyards	X		
REAL COLLOBRIER (Folton, Martin, Arnaud, L'Hermite, & Tolsa, 2019)	France	Vaubardier	1.49	Mediterranean	1,039	1,227	Schist	Forest			X
OHMCV (Boudevillain et al., 2011), ZABR	France	Auzon	100	Mediterranean	1,550–400		Volcanic and limestone	Pasture, crops, and scrubland	X	x	
OHMCV, ZABR	France	Gardon	485	Mediterranean	1,550–400		Schist, granite, and limestone	Forest and scrubland	X		X
ZA BR (GRAIE, n.d.)	France	Asse	657	Mediterranean	650		Marl and limestone	Forest and crops			X
ZA BR	France	Albarine	313	Temperate continental	1,000–1,200		Limestone, quaternary deposits	Forest and crops			X
OHMCV, ZABR	France	Cèze	730	Mediterranean	750		Schist, granite, and limestone	Forest and scrubland	X	X	X

TABLE 2 (Continued)

Observatory/ plateform	Country	Site name	Catchment area (km ²)	Climate	Precipitation (mm/year)	Reference ET (mm/year)	Geology	Land use	Flow restricted to precipitation event	Dry season > flowing season	Flowing season > dry season
AURADE (Ponnou- Delaffon et al., 2020)	France	Montoussé	0.32	Semi-arid	750	550	Sandstone, clay, and limestone	Crops			X
OTHU (Braud et al., 2013)	France	Yzeron	129	Temperate continental	815	743	Gneiss	Forest, crops, and urban			X
OTHU	France	Mercier	6.7	Temperate continental	796	728	Gneiss	Forest and crops			X
OTHU	France	Chaudanne	2.2	Temperate continental	819	756	Gneiss	Crops and urban			X
ZA Loire (Moatar & Dupont, 2016)	France	Toranche	55	Temperate	700	630	Graniteand quaternary deposits	Crops and grasslands			X
AGRHY5 (Fovet et al., 2018)	France	Kervidy-Naizin	5	Temperate oceanic	832	675	Schist	Crops and grasslands			X
AGRHY5	France	Kerrien	0.1	Temperate oceanic	1,125	699	Granite	Crops and grasslands			X

Note: According to Busch et al. (2020), the streams or rivers where flow is “restricted to precipitation event” would be defined as “ephemeral” whereas those with a dry and a flowing season would be defined as “intermittent,” whenever the dry season is longer or shorter than the flowing season.

Abbreviation: ET, evapotranspiration.

^aSince 2012, flow is limited to few events per year. According to piezometric survey, this is due to drastic long-term decrease in groundwater levels due to the combination of pumping for irrigation and of the limited 2012 monsoon (see data in <https://mtropics.obs-mip.fr/catalogue-m-tropics/>).

^bBefore 2012, the Maddur stream was flowing during a longer period than it was dry.

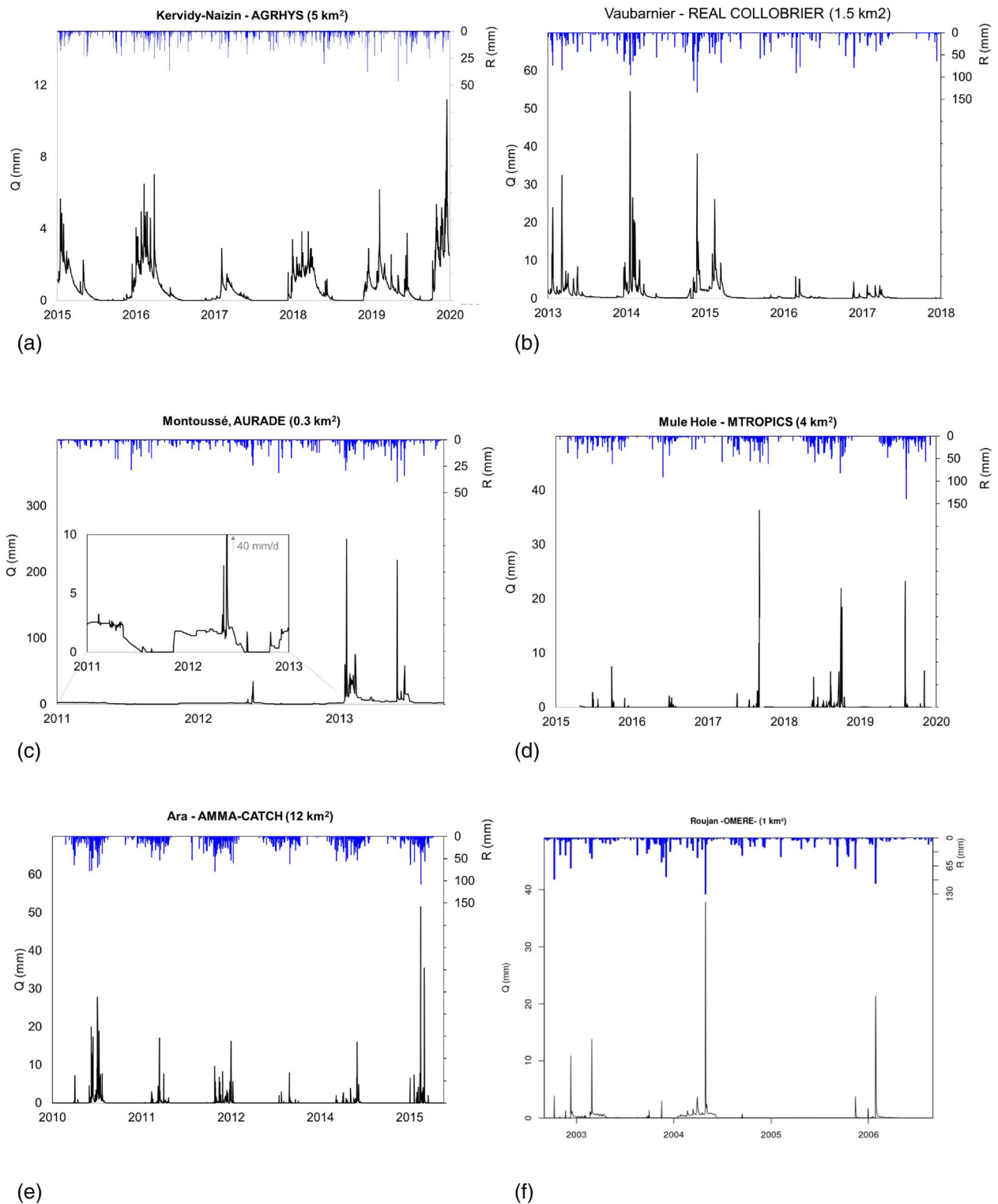


FIGURE 2 The diversity of hydrological intermittence characteristics among flow (Q) and rain (R) records of certain observatories. Characteristics of flow interruption vary widely among sites. Some records illustrate seasonal flow interruption for a short period of the year (≤ 3 months) in temperate (a. AgrHyS), Mediterranean (b. Réal Collobrier), or semi-arid (c. Auradé) climates. Others illustrate a dry phase for most of the year (≥ 6 months) and a wet season during which water flows after storm events in tropical (d. M-TROPICS and e. AMMA-CATCH) or Mediterranean (f. OMERE) climates

disconnect between streams and groundwater, which prevents base flow from sustaining longer-duration streamflow (Hector, Cohard, Séguis, Galle, & Peugeot, 2018; Richard et al., 2013).

To relate intermittence to environmental characteristics at a country-level scale (France), Snelder et al. (2013) suggest that zero flows have low spatial synchronicity due to the high spatial heterogeneity of fine-scale interactions between surface water and groundwater. Moreover, these characteristics may be interdependent (e.g., semi-arid climates often have low vegetation cover and soil crusting), which calls for holistic and complex approaches in order to understand the origin of intermittence (Borg Galea et al., 2019).

