Aqua temporaria incognita

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It has been 12 years since Bishop *et al.* (2008) wrote the Invited Commentary "Aqua Incognita: the unknown headwaters". They highlighted that "In most regions, the overwhelming majority of stream length lies beyond the frontiers of any systematic documentation and would have to be represented as a blank space on the assessment map. This means that for the majority of streams that support aquatic life, a systematic understanding is lacking on water quality, habitat, biota, specific discharge, or even how many kilometers of such streams are there. This blank space is so vast that it deserves a name to help us at least to remember that it is there. We propose calling it '*Aqua Incognita*'" (Bishop *et al.*, 2008; p. 1239). We continue to agree with this statement and the need to understand headwater streams better. In this commentary, we want to draw attention to a particular type of headwater stream that is even less frequently examined: headwater streams that flow intermittently, i.e., the ***Aqua Temporaria Incognita.*** Question 3 of the 23 unsolved problems in hydrology (Blöschl *et al.*, 2019) focuses on ephemeral dryland streams. We argue that this focus needs broadening to headwater temporary streams because they are ubiquitous in all climates. Headwater temporary streams feed larger perennial streams and are particularly sensitive to climate change and other human influences (Jaeger *et al.*, 2014; Reynolds *et al.*, 2015; Pumo *et al.*, 2016). Their effective management and protection, therefore, requires an understanding of both natural and artificial causes of intermittence.

Temporary streams are among the most hydrologically variable headwater systems (Wohl, 2017). They include intermittent streams that flow seasonally, ephemeral streams that only flow in response to rainfall or snowmelt events, and episodic streams that contain flowing water only during extreme rainfall events (Buttle *et al.*, 2012). The terms used for these non-perennial streams vary (Busch *et al.*, 2020) and more classes can be defined to describe the occurrence of pools with standing water (Gallart *et al.*, 2017). Here we use the term temporary stream to refer to all non-perennial streams, but we acknowledge that the exact naming and definition of these water bodies can have important implications for their legal protection (Caruso, 2011; Nikolaidis *et al.*, 2013; Magand *et al.*, 2020). In Switzerland, for instance, streams that flow on average less than 347 days per year (over a 10 year period) are considered non-permanent streams and regulations for permanent streams, such as requirements for permits to discharge or withdraw water, might not apply.

Bishop *et al.* (2008) argued that the majority of the total stream length needs to be represented as a blank space on assessment maps because they are not part of any systematic documentation. Temporary streams in headwater catchments are rarely included in assessments and often not even shown on maps. Levick *et al.* (2008) reported that 59% of the streams in the U.S. (excluding Alaska) are temporary, but their survey was based on 1:100,000 scale topographic maps and did not include stream segments shorter than 1.6 km, such that it excluded all temporary headwater streams. Analyses based on the 1:24,000 scale National Hydrography Dataset (NHDPlus) suggested that 42% of all stream segments in the upper Colorado river are first-order streams with intermittent flow and that temporary streams make up 73% of the total stream length (Caruso and Haynes, 2011). All studies that have actually mapped temporary streams in the field have shown that they are far more prevalent than indicated by the dashed blue lines on maps (Hansen, 2001; Fritz *et al.*, 2013). For example, the Swiss national topographic map shows 0.68 km of streams in the 13 ha upper Studibach catchment but repeated field mapping has shown that there are at least 3.77 km of streams, of which 2.66 km (71%) did not have flowing water during the dry summer of 2018 (van Meerveld *et al.*, 2019). Similarly, field mapping of stream heads during wet conditions in the 68 km^2 Krycklan catchment in northern Sweden showed that 76% of the fully expanded network was missing on the official map (Ågren *et al.*, 2015). A lack of knowledge about the location and extent of temporary streams hampers their protection (Caruso, 2011; Caruso and Haynes, 2011).

