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1 Aqua Temporaria Incognita

2
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13
14
15 It has been 12 years since Bishop *et al.* (2008) wrote the Invited Commentary “Aqua Incognita: the
16 unknown headwaters”. They highlighted that “In most regions, the overwhelming majority of stream
17 length lies beyond the frontiers of any systematic documentation and would have to be represented as
18 a blank space on the assessment map. This means that for the majority of streams that support aquatic
19 life, a systematic understanding is lacking on water quality, habitat, biota, specific discharge, or even
20 how many kilometers of such streams are there. This blank space is so vast that it deserves a name to
21 help us at least to remember that it is there. We propose calling it ‘*Aqua Incognita*’” (Bishop *et al.*,
22 2008; p. 1239). We continue to agree with this statement and the need to understand headwater
23 streams better. In this commentary, we want to draw attention to a particular type of headwater
24 stream that is even less frequently examined: headwater streams that flow intermittently, i.e., the
25 ***Aqua Temporaria Incognita***. Question 3 of the 23 unsolved problems in hydrology (Blöschl *et al.*,
26 2019) focuses on ephemeral dryland streams. We argue that this focus needs broadening to
27 headwater temporary streams because they are ubiquitous in all climates. Headwater temporary
28 streams feed larger perennial streams and are particularly sensitive to climate change and other
29 human influences (Jaeger *et al.*, 2014; Reynolds *et al.*, 2015; Pumo *et al.*, 2016). Their effective
30 management and protection, therefore, requires an understanding of both natural and artificial
31 causes of intermittence.

32 Temporary streams are among the most hydrologically variable headwater systems (Wohl, 2017).
33 They include intermittent streams that flow seasonally, ephemeral streams that only flow in
34 response to rainfall or snowmelt events, and episodic streams that contain flowing water only during

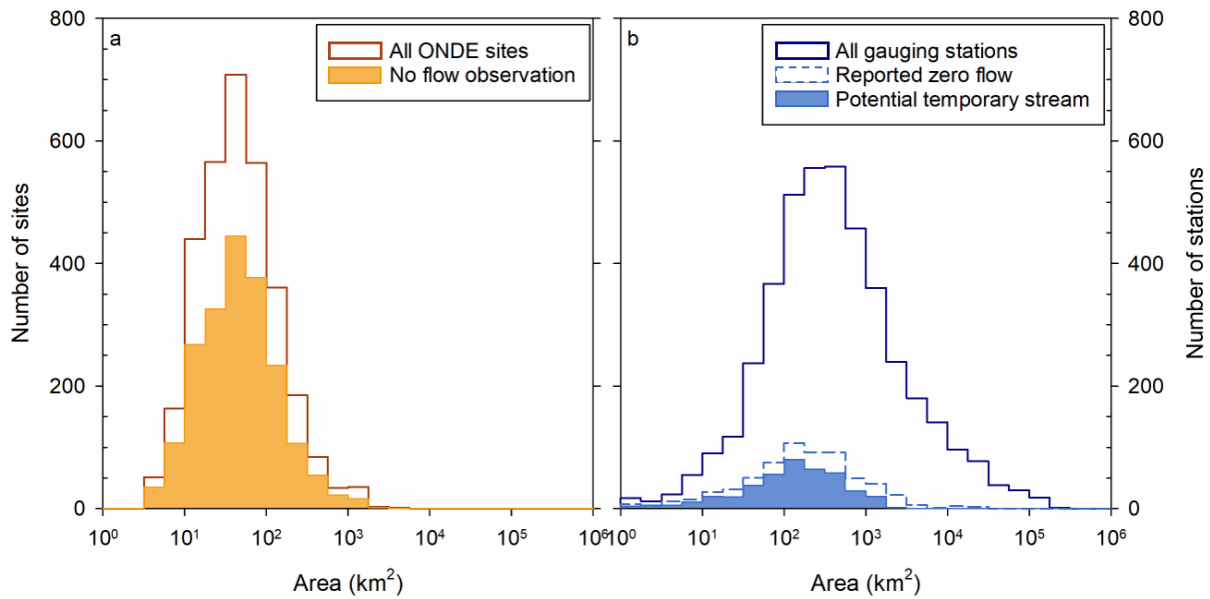
35 extreme rainfall events (Buttle *et al.*, 2012). The terms used for these non-perennial streams vary
36 (Busch *et al.*, 2020) and more classes can be defined to describe the occurrence of pools with
37 standing water (Gallart *et al.*, 2017). Here we use the term temporary stream to refer to all non-
38 perennial streams, but we acknowledge that the exact naming and definition of these water bodies
39 can have important implications for their legal protection (Caruso, 2011; Nikolaidis *et al.*, 2013;
40 Magand *et al.*, 2020). In Switzerland, for instance, streams that flow on average less than 347 days
41 per year (over a 10 year period) are considered non-permanent streams and regulations for
42 permanent streams, such as requirements for permits to discharge or withdraw water, might not
43 apply.