2.3 | Potential trends

Different trends of stream-flow intermittence have been observed in recent years in response to global and local changes. For instance, the Vaubarnier catchment (Réal Collobrier Observatory, Figure 3a) is typical of the Mediterranean climate, which is known for its warm, dry summers and intense storm events, which occur mainly in autumn (Drobinski et al., 2014). In the context of climate change, an annual increase in temperature and reference evapotranspiration but no significant trends in annual precipitation were detected on the Réal Collobrier catchments, decreasing the amount of water available (Folton et al., 2019). However, flows responded not only to the magnitude of changes in precipitation and temperature, but also to the timing of these changes. Thus, large decreases in spring precipitation lead to changes in spring, summer, or autumn flows, depending on catchment characteristics. In the Vaubarnier catchment (Figure 3a), where storage capacity is large (highest mean of base flow index within the observatory), significant decreases in spring precipitation, combined with increased spring and summer temperature and evapotranspiration demand, caused spring, summer, and autumn flows to decrease greatly, leading to an increased intermittence.

An opposite trend has been observed in the Sahel. In the second half of the 20th century, the Sahelian region has experienced a dramatic precipitation deficit concurrent with a paradoxical increase in surface runoff in many areas (Descroix et al., 2018). For instance, in the Agoufou catchment (Figure 3b), runoff coefficients increased from ca. 0% in the 1970s to 5.5% in the 2000s (Gal et al., 2016). In this catchment, dynamics of the coupled vegetation/erosion/drainage system has been shown to play a pivotal role in this trend, with a change in regime from a predrought state, with well-developed vegetation and low surface runoff, to a postdrought state, with degraded vegetation, eroded soils, and drainage network development (Gal, Grippa, Hiernaux, Pons, & Kergoat, 2017). Given the intermittent and event-based state of runoff in these areas, the future trend of these eco-hydrosystems and its impact on water quantity and quality remains difficult to predict, but a return to the predrought state remains improbable (Wendling et al., 2019).

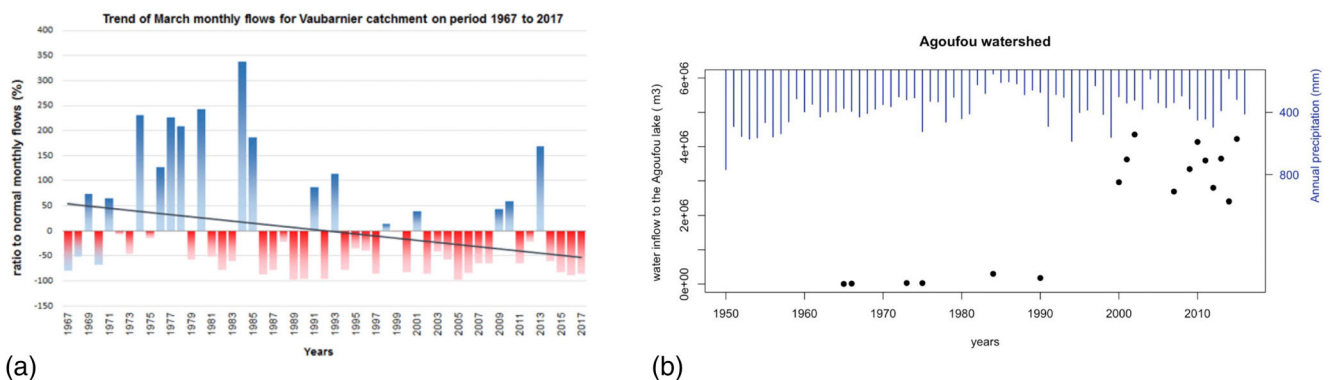


FIGURE 3 Contrasting trends of intermittent stream flow in two OZCAR observatories. (a) In the Vaubarnier catchment (Réal Collobrier Observatory, France), there is a significant decreasing trend of monthly flows for March from 1967–2017 (Sen's slope of linear trend = -0.862 mm/month, adapted from Folton et al. (2019), data are available on the BDOH database: <https://bdoh.irstea.fr/REAL-COLLOBRIER/>). (b) In Agoufou catchment (Amma-Catch Observatory, Mali), annual inflow into Lake Agoufou clearly increased from 1960–1990 to 2000–2015 (data sets: DOI: 10.17178/AMMA-CATCH.CL.Rain_GT and 10.17178/AMMA-CATCH.CL.Pond_Gha)

3 | ACTIONS AND FEEDBACKS IN SOCIO-ECOSYSTEMS IN A CONTEXT OF GLOBAL CHANGE

Human societies interact with IRES in many ways, and some of these interactions can alter the intermittence, biogeochemistry, and ecology of these systems. Hydrological, ecological, and biogeochemical processes of intermittence and their potential trends cannot be investigated without describing the many human-induced stressors of IRES and their interactions.

3.1 | Artificial, intensified, or mitigated intermittence

3.1.1 | Landscape management of headwaters and upstream catchments

Before reaching rivers, water flows through the headwater catchments, and when the catchments are used for agriculture, farmers dig networks of ditches to channel runoff, and decrease water erosion of fields, which has a strong impact on the hydrology at these catchments' outlets (e.g., Moussa, Voltz, & Andrieux, 2002, OMERE CZO or Carluer & Marsily, 2004, AgrHyS CZO). The hydrology of these networks is influenced in two ways: directly, through modifying network connectivity by adding or removing ditches, and indirectly, by managing ditch vegetation and morphology. For the former, simulations demonstrated how the density and configuration of a ditch network can mitigate the intermittence of the water flow that reaches a catchment's outlet by reducing peak discharge (Levavasseur, Bailly, Lagacherie, Colin, & Rabotin, 2012). For the latter, vegetation inside ditches smoothes flow variations by resisting flow in proportion to the channel section that it occupied (Green, 2005), which tend to reduce flow intermittence at catchment outlet. Experiments showed that plant density and properties can increase water friction by a factor of four compared to that of a ditch without vegetation (Vinatier, Bailly, & Belaud, 2017). Thus, managing vegetation cover by dredging, mowing, chemical weeding, or burning, either by farmers or municipal services (for ditches along roads), helped restore ditches' conveyance capacities and ephemerality of flow. Nonetheless, according to the maintenance schedule and seasonal growth of vegetation, water friction varied greatly throughout the year, which had direct consequences on outlet hydrology (Vinatier et al., 2018, OMERE CZO). The regime at outlets of IRES must be considered according to these elements.

3.1.2 | Green water and Blue water uptakes

Human action can alter the hydrological regimes of rivers, including their flow intermittence patterns. To understand the underlying mechanisms, it is necessary to distinguish two main types of action: the first type is related to blue water uptakes, and the second type to green water. The first corresponds to water withdrawals from rivers by direct pumping, by building dams that intercept flowing water, and by diverting rivers. One of the most famous examples is central Asia, where intensification of the diversion and withdrawals of water for irrigation in the 1960s and 1970s caused rivers to stop flowing and the Aral Sea to dry up (Micklin, 1988). More recently, the multiplication of small dams in many countries across the world may have caused perennial rivers to become intermittent (Habets, Molénat, Carluer, Douez, & Leenhardt, 2018; Nathan & Lowe, 2012). However, managing dam water can also help sustain rivers during low-flow periods and thus reduce the risk of intermittence (Thomas, Steidl, Dietrich, & Lischeid, 2011). Groundwater withdrawals can also cause rivers to dry up when they are located close to the riverbed or to the main source. This is the case of the Lez spring (MEDYCYSS CZO), where the high pumping rate (annual average of 1 m³/s) exceeds the natural flow of the source in summer and causes the spring to dry up for several months (Charlier, Ladouche, & Maréchal, 2015; Ladouche, Marechal, & Dorfliger, 2014).