Temporary streams have high biodiversity and are home to many endemic species (Stanley *et al.*, 1997; Meyer *et al.*, 2007; Stubbington *et al.*, 2017); the dry riverbed is an egg bank for aquatic invertebrates and seed bank for aquatic plants (Brock *et al.*, 2003; Steward *et al.*, 2012). The onset and cessation of flow significantly affects the species assemblage (Pařil *et al.*, 2019; Sarremejane *et al.*, in press). Connectivity of previously disconnected stream segments increases streamflow (e.g., Godsey and Kirchner, 2014; Jensen *et al.*, 2017; Pate *et al.*, 2020). Sediment and organic material that has collected in the dry river bed is flushed during the onset of flow, leading to high sediment and nutrient fluxes (Hladyz *et al.*, 2011; Fortesa *et al.*, 2021) and high rates of biogeochemical transformations and ecosystem respiration (Acuña *et al.*, 2005; Romaní *et al.*, 2006; von Schiller *et al.*, 2017; Hale and Godsey, 2019). The expansion of the flowing stream network during wet periods, furthermore, leads to a more direct connection between the hillslopes and the stream, resulting in shorter travel times (van Meerveld *et al.*, 2019) and the potential bypassing of riparian buffer strips (Wigington *et al.*, 2005).

Even though it is the repeated presence and absence of flowing water that shapes temporary stream ecosystems and the onset and duration of flow in headwater temporary streams affect water quantity and quality in downstream perennial streams, there are very limited hydrological data for temporary streams. Temporary streams are generally not included in stream monitoring networks, and where present, they are sometimes only operated seasonally as the dry period is not considered interesting for water management (Peters *et al.*, 2012). Even in experimental headwater catchments, gauging stations are usually placed at the point of perennial flow. As a result, temporary streams are largely underrepresented in hydrological studies and monitoring networks (Benstead and Leigh, 2012; Snelder *et al.*, 2013; Godsey and Kirchner, 2014). The lack of gauging of temporary streams has to be kept in mind when datasets are compiled to determine the abundance and variation in temporary stream dynamics. The catalogue of temporary streams in Europe collected as part of the SMIRES initiative (Sauquet *et al.*, 2020) highlights the high variation in their hydrological response. Still, systematic analyses of the spatial patterns in the onset and cessation of flow or trends therein are difficult due to the lack of data (Tramblay *et al.*, in press). For example, only 7% of the U.K. benchmark network of near-natural catchments that are considered suitable for the analysis of trends in streamflow are non-perennial (Harrigan *et al.*, 2018).Only 10% of the more than 4000 gauging stations in France with daily discharge data available in the national HYDRO database (http://www.hydro.eaufrance.fr) are likely naturally intermittent (Figure 1b). The fraction was highest (22%) for gauging stations with a catchment area ≤10 km^2. The ONDE (Observatoire National des Etiages) network was designed by the French Biodiversity Agency, https://ofb.gouv.fr/) to complement the hydrometric network and reports the hydrological state (flowing water, standing water in isolated pools, dry streambed) for 3350 tributary streams at least five times per year (once per month between May and October). Most sites (85%) are located on streams with a catchment area ≤100 km^2 and 20% of the sites have a catchment area ≤10 km^2 (Figure 1a). For almost half (49%) of the sites, there was at least one observation of no flow prior to January 2020 (Figure 1a).