44 Bishop *et al.* (2008) argued that the majority of the total stream length needs to be represented as a
45 blank space on assessment maps because they are not part of any systematic documentation.
46 Temporary streams in headwater catchments are rarely included in assessments and often not even
47 shown on maps. Levick *et al.* (2008) reported that 59% of the streams in the U.S. (excluding Alaska)
48 are temporary, but their survey was based on 1:100,000 scale topographic maps and did not include
49 stream segments shorter than 1.6 km, such that it excluded all temporary headwater streams.
50 Analyses based on the 1:24,000 scale National Hydrography Dataset (NHDPlus) suggested that 42%
51 of all stream segments in the upper Colorado river are first-order streams with intermittent flow and
52 that temporary streams make up 73% of the total stream length (Caruso and Haynes, 2011). All
53 studies that have actually mapped temporary streams in the field have shown that they are far more
54 prevalent than indicated by the dashed blue lines on maps (Hansen, 2001; Fritz *et al.*, 2013). For
55 example, the Swiss national topographic map shows 0.68 km of streams in the 13 ha upper Studibach
56 catchment but repeated field mapping has shown that there are at least 3.77 km of streams, of
57 which 2.66 km (71%) did not have flowing water during the dry summer of 2018 (van Meerveld *et al.*,
58 2019). Similarly, field mapping of stream heads during wet conditions in the 68 km² Krycklan
59 catchment in northern Sweden showed that 76% of the fully expanded network was missing on the
60 official map (Ågren *et al.*, 2015). A lack of knowledge about the location and extent of temporary
61 streams hampers their protection (Caruso, 2011; Caruso and Haynes, 2011).

62 Temporary streams have high biodiversity and are home to many endemic species (Stanley *et al.*,
63 1997; Meyer *et al.*, 2007; Stubbington *et al.*, 2017); the dry riverbed is an egg bank for aquatic
64 invertebrates and seed bank for aquatic plants (Brock *et al.*, 2003; Steward *et al.*, 2012). The onset
65 and cessation of flow significantly affects the species assemblage (Pařil *et al.*, 2019; Sarremejane *et al.*,
66 *in press*). Connectivity of previously disconnected stream segments increases streamflow (e.g.,
67 Godsey and Kirchner, 2014; Jensen *et al.*, 2017; Pate *et al.*, 2020). Sediment and organic material that
68 has collected in the dry river bed is flushed during the onset of flow, leading to high sediment and

69 nutrient fluxes (Hladyz *et al.*, 2011; Fortesa *et al.*, 2021) and high rates of biogeochemical
70 transformations and ecosystem respiration (Acuña *et al.*, 2005; Romaní *et al.*, 2006; von Schiller *et*
71 *al.*, 2017; Hale and Godsey, 2019). The expansion of the flowing stream network during wet periods,
72 furthermore, leads to a more direct connection between the hillslopes and the stream, resulting in
73 shorter travel times (van Meerveld *et al.*, 2019) and the potential bypassing of riparian buffer strips
74 (Wigington *et al.*, 2005).