The second type of human action that can change the hydrological regime is land use change, such as deforestation, afforestation (i.e., modifying native vegetation by planting trees), and agricultural practices. Land use change alters the water partitioning between runoff, infiltration, evaporation and transpiration, and groundwater recharge, thus altering the base flow. Studies of land-use change impacts on intermittence have yielded highly variable conclusions depending on the climatic and geological context and, of course, the type of change involved (Lacombe

et al., 2016). Andréassian (2004) stated that “flow periods (in general) are shortened by reforestation, which can even cause the flow to cease”. Increased evapotranspiration and decreased groundwater recharge decrease base flow and thus trigger or accentuate intermittence. This has been confirmed by recent studies that showed that afforestation can cause a shift from a perennial to intermittent flow regime (Brown, Western, McMahon, & Zhang, 2013; Scott & Prinsloo, 2008). However, afforestation may also have no clear effect on intermittent streamflow if it affects groundwater storage but without a strong contribution of this groundwater to intermittent streams (Dresel et al., 2018). In agricultural areas, practices that promote infiltration and groundwater base flow reduce the risk of intermittence, as shown by Schilling and Libra (2003) for tile drains in Iowa, United States. However, cropping practices that increase runoff can decrease groundwater recharge and base flow, which increases the risk of intermittence (e.g., Gal et al., 2017, AMMA-CATCH CZO).

3.1.3 | Artificial flow sustained by waste water and rain water discharge

In urbanized areas, streams and rivers receive treated industrial or domestic waste, and during the dry season wastewater can contribute up to 100% of the flow (Perrin et al., 2018). Consequently, natural IRES may become perennial when sustained by wastewater discharge (Luthy, Sedlak, Plumlee, Austin, & Resh, 2015). By sustaining river flows, wastewater discharges influence the water cycle (e.g., groundwater recharge) and have strong impacts on the water quality of IRES, especially at low flow and during naturally dry phases because of a strongly decreased ability to dilute these point sources. Indeed, treated wastewater influences pollution from nutrients (David et al., 2011; De Girolamo & Lo Porto, 2020), organic carbon (Westerhoff & Anning, 2000), bacteria (Chahinian et al., 2012), and heavy metals (Perrin et al., 2010), but also stream metabolism (Bernal et al., 2020) and ecological habitats (Prat & Munné, 2000). These effects have been documented mostly in arid climates (see also e.g., Bicknell, Regier, Van Horn, Feeser, & González-Pinzón, 2020; Stromberg et al., 2007).

Rainwater management can also disturb (peri-)urban rivers. When managed with combined sewer systems (which collect both waste and rainwaters), Sewer Overflow Devices (SODs) are usually installed to prevent saturation of sewer systems. When activated, they release polluted water into natural river courses. Braud et al. (2013) quantified the impact of sewers and SODs on the hydrological regime of the Chaudanne River (Yzeron catchment observatory, OTHU CZO) and highlighted (i) that seasonal infiltration of clean groundwater into the sewer network increased the intermittence of the river and (ii) the contribution of SODs to maintaining higher flow in the river during low-flow periods.

3.2 | Perceptions and management of IRES

Most water stakeholders have focused their attention on perennial streams rather than on IRES (Acuña et al., 2014; Fritz, Cid, & Autrey, 2017). Just recently, several attempts to remove IRES from legislations have been on-going. For instance, in the United States (Marshall et al., 2018) and France, IRES were removed from maps and definitions of national streams, which ends management practices of these systems and jeopardize the ecological integrity of river networks. These practices reflect the low value associated with these streams. There is today a growing recognition of IRES value due to changes in climate and land use, and from a growing demand for clean fresh water. This is combined with a dramatic increase in scientific knowledge about these systems and how they are important at the river-network scale for hydrological, geomorphological, biogeochemical, and biological processes (Datry, Bonada, & Boulton, 2017; Larned et al., 2010; Shanafield et al., 2020), and finally for the production of ecosystem services (Datry, Boulton, et al., 2018). However, in the paradigm of integrated and participative management of streams, this scientific value attached to IRES is not sufficient. The value must be shared socially so that the preservation of IRES is supported in the political arenas of water governance. To date, very few studies have focused on the social value associated with IRES. The few initial studies published on this subject showed a devaluation of IRES, at least where pressure on the resource is low, because local stakeholders attribute only low aesthetic and recreational value to the channel during dry periods (Armstrong et al., 2012; Cottet, Robert, & Datry, 2019; Rodríguez-Lozano et al., 2020). This devaluation has been shown to depend on the link between people and the river, especially the frequency of their visit or whether they live close to a river (Rodríguez-Lozano et al., 2020). In general, people tend to favor “rivers with water” (Armstrong et al., 2012). The perception of river landscapes—due to their aesthetic dimension or the pleasant setting they offer for leisure activities—is a determining factor of their associated value (Gobster, Nassauer, Daniel, & Fry, 2007). It has long been known that people prefer landscapes that they consider to be

orderly, clean, and well-maintained (Nassauer, 2011). Certain stakeholders perceived IRES as degraded and abandoned because of the river dryness and spontaneous and pioneer vegetation that colonize the channel (Cottet et al., 2019, Albarine River in LTSER ZABR). Evidence of care in the landscape has a powerful influence on engagement that needs to be considered further when planning strategies that benefit environmental health and ecosystem services at larger scales (Nassauer, 2011). Further studies on the stakeholders' perceptions of IRES would allow for a better understanding of the reasons for this devaluation and for identifying levers, both in terms of communication and participation of stakeholders, to activate for a more ambitious preservation policy of IRES.

4 | AVAILABLE TOOLS AND DATA FOR STUDYING IRES: LIMITATIONS AND DEVELOPMENTS

4.1 | Quantitative data on flow, concentrations, and ecology of IRES from regulatory monitoring networks

For socio-economical, hydrological, and practical reasons, flow-gauging and water-quality monitoring stations are usually concentrated in the lower parts of river networks where IRES are naturally less frequent than perennial reaches (Datry, Arscott, & Sabater, 2011; Snelder et al., 2013; Zimmer et al., 2020). Consequently, headwater streams are poorly monitored (Bishop et al., 2008), and IRES are poorly represented in current monitoring networks (Costigan et al., 2017; Eng et al., 2016; Giuntoli, Renard, Vidal, & Bard, 2013; Kennard et al., 2010). In France, flow gauging has been driven historically by issues such as public safety (e.g., flood risks and hydraulic devices) and water-resource sharing (e.g., drinking water and irrigation), for which IRES were not considered important, and placing water-quality stations on downstream rivers reaches covers the largest areas possible (Puechberty et al., 2017). Snelder et al. (2013) found that less than 20% of national French gauging stations were on intermittent rivers. In more arid regions, the hydrographic network is assumed to be intermittent by default unless perennial flow is observed, but the number of gauging stations is small, and stations tend to be located on perennial rivers (Datry, Arscott, & Sabater, 2011; Zimmer et al., 2020). The distribution rules are similar for water-quality stations: even when they are not co-located with flow-gauging stations, they are located at the outlet of large drainage areas and where flow is perennial. This is exemplified in Burkina Faso (Figure 4), where we calculated from the national services that 99% of the hydrographic network as IRES, with perennial streams and gauging stations limited to high Strahler orders. The CZO and LTSER can provide complementary

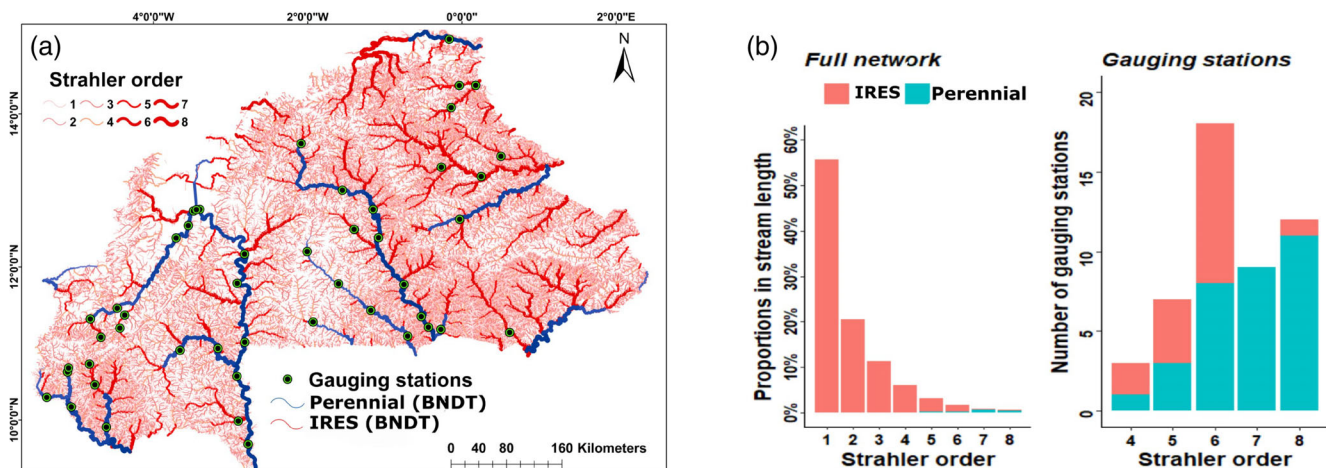


FIGURE 4 (a) The hydrographic river network in Burkina Faso at 1:200,000 scale showing intermittent rivers and ephemeral streams (IRES, in red) and perennial streams (in blue)