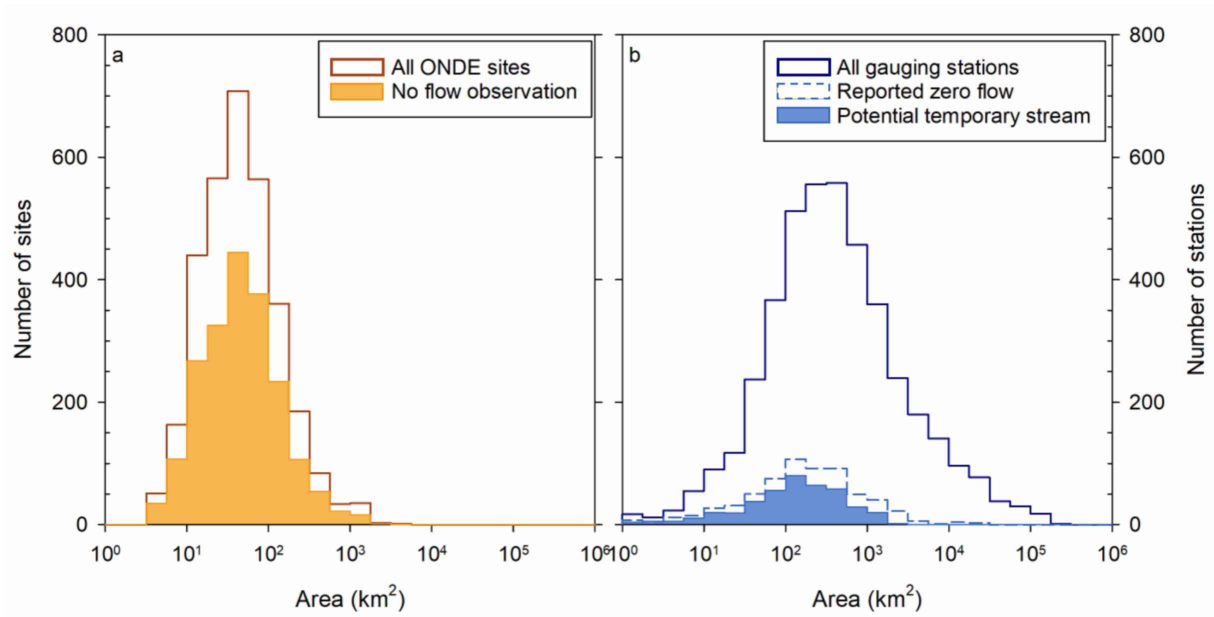

Figure 1. Frequency distribution of the number of sites in the ONDE network (a) and the number of French gauging stations available in the HYDRO database (b) as a function of catchment area. The sites for which at least once no flowing water (i.e., dry streambed or standing water in isolated pools) was observed and stations on potential intermittent streams are indicated by the filled area. For the gauging stations (b), all stations that include an occurrence of zero flow are shown with a dashed line (all data until 01.01.2020).

Hydrometric challenges in measuring very low flows may mean that the stream is considered to be flowing, even though it is dry (or vice versa). Furthermore, the reported zero flows often reflect a data issue rather than a real measurement of zero flow (Zimmer *et al.*, 2020). This means that data on zero flows cannot be used without looking at their quality codes. For example, analysis of the data in the aforementioned French HYDRO database showed that a notable proportion of the 730 gauging stations for which an occurrence of zero flow was reported, are unlikely to be temporary streams (Figure 1b). This (admittedly fairly subjective) assessment involved data screening of no-flow occurrence (seasonality of null values, consistency with historical droughts, etc.), recession curves (changes in discharge before and after the sequence of null values, etc.), additional information from nearby ONDE sites, and information from the hydrometric services (personal communication). For publicly available datasets knowledge about specific practices is needed before the discharge data can be used to compute statistics on no-flow events. For example, Environment Canada used to denote flows smaller than 1 l s^{-1} as zero (Peters *et al.*, 2012). We, therefore, recommend that especially for stations in temperate climates, where intermittence is not frequently observed, a label “temporary stream” should be added to the metadata of gauging stations to avoid any ambiguity. Nevertheless, this status needs to be updated regularly, particularly after droughts.

For many applications (e.g., understanding ecological processes and biogeochemical cycling) it is crucial to know whether there is flowing water, or pools with standing water, or if the streambed is dry (Gallart *et al.*, 2012; Bonada *et al.*, 2020). Gauging stations are designed to measure flow, not to provide information on the presence of pools. Pools of standing water are common and provide important refugia during dry periods (e.g., Marshall *et al.*, 2016). At 39% of the sites in the ONDE network pools were observed at least once. For comparison, dry streambeds were observed at least once for 34% of the sites.

In light of the difficulties in gauging temporary streams, the costs associated with establishing and maintaining gauging stations, and the extremely high spatial variation in the occurrence of flow along the channel, new approaches to obtain data on the state of temporary streams are being tested. While field mapping provides the most detailed spatial data (Wigington *et al.*, 2005; Malard *et al.*, 2006; Doering *et al.*, 2007; Godsey and Kirchner, 2014; Jensen *et al.*, 2017; Sefton *et al.*, 2019), it is difficult to do in headwater catchments during rainfall events because conditions can change quickly. Some studies have used drones with cameras for the mapping (Spence and Mengistu, 2016; Borg Galea *et al.*, 2019; Calsamiglia *et al.*, 2020) but this is difficult for very small headwater streams, where vegetation is dense, or during intense rainfall events. Other studies have used low-cost electrical resistance (Blasch *et al.*, 2002; Goulsbra *et al.*, 2009; Bhamjee and Lindsay, 2011; Sherrod *et al.*, 2012; Chapin *et al.*, 2014; Paillex *et al.*, 2020) or temperature (Ronan *et al.*, 1998; Constantz, 2008) sensors to determine the onset and cessation of flow. The sensor networks developed by Bhamjee *et al.* (2016) and Assendelft and van Meerveld (2019) even allow differentiation of standing water (pools) and flowing water. Even though the initial tests of these sensors are promising, their use has yet to become commonplace, likely due to the need to invest in sensor development and maintenance. Aerial photographs, images from Google Street View and interviews with inhabitants have been used determine the medium-term state of temporary streams in populated areas (Gallart *et al.*, 2017). Physical and biological indicators can also be used to determine the duration of the flowing state for temporary streams (Fritz *et al.*, 2020).