75 Even though it is the repeated presence and absence of flowing water that shapes temporary stream
76 ecosystems and the onset and duration of flow in headwater temporary streams affect water
77 quantity and quality in downstream perennial streams, there are very limited hydrological data for
78 temporary streams. Temporary streams are generally not included in stream monitoring networks,
79 and where present, they are sometimes only operated seasonally as the dry period is not considered
80 interesting for water management (Peters *et al.*, 2012). Even in experimental headwater catchments,
81 gauging stations are usually placed at the point of perennial flow. As a result, temporary streams are
82 largely underrepresented in hydrological studies and monitoring networks (Benstead and Leigh,
83 2012; Snelder *et al.*, 2013; Godsey and Kirchner, 2014). The lack of gauging of temporary streams has
84 to be kept in mind when datasets are compiled to determine the abundance and variation in
85 temporary stream dynamics. The catalogue of temporary streams in Europe collected as part of the
86 SMIRES initiative (Sauquet *et al.*, 2020) highlights the high variation in their hydrological response.
87 Still, systematic analyses of the spatial patterns in the onset and cessation of flow or trends therein
88 are difficult due to the lack of data (Tramblay *et al.*, in press). For example, only 7% of the U.K.
89 benchmark network of near-natural catchments that are considered suitable for the analysis of
90 trends in streamflow are non-perennial (Harrigan *et al.*, 2018). Only 10% of the more than 4000
91 gauging stations in France with daily discharge data available in the national HYDRO database
92 (<http://www.hydro.eaufrance.fr>) are likely naturally intermittent (Figure 1b). The fraction was
93 highest (22%) for gauging stations with a catchment area ≤ 10 km². The ONDE (Observatoire National
94 des Etiages) network was designed by the French Biodiversity Agency, (<https://ofb.gouv.fr/>) to
95 complement the hydrometric network and reports the hydrological state (flowing water, standing
96 water in isolated pools, dry streambed) for 3350 tributary streams at least five times per year (once
97 per month between May and October). Most sites (85%) are located on streams with a catchment
98 area ≤ 100 km² and 20% of the sites have a catchment area ≤ 10 km² (Figure 1a). For almost half (49%)
99 of the sites, there was at least one observation of no flow prior to January 2020 (Figure 1a).



100
 101 **Figure 1.** Frequency distribution of the number of sites in the ONDE network (a) and the number of French
 102 gauging stations available in the HYDRO database (b) as a function of catchment area. The sites for which at
 103 least once no flowing water (i.e., dry streambed or standing water in isolated pools) was observed and stations
 104 on potential intermittent streams are indicated by the filled area. For the gauging stations (b), all stations that
 105 include an occurrence of zero flow are shown with a dashed line (all data until 01.01.2020).

106
 107 Hydrometric challenges in measuring very low flows may mean that the stream is considered to be
 108 flowing, even though it is dry (or vice versa). Furthermore, the reported zero flows often reflect a
 109 data issue rather than a real measurement of zero flow (Zimmer *et al.*, 2020). This means that data
 110 on zero flows cannot be used without looking at their quality codes. For example, analysis of the data
 111 in the aforementioned French HYDRO database showed that a notable proportion of the 730 gauging
 112 stations for which an occurrence of zero flow was reported, are unlikely to be temporary streams
 113 (Figure 1b). This (admittedly fairly subjective) assessment involved data screening of no-flow
 114 occurrence (seasonality of null values, consistency with historical droughts, etc.), recession curves
 115 (changes in discharge before and after the sequence of null values, etc.), additional information from
 116 nearby ONDE sites, and information from the hydrometric services (personal communication). For
 117 publicly available datasets knowledge about specific practices is needed before the discharge data
 118 can be used to compute statistics on no-flow events. For example, Environment Canada used to
 119 denote flows smaller than 1 l s^{-1} as zero (Peters *et al.*, 2012). We, therefore, recommend that
 120 especially for stations in temperate climates, where intermittence is not frequently observed, a label
 121 “temporary stream” should be added to the metadata of gauging stations to avoid any ambiguity.
 122 Nevertheless, this status needs to be updated regularly, particularly after droughts.