(source: Base Nationale de Données Topographiques of the Institut Géographique du Burkina Faso) and gauging stations of the national hydrometric services

(source: Direction Générale des Ressources en Eau) with more than 4 years of discharge data. (b) Distribution of IRES and perennial streams in Burkina Faso as a function of Strahler order in the full network and at the gauging stations. The Strahler order (Strahler, 1957) of the river network was calculated using Rivex (Hornby, Duncan, 2020), under ESRI ArcGIS software (version 10.6.1)

long-term flow records from IRES because they include stations located at headwater catchments' outlet (e.g., AgrHyS, OMERE, Aurade, Real Collobrier, and M-TROPICS, see Figure 1, Table 2) and in less represented climates such as monsoon climate (e.g., AMMA-CATCH and M-TROPICS CZO).

Since biological data from IRES are fragmented, the Intermittent River Biodiversity Analysis and Synthesis (IRBAS, <http://irbas.inrae.fr/>, Leigh et al., 2017) initiative was developed to summarize biodiversity data on these systems. The IRBAS database lists more than 2000 samples from six countries and three continents that describe aquatic invertebrate taxa during the flowing phase. IRBAS includes several LTSER such as the ZABR, and in several LTSER other local data on aquatic communities exist. In CZOs, data related to aquatic communities are less frequent than hydrological observations but some do exist (e.g., in Real Collobrier, Auradé, AgrHyS CZOs) and have to be acquired more systematically and consistently with existing protocols such as IRBAS. On-going extension of the IRBAS database will include taxa

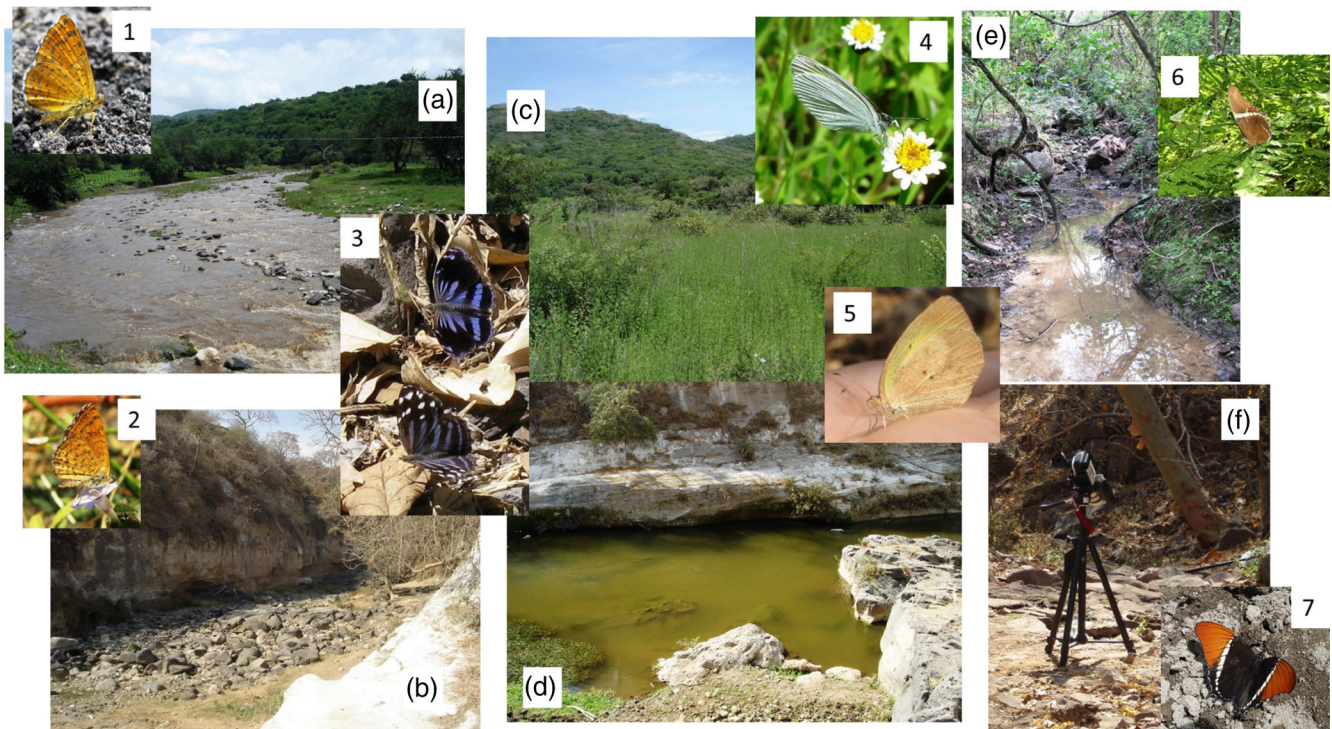


FIGURE 5 Adaptation of butterflies to alternating wet and dry seasons in relation to dynamics of intermittent rivers and ephemeral streams (IRES) in dry tropical forests. Case study of Morelos State (UNESCO Biosphere reserve of the “Sierra de Huautla” and State reserve of the “Sierra de Montenegro”, central Mexico). Although most butterfly species diapause in the dry season, and some species reduce their densities considerably, other species have strategies related to the available water features and dynamics of IRES. Four main strategies are observed (numbers indicate example species) at certain types of sites (bold letters), descending order of frequency. (1) During the wet season, 60–70% of the species fly in open areas **c** but take refuge near remaining muddy areas along IRES **d** during the dry season or alternatively reach the coolest areas of primary forest **e**. Example of *Eurema daira* (Coliadinae, Pieridae) whose color changes by season: **4** in the wet season; **5** in the dry season (Jones & Rienks, 1987; Legal, Dorado, Albre, Bermúdez Torres, & Lopez, 2017; Legal et al., 2020; Young, 1982). (2) Some species are rarely observed during the wet season because they fly exclusively along little streams occurring in deep forest **e**, with water flowing only during the wet season. During the dry season, these species fly down the catchment (from **E** and **F**, with a recording camera) to the main course (**d** and **b**—small deep canyons) to seek moisture. Example of *Siproeta epaphus*: **6** and **7**, (Nymphalinae, Nymphalidae), a rare species for Morelos (Legal et al., 2017). (3) Certain species (Nymphalidae, Biblidinae), which feed on rotting fruit, change sexual behavior by season. The model species is *Myscelia cyananthe*: **3** (Torres, Osorio-Beristain, Mariano, & Legal, 2009). During the wet season, males and females are widespread in all cool forest areas **e**, while during the dry season, females move massively along IRES **b**, **d** where rotten wet fruit is available (Torres et al., 2009). (4) The genus *Calephelis* (Riodininae, Lycaenidae) is one of the most diverse in the Americas, with ca. 50 morphologically similar species. In the study area, two species closely related to IRES fly: *Calephelis matheri* **1** and *Calephelis yautepecensis* **2**. The former flies only during the wet season along rivers **a** and at lower densities in open fields **c**, while the latter flies only along the widest IRES **b**, **d** and only during the dry season. The hypothesis of a single species with two seasonal forms has been explored. The two species have identical mitochondrial DNA, but significantly different nuclear DNA markers (ISSR) (Legal et al., 2017). Source of images: Luc Legal©

collected during dry or nonflowing phases. Data on terrestrial communities would also be useful to explore population strategies related to the dynamics of IRES. Indeed, hydrological regimes of IRES influence not only aquatic, but also terrestrial populations such as the vegetation of ditches (Rudi et al., 2020) or terrestrial insects as shown for the seasonal dynamics in densities and spatial niches of Butterflies of a dry tropical forest in Mexico (Figure 5).