Crowdsourcing or citizen science is an alternative approach to obtaining data on the state of temporary streams (Kampf *et al.*, 2018). Visual observations at a range of locations can lead to data with a relatively high temporal resolution (Figure 2) or to obtain detailed maps of the presence of flow along rivers (Turner and Richter, 2011; Allen *et al.*, 2019). Although initial analyses suggest high interrater agreement (Seibert *et al.*, 2019), the accuracy and usefulness of these data still need to be determined. Furthermore, the involvement of the public is a challenge, particularly for national or international projects for which it is more difficult to organize local outreach events to raise awareness of the project and the importance of temporary stream observations. The involvement of the public can be a challenge as dry streams are valued less than flowing streams (Armstrong *et al.*, 2012) and because small streams are often overlooked. Citizen science helps to increase public awareness on environmental issues, and short-term, large-scale projects are particularly well-suited for this (Pocock *et al.*, 2013). To obtain repeated data from many sites, it is useful to engage environmental management agencies. When they include the quick citizen science-based approaches in their regular monitoring, a large number of additional data points can be collected. For example, the French authority SR3A in charge of water management for tributaries to the Rhone River used the CrowdWater approach (www.crowdwater.ch) to map the presence of flow in temporary streams (Figure 3). Together with the data from the ONDE network, these observations contributed to real-time monitoring of the state of the rivers and supported water restriction measures. Similarly, in the UK, 1050 observations were submitted for 145 spots between January 2019 and July 2020 using the CrowdWater app, mostly on chalk streams in the south-east of England. These observations complement surveys conducted by the Environment Agency. Knowledge of the patterns of intermittence for these groundwater-fed streams helps the agency to identify the impacts of abstractions and other stressors, track droughts, and inform ecological flow requirements.