123 For many applications (e.g., understanding ecological processes and biogeochemical cycling) it is
 124 crucial to know whether there is flowing water, or pools with standing water, or if the streambed is

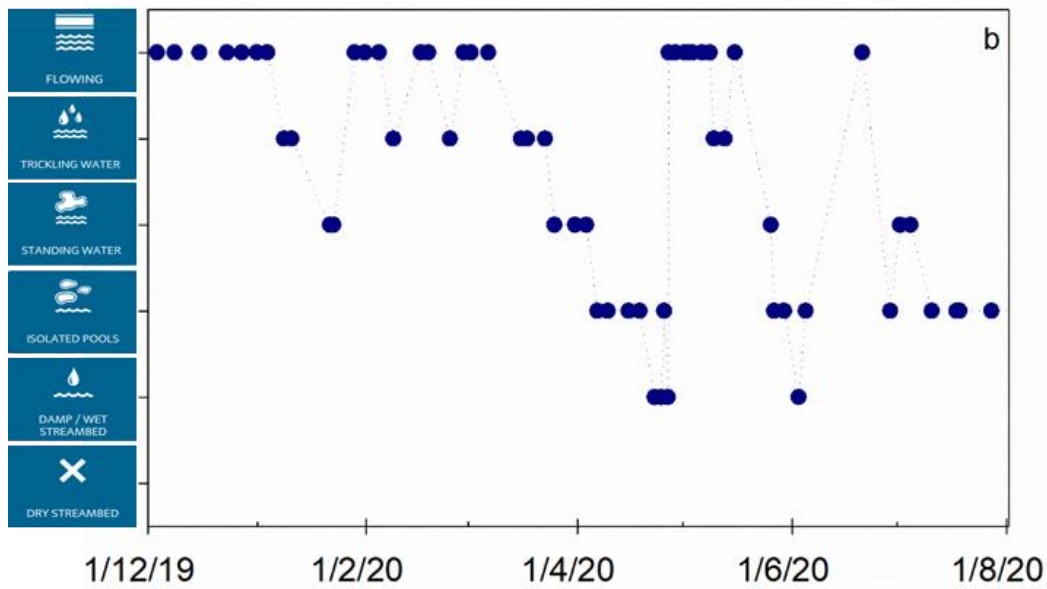
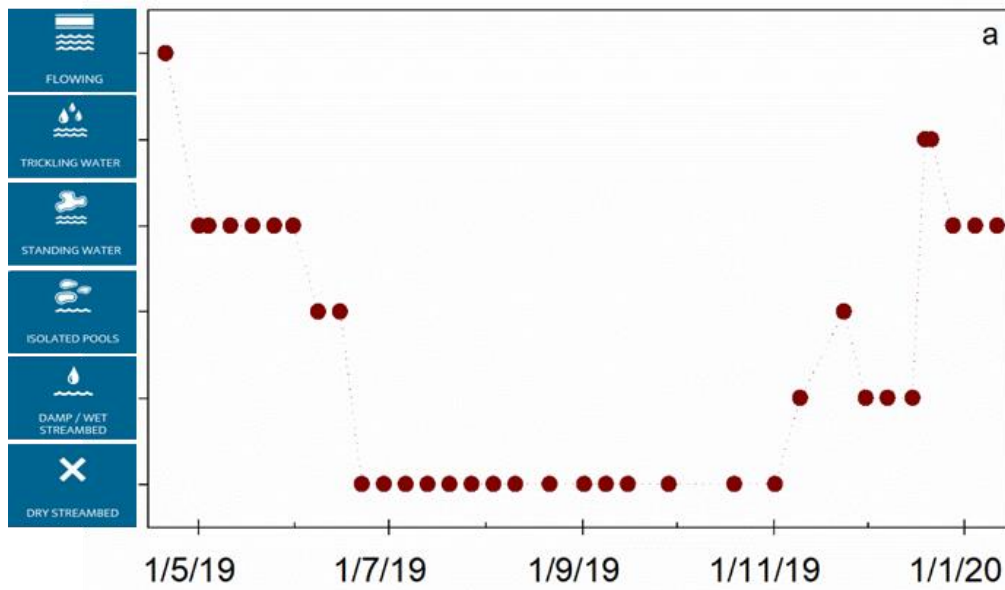
125 dry (Gallart *et al.*, 2012; Bonada *et al.*, 2020). Gauging stations are designed to measure flow, not to
126 provide information on the presence of pools. Pools of standing water are common and provide
127 important refugia during dry periods (e.g., Marshall *et al.*, 2016). At 39% of the sites in the ONDE
128 network pools were observed at least once. For comparison, dry streambeds were observed at least
129 once for 34% of the sites.