At the same time, aquatic biomonitoring tools initially designed for perennial rivers and streams urgently need to be adapted (Stubbington et al., 2018; Stubbington et al., 2019). This is required because most taxa used for assessing the ecological status of river reaches are also sensitive to drying, which severely limits application of biomonitoring tools to IRES. Nonetheless, IRES are being degraded at alarming rates and require effective protection (Acuña et al., 2014). In the European Union, there are attempts to provide such protection, as for instance several research projects delivered manuals for managers (see e.g., Sauquet et al., 2020).

4.2 | Measuring the discharge of IRES

Characterizing the hydrological regime of IRES requires quantifying their drying and flowing phases; however, measuring stream water velocity and discharge is difficult in some IRES (Zimmer et al., 2020). Measuring the low flows of the drying phase, such as when discharge stops, with acceptable accuracy is a hydrometric challenge, the relative uncertainty in discharge derived from traditional stage-discharge rating curves increases dramatically. At gauging stations with large width-to-depth ratios, this uncertainty is due to the decreased stage-discharge sensitivity of the control, which magnifies errors in measuring the water level (Freestone, 1983; Horner et al., 2018; Zimmer et al., 2020). This calls for establishing gauging stations in IRES upstream of narrowing section controls in the form of natural riffles or artificial (e.g., V-notch) weirs. Measuring higher flows is also challenging due to (i) fast and violent flow variations during rewetting phases that follow dry phases of variable frequency (e.g., Reid, Laronne, & Powell, 1998), (ii) the flashiness and unpredictability of storm events (which can occur in perennial streams but which are frequent in IRES, [e.g., Nord et al., 2017]), and (iii) the hazardous nature of flash floods (e.g., Le Boursicaud, Pénard, Hauet, Thollet, & Le Coz, 2016). Video-based velocimetry and hydrometry techniques developed in the past two decades (Muste, Fujita, & Hauet, 2008) provide new opportunities to capture information about flood dynamics using an instantaneous surface-velocity field. Measurements do not require contact between the flow and an operator or an instrument. In addition to punctual gauging, automatic stations can be installed, and participative data provided by nonprofessional videos can be analyzed. Portable velocity radar (Welber et al., 2016) is another nonintrusive technique that can be used to measure flashy stream flow in intermittent rivers. A few examples of applications in research observatories from CZO and LTSER networks illustrate the potential and limitations of the video method in IRES. Using the free software Fudaa-LSPIV, Le Coz, Jodeau, Hauet, Marchand, and Le Boursicaud (2014) and Le Boursicaud et al. (2016) analyzed a video produced by a flood-chaser to estimate high flow fluctuations during a storm in the mountain stream of the ZABR (Arc-Isère, Saint Julien mountain stream). The automatic station on the Auzon stream (ZABR, Rivières Cévenoles, and OHMCV CZO) also used Fudaa-LSPIV to trigger acquisition of image sequences when the stream reached a threshold depth (Nord et al., 2014). These images can be combined with measurements from portable radar or other techniques to rapidly establish the rating curve of the station (Figure 6).

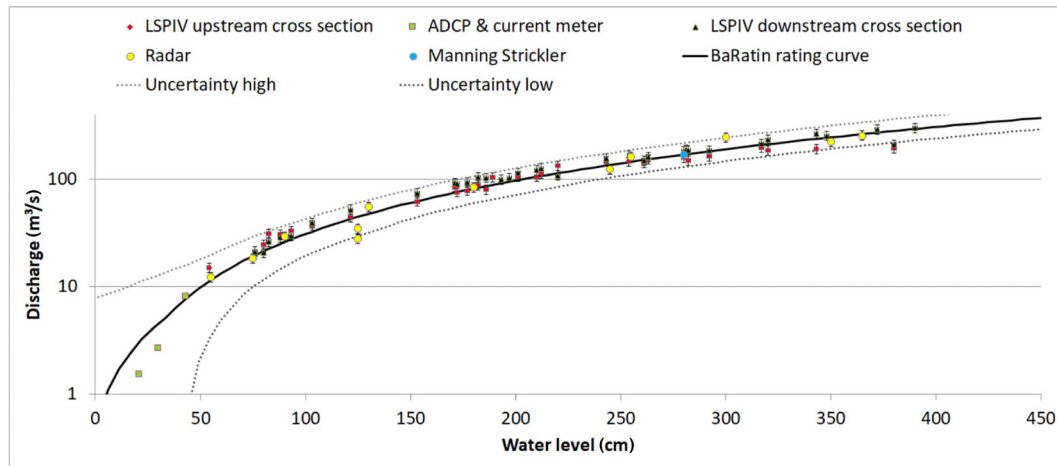
4.3 | Qualitative monitoring of flow occurrence using participative sciences or proxies

To expand the national hydrographic monitoring network in France, an additional network called ONDE (<https://onde.eaufrance.fr>; Beaufort, Lamouroux, Pella, Datry, & Sauquet, 2018) was established in 2012 by the French Office for Biodiversity to target headwater catchments. At each station, government agents conduct monthly field observations from May–September to record qualitatively the flow presence or not. An extension of this network (En Quete d'Eau: <https://enquetedeau.eaufrance.fr>) has been developed through a program of participative sciences to increase the number of observed headwater stations and to disseminate knowledge about IRES. Such initiatives can be used to refine the mapping of IRES. The collaborative approach is also developing worldwide and involves data collection by local populations who live along streams and rivers to map IRES (Allen et al., 2019; Datry, Corti, Foulquier, von Schiller, & Tockner, 2016; Davids, van de Giesen, & Rutten, 2017). Similar protocols could be used within the CZO and LTSER platforms (and will be soon, e.g., in the LTSER ZABR: a Smart Phone application is currently in development).



(a)

(b)



(c)



(d)

FIGURE 6 Hydrometric station (ZABR Rivières Cévenoles, OHMCV observatory) of the Auzon River at Vogüé-Gare, an intermittent tributary of the Ardèche River (France): (a) location of the camera and radar gauge, (b) example of a surface-velocity field calculated from an image sequence during a flash-flood event, (c) the stage-discharge rating curve established mostly from nonintrusive radar and video (LSPIV) gaugings for only 3 years, and (d) views of the river for dry, low-flow, and flood conditions, from left to right

Moreover, such qualitative but spatially-rich information could be combined with the quantitative and detailed observations from local CZO or LTSER platforms to extrapolate the latter at wider regional scale.

For ungauged streams, it is also possible to record flow occurrence using proxies such as temperature, electrical conductivity, and water level (Assendelft & van Meerveld, 2019; Ayral, Braud, Nord, Gonzalez-Sosa, & Spinelli, 2017; Bhamjee & Lindsay, 2011; Chapin, Todd, & Zeigler, 2014; Constantz, Stonestorm, Stewart, Niswonger, & Smith, 2001; Jaeger & Olden, 2012). Because of their relatively low cost, sensors for these proxies can be used at multiple locations to track, for instance rewetting and drying fronts and thus can help to examine spatial drying patterns poorly documented in the literature (Allen et al., 2019). Kaplan et al. (2019) combined electric conductivity and stage measurements with time-lapse imagery (Figure 6d) to monitor the presence or absence of streamflow within nested sub-catchments. Some studies attempted to assess dynamics of river networks using distributed water-level sensors (e.g., Fuamba et al., 2019; Marechal, Ayral, Bailly, Puech, & Sauvagnargues-Lesage, 2013) combined with high-resolution Digital Terrain Models (DTMs). Their results highlighted using a fixed-area threshold to extract river networks automatically from DTMs (Lane, Reaney, & Heathwaite, 2009) is not fully appropriate because the threshold value tends to vary with the different degrees of connectivity of river reaches to the main river network depending on the geomorphology of the river reach and the season. This approach based on distributed network of water-level sensors seems effective for monitoring spatio-temporal dynamics of a river network, and thus its intermittence, such dynamics being not captured by a single outlet gage. However, managing networks of water-level sensors remains time-consuming.