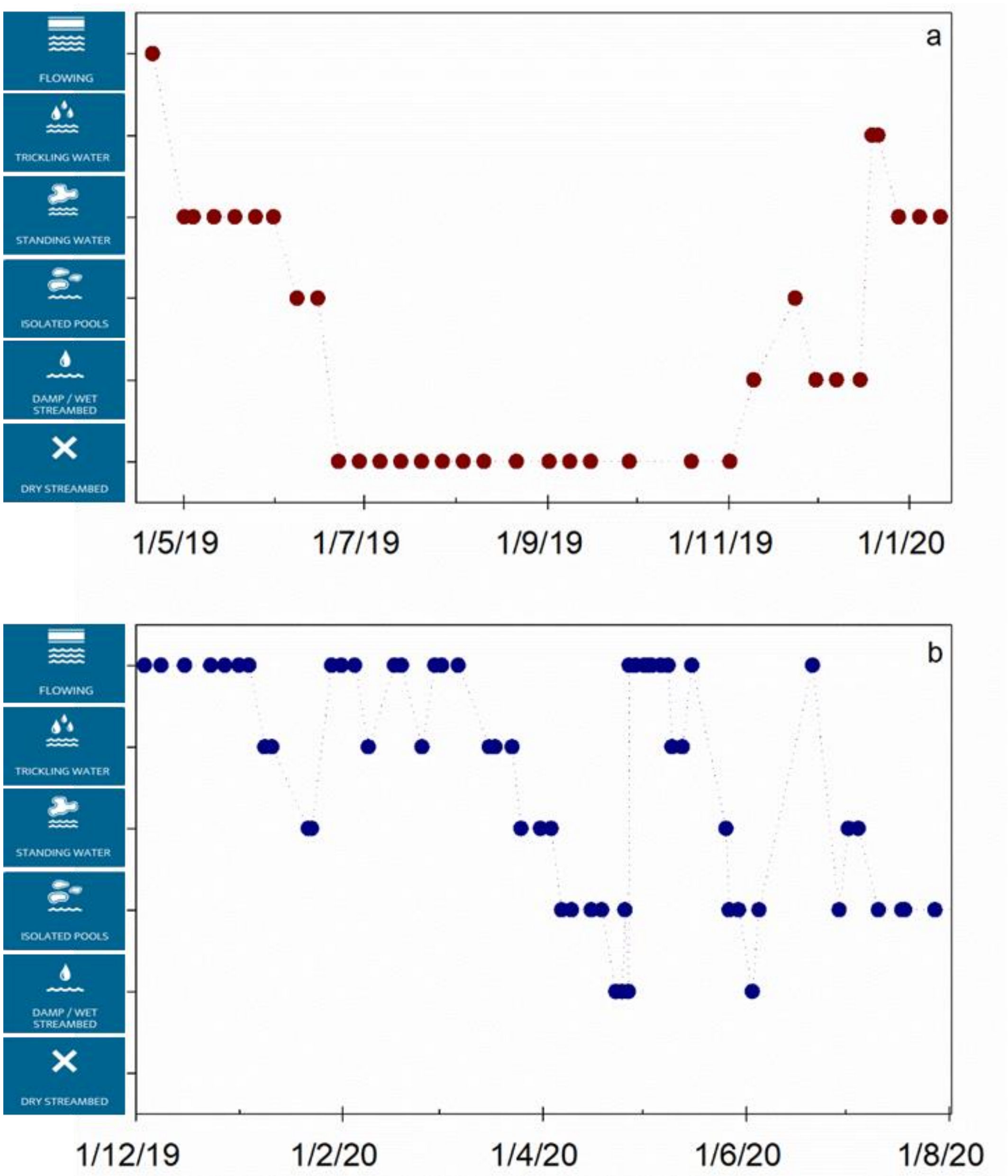

Figure 2. Examples of eight-month time series of observations of the hydrological state of temporary streams made with the CrowdWater app for a site in Portugal (a) and a site in Switzerland (b). Note that the two Figures show a different period. Source: https://www.spotteron.com/crowdwater/spots/89106 (a) and https://www.spotteron.com/crowdwater/spots/245853 (b).