4.4 | Mapping of IRES and flow intermittence patterns

Several methods can be used to map IRES, from field survey to aerial and satellite images. However, conducting field surveys for exhaustive mapping of IRES over a large area is difficult and laborious. Using remote sensing, it often remains challenging to map the small IRES. Even if vegetation can often be used to infer stream presence (Fu & Burgher, 2015), it is not always the case, and opacity from both vegetation and cloud cover are recognized obstacles to precise stream identification (Turner & Richter, 2011). Another frequent limitation comes from image resolution, which is often too low to identify these streams (Kaplan et al., 2019). The use of drones makes it possible to obtain very-high-spatial (<10 cm/pixel) and temporal resolution images at low cost and which should help to map the small IRES (Borg Galea et al., 2019). Some studies have already shown satisfactory data collection results using drones to map IRES (Spence & Mengistu, 2016).

To address larger domains, statistical modeling can be used to infer relationships between stream-flow characteristics extracted from local records (Section 4.1) and environmental variables (climate, geology, and land use) and predict stream intermittence spatially. These methods have been applied in national studies in France (Snelder et al., 2013), Australia (Kennard et al., 2010), and Burkina Faso (Perez-Saez et al., 2017), and in the Deva-Cares catchment in northern Spain (González-Ferreras & Barquín, 2017). For instance, 20–39% of the total river length in France was estimated to be prone to intermittent flow (Snelder et al., 2013). However, these methods are limited by the spatial distribution and temporal length of flow records (Beaufort et al., 2018; Moliere et al., 2009). In order to characterize adequately spatial variation in hydrological regimes, a flow record length of at least 15 years is recommended (Kennard, Mackay, Pusey, Olden, & Marsh, 2010).

A recent approach to map the potential of the terrain to be hydrologically connected or not to perennial and intermittent networks (Pinson & Charlier, 2018) has been developed using the Index of Development and Persistency of River networks (IDPR, Mardhel, Frantar, Uhan, & Miso, 2004) based on a comparison of theoretical talweg (from Digital Elevation Model) and observed hydrographic network. At catchment scale, IDPR is highly correlated with the drainage density and is well correlated with runoff coefficient for several lithology (Le Mesnil et al., 2020). Use of IDPR mapping to distinguish intermittent streams and perennial streams at the regional scale (southern France) has shown that the presence of karst units (limestone geology) larger than ca. 5 km² statistically promotes intermittent reaches, illustrating the geological control of IRES. At this small scale (i.e., several km², catchment scale), Ward et al. (2018) also showed the geological control of network dynamics during relatively low discharge conditions. However, at the regional scale, the geological control of IRES becomes hidden by other hydro-climatic drivers. This is the case in two other recent regional studies, aiming at map streamflow permanence from land use (forest cover) and hydro-climatic databases, and reporting good performances without accounting for geology (González-Ferreras & Barquín, 2017; Jaeger et al., 2019).

At the global scale, the AQUAMAPS database (FAO, 2014) distinguishes intermittent streams from perennial streams using a simple algorithm based on Strahler order and aridity index, which was trained using the IRES in the African Water Resources Database (Jenness, Dooley, Aguilar-Manjarrez, & Riva, 2007). The global hydrographic

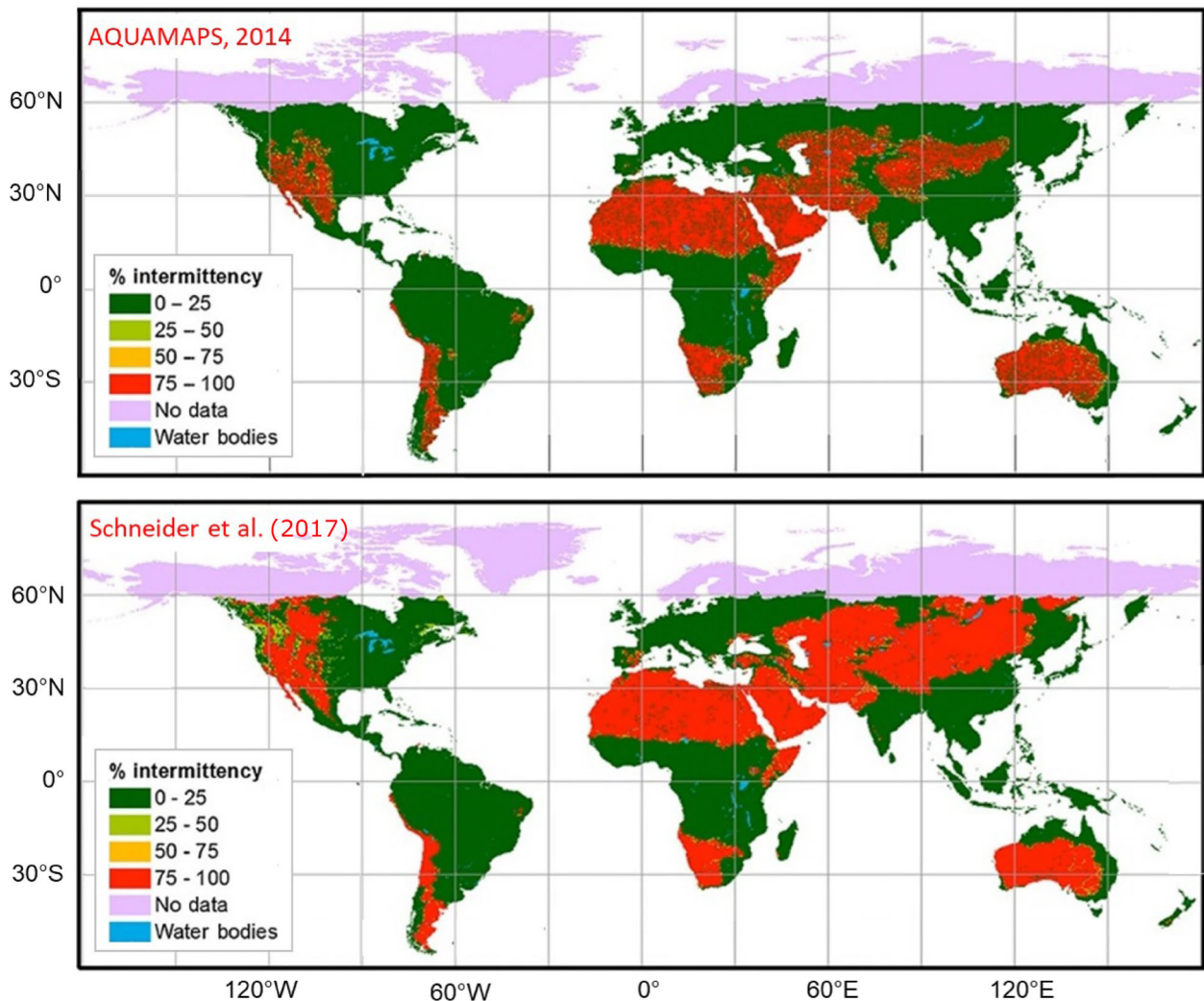


FIGURE 7 Global maps of the intermittent rivers and ephemeral streams (IRES) percentage (calculated as the ratio of IRES length to total stream length at a 7.5 arc-sec resolution) according to AQUAMAPS (FAO, 2014) and Schneider et al. (2017). The violet color north of 60°N indicates where HydroSHEDS topographic data (Lehner, Verdin, & Jarvis, 2008), on which both datasets are based, are missing. Adapted from Schneider et al. (2017)

network of Schneider et al. (2017) was conceived to include smaller streams than AQUAMAPS, but the characterization of IRES is cruder: all stream initiated in areas where annual mean precipitation $<500 \text{ mm year}^{-1}$ are classified as IRES until they flow in areas with a higher precipitation. The precipitation threshold was calibrated to match the distribution of IRES in Australia according to AQUAMAPS. The two classifications are therefore largely consistent by construction (Figure 7): they estimate a similar percentage of IRES across the world (29% in AQUAMAPS, 34% in Schneider et al. (2017)). Yet, none of them has been validated with independent data, and CZO surveys and monitoring, which encompass a wide range of hydrologic conditions, could be usefully exploited to this end. Their diversity also offers an interesting potential to reveal and understand the influence of important drivers of intermittency, such as geology, the cryosphere, precipitation intermittency (Section 2.2), and human activities (Section 3), which are ignored by both global IRES maps.

The CZO can typically provide water-level data sets from high-density point measurements over small hydrographic networks (e.g., Fuamba et al., 2019 in OTHU CZO or Marechal et al., 2013 in OHMCV CZO) while in LTSER platforms, the involvement of local stakeholders in data collection or experiments is at the heart of the approach (see e.g., Bretagnolle et al., 2019 in the LTSER ZA Plaine et Val de Sèvre). In addition, data on land uses, lithology, meteorological, and human pressures are usually available on these sites with high precision and can be used to guide interpolations. Combining in-situ measured data (Sections 4.1 and 4.2), in-situ citizen observations (Section 4.3) and high-spatial-resolution remote sensing offers a high potential to improve the mapping of IRES.

5 | POTENTIAL AND RELEVANCE OF THE CZO-LTSER NETWORK FOR ADDRESSING RESEARCH CHALLENGES OF INTERMITTENT STREAMS

5.1 | An interdisciplinary approach to characterize the origins and consequences of intermittence

The CZO and LTSER communities promote an interdisciplinary approach to study interfaces of continental surfaces and ecosystems, some of which are of particular relevance for IRES (Table 1).

As a major interface, *groundwater-surface water exchanges* are a key topic for investigating IRES. Many river reaches that cross permeable geology, especially karst, are influenced by intermittence related to large river losses (Charlier et al., 2015; Charlier, Moussa, David, & Desprats, 2019; Dvory et al., 2018) and interbasin groundwater flows (Le Mesnil et al., 2020). These losses have a large influence on groundwater recharge (Lange, 2005) and attenuation of river flood peaks during initial recharge events (Charlier et al., 2019; Charlier, Moussa, et al., 2015; López-Chicano, Calvache, Martín-Rosales, & Gisbert, 2002; Maréchal, Ladouche, & Dörfliger, 2008). In the dry tropical forest in India (M-TROPICS), infiltration from IRES into hard-rock aquifers is nearly equivalent to direct groundwater recharge by precipitation (Maréchal et al., 2009). In the Sahelian region, most groundwater recharge is located in ephemeral or drainage networks and ponds that collect endorheic networks (Cuthbert et al., 2019; Pfeffer et al., 2013). In temperate headwater catchments, the dynamics of stream flow, and thus of zero flow depends greatly on seasonal fluctuations in shallow groundwater (Molénat, Davy, Gascuel-Oudou, & Durand, 1999). Therefore, the next challenging issue relates to a better quantification of these groundwater-surface water fluxes, in terms of seasonality and trends when accounting for long term evolutions of groundwater recharge in a context of climate warming. Another key issue refers to water quality in IRES, in link with groundwater quality affected by river losses and responsible of surface water quality when the connection is effective.

The *influence of vegetation cover on water and element fluxes* is another relevant interdisciplinary topic for IRES. First, geochemical processes in catchments that drain IRES are poorly documented (Cartwright, Morgenstern, & Hofmann, 2020) or limited to carbon and nutrients (Bernal, Butturini, & Sabater, 2005; Hale & Godsey, 2019). However, in the absence of base flow, the origin of elements exported from IRES is expected to differ from that of elements exported from perennial streams, with an increased contribution of processes that occur at the ground surface or sub-surface, usually those that involve terrestrial vegetation, and a small contribution of “direct” chemical weathering. For instance, in the dry tropical forest of Mule Hole (M-TROPICS, southern India), Riotte et al. (2014) and Braun et al. (2017) estimated that more than 80% of major dissolved element fluxes exported from an IRES transited through forest vegetation. In this catchment, the weathering fluxes are exported via groundwater, which is disconnected from the surface, thus making them more difficult to measure (Maréchal et al., 2011). Secondly, IRES supported the growth of terrestrial vegetation within their channels, which is less permeable to water flows than aquatic vegetation (Rubol, Ling, & Battiato, 2018). Terrestrial vegetation of IRES is known to be critically important in driving water flows and chemical elements in landscapes (Katz & Denslow, 2012; Rudi et al., 2020; Stromberg & Merritt, 2016), but remains poorly documented, especially regarding its functional traits and ecological distribution.

The *bio-physico-geochemical behavior of streambeds* subjected to dry-wet cycles remains unclear, mainly because they provide an environment at the interface between soil and freshwater, each of which is studied relatively independently (Arce et al., 2019; Steward et al., 2012). Soil properties of streambeds, which differ from other landscape elements, suffer from a lack of description because their limited spatial coverage. However, streambeds' soils have specific permeability (Shanafield & Cook, 2014) and specific pollutant sorption properties (Dollinger et al., 2018; Dollinger, Dagès, Negro, Bailly, & Voltz, 2016) and could help mitigate water pollution. Combining sediment biogeochemistry, microbiology, and soil science is a challenge that can be taken up by CZ and socio-ecology communities, which brings together researchers from a variety of disciplines in the same study areas.

There is a large set of *hydrological, biogeochemical, and isotopic tracers* (stable water isotopes, major and trace elements such as heavy metals including Rare Earth Elements, stable or radiogenic isotopes of C, N, Li, Sr, Pb, Mg, Ca, U, and Th) which are used in CZ science to deconvolute flowpaths and estimate residence and transit times (e.g., Farrick & Branfireun, 2015; Ladouche et al., 2001; Porcelli, Andersson, Baskaran, & Wasserburg, 2001). For IRES, using tracers alone or in combination could be particularly useful for understanding drying and rewetting processes and flow-paths. For example, Klaus, McDonnell, Jackson, Du, and Griffiths (2015) used a dual-isotope data approach (^{18}O and ^2H) in a lowland forested watershed in South Carolina to show how the riparian zone controls baseflow and “resets” the stable isotope composition of stream water, although the lack of temporal dynamics for individual tracers limited a temporal analysis. Performing certain tracing experiments during the drying phase could provide information

about the water flowpaths and velocity, such as: the last source of water before drying and whether drying is due to water being interrupted before it reaches the outlet or to infiltrating below the stream. For instance, Knighton, Saia, Morris, Archiblad, and Walter (2017) used a model-data approach at the Shale Hills CZO (USA) to suggest that the soil water mixing dynamics (itself controlled by evapotranspiration patterns) exerts an increasing influence on stream water signature (in ^{18}O and ^2H) as the channel dries up during the summer months. Water quality sensors with high temporal resolution (Blaen et al., 2017) could be used to capture the rewetting phase and associated biogeochemical processes. Benettin et al. (2015) further combined experimental and modeling results to explore the link between weathering solute and water age at Hubbard Brook Experimental Forest (USA). They found that median travel time ranged from 40–60 days during wet periods (after intense storms, during spring snowmelt) and from 180 to 200 days during dry summers when most of the first-order streams dry up. The above examples in IRES remain somewhat scarce compared to the fast-growing literature of tracer-based studies hydrology, yet they highlight that adapting water-age tracers to IRES is an interdisciplinary and relevant challenge (Bansah & Ali, 2019; Cartwright et al., 2020).

5.2 | A network of facilities for and skills in observing and modeling flow intermittence

The CZO and LTSER communities contribute to methodological advances generated via their network of observatories and platforms, and via modeling approaches. In the following section, we describe few examples that could be of particular relevance for IRES (Table 1).