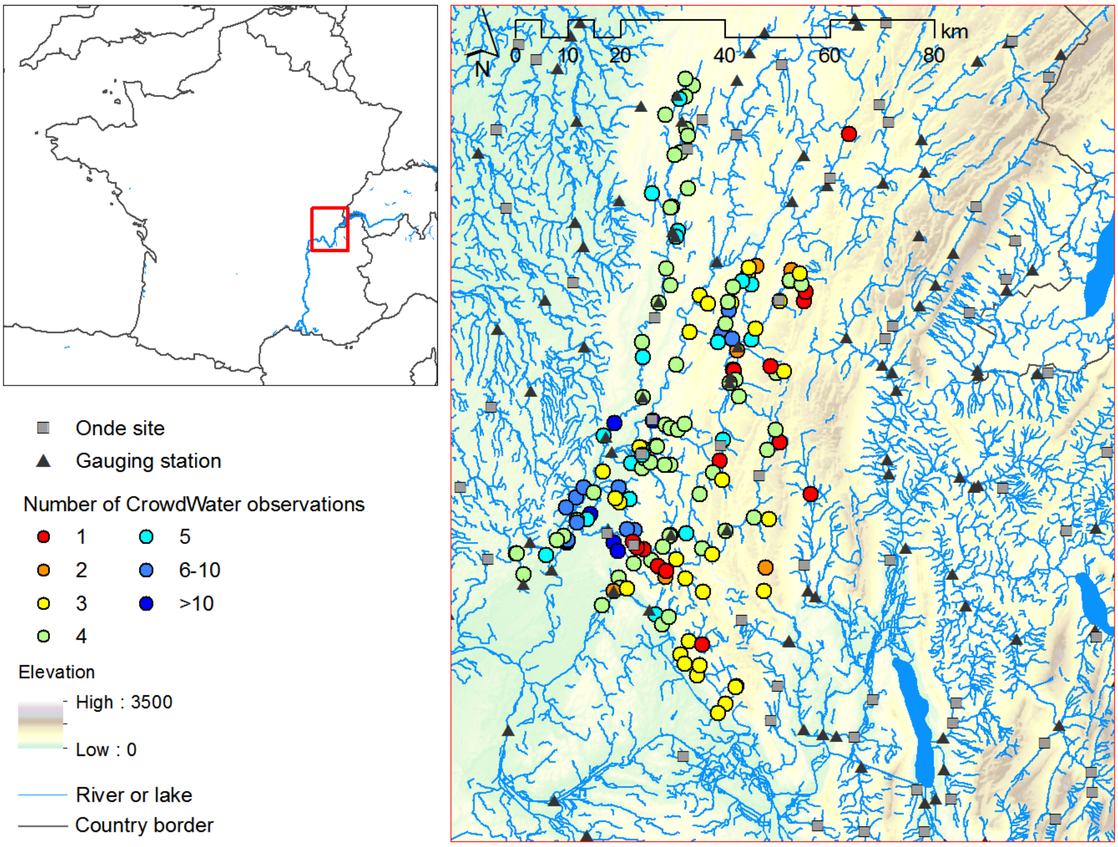

Figure 3. The number of observations made with the CrowdWater app (Seibert *et al.*, 2019) for temporary streams (colored circles,) by August 9, 2020, as well as the locations of the gauging stations (black triangles) and the ONDE sites (grey squares). The inset shows the location of the area in France and the Rhone river. Background elevation data from https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1-0-and-derived-products. The stream network was obtained from http://www.sandre.eaufrance.fr/.

Hydrological models (Williamson *et al.*, 2015; Ward *et al.*, 2018; Yu *et al.*, 2018; Gutiérrez-Jurado *et al.*, 2019), topographic data (Prancevic and Kirchner, 2019) and statistical approaches (Snelder *et al.*, 2013; Russell *et al.*, 2015; González-Ferreras and Barquín, 2017; Beaufort *et al.*, 2019; Jaeger *et al.*, 2019; Konrad and Rumsey, 2019; Durighetto *et al.*, 2020) have been used to predict where streams are temporary and can be used to determine where additional data on the state of temporary streams may be most useful. However, to train and validate these models, more observations of the state of temporary streams and stream network dynamics are needed. Data on the presence or absence of flowing water in different tributaries or the total flowing stream length can be used to calibrate hydrological models (Stoll and Weiler, 2010) or to validate the simulations of the stream network from physically-based coupled surface-subsurface flow models. The comparison of observations and simulations is less direct for conceptual (i.e., bucket-type) models, but observations can be used indirectly in model calibration or validation because they provide information on storage dynamics.

The basic approach, in this case, is to compare the average or typical stream conditions to the dynamics of the simulated (groundwater) storage.

Previous model studies have focused on climate change and other human impacts on flow intermittence, particularly for Mediterranean catchments (Jaeger *et al.*, 2014; Reynolds *et al.*, 2015; Pumo *et al.*, 2016; Querner *et al.*, 2016; Tzoraki *et al.*, 2016; De Girolamo *et al.*, 2017) or globally (e.g., Döll and Schmied, 2012). They predict a shift from perennial to intermittent flow regimes and an increased duration of the dry state, which will impact freshwater ecosystems (e.g., Cipriani *et al.*, 2014; Jaeger *et al.*, 2014). Observations of trends in flow persistence in headwater streams can provide important information and an early warning of how the dynamics of larger streams may change due to climate or land-use change because even small changes can cause them to switch from being perennial to temporary.

We add our call for more studies on temporary streams to those of similar commentaries (Larned *et al.*, 2010; Datry *et al.*, 2011; Kampf *et al.*, 2018; Shanafield *et al.*, 2020). In particular, we call on hydrologists *and* citizens to observe, sense and report the hydrological state of the *aqua temporaria incognita*. These data will improve our understanding of these unique streams and the impacts of climate and land use change and water management on them, both directly and through the testing and refinement of hydrological models. Without these data, it is as if we are trying to complete a puzzle on how headwater catchments function and how water affects ecological processes, while the majority of the puzzle pieces are hidden under the carpet. Recent studies provide some information on how many of the pieces are hidden, but our knowledge is so limited that we do not even know what is printed on them. This makes it impossible to complete the puzzle of our landscape and how it functions. Developing that understanding will not only expand our knowledge about temporary streams but will also entail a fundamental rethinking of how water is connected to landscapes. That is because the current understanding of high flows, when much of the water leaves the landscape, has not included a large component of the land-water interface during and after these high flows - *aqua temporaria incognita*.

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