The CZO and LTSER networks include *observatories and platforms that are distributed along gradients of climate, geology, and socio-ecosystems* (Figure 1, Table 2). This approach promotes exploration of a variety of contexts, including gradients of human–ecosystem interactions, and acquisition of *coupled hydrological, biogeochemical, ecological, and sociological data* in each context using long-term (from 10 to more than 50 years) monitoring of one or more sites. Indeed, systematic co-location of long-term monitoring of these data remains partial but is improving due to their gathering in the eLTER (European Long-Term Ecosystem Research) infrastructure, which should improve the ability to develop a systemic approach to IRES and to connect scientific communities that are not always used to work together (Table 1). The diversity of human actions on intermittence described in Section 3.1 is well represented within CZO and LTSER where information already exist to quantify or at least estimate their effects (e.g., in M-TROPICS CZO water pumping in Indian sites and land use changes in East Asia, or water diverting in OMERE, Aurade, and OHMCV CZOs). As local human components are already well documented at the sites this may also provide relevant information for studying strategies to mitigate and adapt to intermittence. For instance, in the Sahel, due to increased intermittent runoff since the drought of the 1970s (Sahelian paradox, Figure 3b), water and soil conservation techniques have been implemented since the 1980s for hillslope soils to increase infiltration and woody cover regeneration (Warzagan, 2019). Moreover, because each observatory or platform has put down roots in the region it may favor knowledge co-production (Norström et al., 2020), especially with local stakeholders. Indeed, in the CZO and LTSER sites, the local stakeholders are already well identified and very often already in contact with the scientists too, which give an advantage to these sites for investigating the questions described in Section 3.2.

Both types of infrastructure support skills and techniques for acquiring new data and analyzing data using innovative methods. In particular, the forthcoming generation of new satellite sensors and aerial images (Section 4.4) will increase the ability to use high-spatial-resolution remote sensing data to better characterize IRES. For example, using very-high-spatial-resolution multispectral imagery of 15 cm resolution and integrating into an algorithm characteristic information of the desert landscape such as land use and land cover, Hamada, O'Connor, Orr, and Wuthrich (2016) were able to map a density of IRES that is underestimated by the National Hydrography Database of USA. These data can help estimate surface hydrology and land-cover characteristics (Gal et al., 2017), as well as serve as proxies for water levels and runoff (Gal et al., 2016; Grippa et al., 2019) and indicators of water quality (Robert et al., 2017). Such data should help map IRES, but also their dynamics. Recent advances in geophysics (e.g., gravimetry, magnetic resonance, and seismic methods) can help measure water storage in catchments and aquifers (Hector et al., 2015; Lecocq, Longuevergne, Pedersen, Brenguier, & Stammer, 2017; Mazzilli et al., 2016) and could be applied to IRES catchments to refine local processes involved in intermittence. Regarding analysis methods, hydrological signatures have been put forward as a way to relate hydrological processes to indicators derived from climate and hydrological time series (see McMillan, 2020 for a review). However, classic signatures were developed from gauging stations on perennial streams (Reynolds et al., 2015). CZO and LTSER facilities provide long-term instrumented sites that can be used to assess previously developed indicators of intermittence (e.g., measurements of the frequency of zero-flow, of the duration, and

timing of zero flow periods, and if possible spatial metrics of the connected stream network; Costigan et al., 2017; Eng et al., 2016; Hale & Godsey, 2019; Kennard et al., 2010; Knoben et al., 2018; Leigh & Datry, 2017; Reynolds et al., 2015; Sauquet et al., 2020). Indeed, characterizing intermittence only at the catchment outlet is not sufficient (Allen et al., 2019), and new distributed equipment and indicators can help to characterize spatiotemporal dimensions of river intermittence as shown in Section 4.3.

Several *models* are able to simulate intermittence (e.g., Chahinian, Tournoud, Perrin, & Picot, 2011; Gal et al., 2017; Hector et al., 2018; Maneta, Schnabel, & Jetten, 2008; Perrin & Tournoud, 2009). Models may help understand the origins of intermittence, as well as the start and end of flow. However, most models have not been designed specifically for this task, and their predictive ability (e.g., to simulate future intermittence characteristics under changing conditions) may suffer from ignoring CZ processes whose importance may change over time, such as vegetation cover and thus local evapotranspiration. One solution may be to connect models that simulate compartments or variables of the CZ, or to develop new integrated models (e.g., to represent groundwater transfer, channel hydraulics and surface hydrology). One option is to use uncalibrated physical-based CZ models and perform virtual experiments (Schilling et al., 2020). For instance, Hector et al. (2018) identified that one factor that significantly influenced intermittence of hydrosystems in West African inland valleys was their pedological and geomorphological structure, simply by virtually “removing” this specific structure. Using such models across CZ sites may help map factors that influence intermittence by virtually swapping the properties of different CZ observatories. Another solution is to foster the use of data sciences techniques at well-documented sites to explore the current distribution of these factors (e.g., Rinderer et al., 2018).

6 | CONCLUSION

IRES are attracting increasing research efforts, although many challenges remain for characterizing their biophysical and social functions and functioning. Understanding these unique and complex ecosystems and their evolution is particularly relevant in the context of global changes.

We argue that the research communities of the CZ and socio-ecology can provide significant advances to address these research challenges because:

- These communities are based on an integrated approach to understanding ecosystems that combines hydrological, ecological, and biogeochemical processes, and that includes humans as a full component of the ecosystem, and connect local stakeholders with science.
- They rely on a diversity of long-term observatories that cover wide ranges of climatic, geological, and human pressures that create multiple contexts.
- They pioneer development and testing of advanced techniques of observation, data analysis, and modeling that can be used to improve understanding of IRES eco-hydrology.

In particular, we have identified the need for a more intensive monitoring of the following:

- flow regimes in IRES, either directly (using video and radar hydrometry, water level loggers, and high-resolution images) or indirectly (using temperature or conductivity proxies and participative sciences) to develop hydrological signatures or indices that would be relevant for IRES
- groundwater resources in IRES and their interactions with surface water
- water biogeochemistry in IRES, to identify the characteristics of element fluxes during flowing and drying phases and of dry riverbeds upon rewetting
- biological populations of IRES, to develop biomonitoring indices that would be relevant for IRES or biological proxies of IRES regimes
- human perceptions of and actions on IRES, to investigate how perceptions influence human actions that can influence the water flow or quality, which themselves can influence the biological quality of IRES

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questions: (i) What challenges are related to the intermittent nature of hydrosystems in environmental research? and (ii) What are the main knowledge or methodological barriers to addressing these challenges to develop a holistic/integrated understanding of these systems? The authors warmly acknowledge all those involved in acquiring and disseminating data in the OZCAR and RZA networks. CZO and LTSER platforms are funded by national research institutions, public agencies, and sometimes, private companies.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Ophelie Fovet: Conceptualization; funding acquisition; writing-original draft; writing-review & editing. **Axel Belemtougri:** Writing-original draft; writing-review & editing. **Laurie Boithias:** Conceptualization; writing-original draft; writing-review & editing. **Isabelle Braud:** Conceptualization; writing-original draft; writing-review & editing. **Jean-Baptiste Charlier:** Conceptualization; writing-original draft; writing-review & editing. **Marylise Cottet:** Writing-original draft; writing-review & editing. **Kevin Daudin:** Conceptualization; writing-review & editing. **Guillaume Dramais:** Writing-original draft. **Agnes Ducharne:** Conceptualization; writing-original draft; writing-review & editing. **Nathalie Folton:** Conceptualization; writing-original draft. **Manuela Grippa:** Conceptualization; funding acquisition; writing-original draft; writing-review & editing. **Basile Hector:** Conceptualization; funding acquisition; writing-original draft. **Sylvain Kuppel:** Conceptualization; writing-original draft. **Jerome Le Coz:** Conceptualization; writing-original draft; writing-review & editing. **Luc Legal:** Conceptualization; writing-original draft; writing-review & editing. **Philippe Martin:** Conceptualization; writing-original draft. **Florentina Moatar:** Conceptualization; writing-review & editing. **Jerome Molenat:** Conceptualization; funding acquisition; writing-original draft. **Anne Probst:** Conceptualization; writing-original draft. **Jean Riotte:** Conceptualization; writing-original draft; writing-review & editing. **Jean-Philippe Vidal:** Conceptualization; writing-original draft. **Fabrice Vinatier:** Conceptualization; writing-original draft; writing-review & editing. **Thibault Datry:** Conceptualization; funding acquisition; writing-original draft; writing-review & editing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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