130 In light of the difficulties in gauging temporary streams, the costs associated with establishing and
131 maintaining gauging stations, and the extremely high spatial variation in the occurrence of flow along
132 the channel, new approaches to obtain data on the state of temporary streams are being tested.
133 While field mapping provides the most detailed spatial data (Wigington *et al.*, 2005; Malard *et al.*,
134 2006; Doering *et al.*, 2007; Godsey and Kirchner, 2014; Jensen *et al.*, 2017; Sefton *et al.*, 2019), it is
135 difficult to do in headwater catchments during rainfall events because conditions can change quickly.
136 Some studies have used drones with cameras for the mapping (Spence and Mengistu, 2016; Borg
137 Galea *et al.*, 2019; Calsamiglia *et al.*, 2020) but this is difficult for very small headwater streams,
138 where vegetation is dense, or during intense rainfall events. Other studies have used low-cost
139 electrical resistance (Blasch *et al.*, 2002; Goulsbra *et al.*, 2009; Bhamjee and Lindsay, 2011; Sherrod *et*
140 *al.*, 2012; Chapin *et al.*, 2014; Paillex *et al.*, 2020) or temperature (Ronan *et al.*, 1998; Constantz,
141 2008) sensors to determine the onset and cessation of flow. The sensor networks developed by
142 Bhamjee *et al.* (2016) and Assendelft and van Meerveld (2019) even allow differentiation of standing
143 water (pools) and flowing water. Even though the initial tests of these sensors are promising, their
144 use has yet to become commonplace, likely due to the need to invest in sensor development and
145 maintenance. Aerial photographs, images from Google Street View and interviews with inhabitants
146 have been used determine the medium-term state of temporary streams in populated areas (Gallart
147 *et al.*, 2017). Physical and biological indicators can also be used to determine the duration of the
148 flowing state for temporary streams (Fritz *et al.*, 2020).

149 Crowdsourcing or citizen science is an alternative approach to obtaining data on the state of
150 temporary streams (Kampf *et al.*, 2018). Visual observations at a range of locations can lead to data
151 with a relatively high temporal resolution (Figure 2) or to obtain detailed maps of the presence of
152 flow along rivers (Turner and Richter, 2011; Allen *et al.*, 2019). Although initial analyses suggest high
153 interrater agreement (Seibert *et al.*, 2019), the accuracy and usefulness of these data still need to be
154 determined. Furthermore, the involvement of the public is a challenge, particularly for national or
155 international projects for which it is more difficult to organize local outreach events to raise
156 awareness of the project and the importance of temporary stream observations. The involvement of
157 the public can be a challenge as dry streams are valued less than flowing streams (Armstrong *et al.*,
158 2012) and because small streams are often overlooked. Citizen science helps to increase public

159 awareness on environmental issues, and short-term, large-scale projects are particularly well-suited
160 for this (Pocock *et al.*, 2013). To obtain repeated data from many sites, it is useful to engage
161 environmental management agencies. When they include the quick citizen science-based approaches
162 in their regular monitoring, a large number of additional data points can be collected. For example,
163 the French authority SR3A in charge of water management for tributaries to the Rhone River used
164 the CrowdWater approach (www.crowdwater.ch) to map the presence of flow in temporary streams
165 (Figure 3). Together with the data from the ONDE network, these observations contributed to real-
166 time monitoring of the state of the rivers and supported water restriction measures. Similarly, in the
167 UK, 1050 observations were submitted for 145 spots between January 2019 and July 2020 using the
168 CrowdWater app, mostly on chalk streams in the south-east of England. These observations
169 complement surveys conducted by the Environment Agency. Knowledge of the patterns of
170 intermittence for these groundwater-fed streams helps the agency to identify the impacts of
171 abstractions and other stressors, track droughts, and inform ecological flow requirements.

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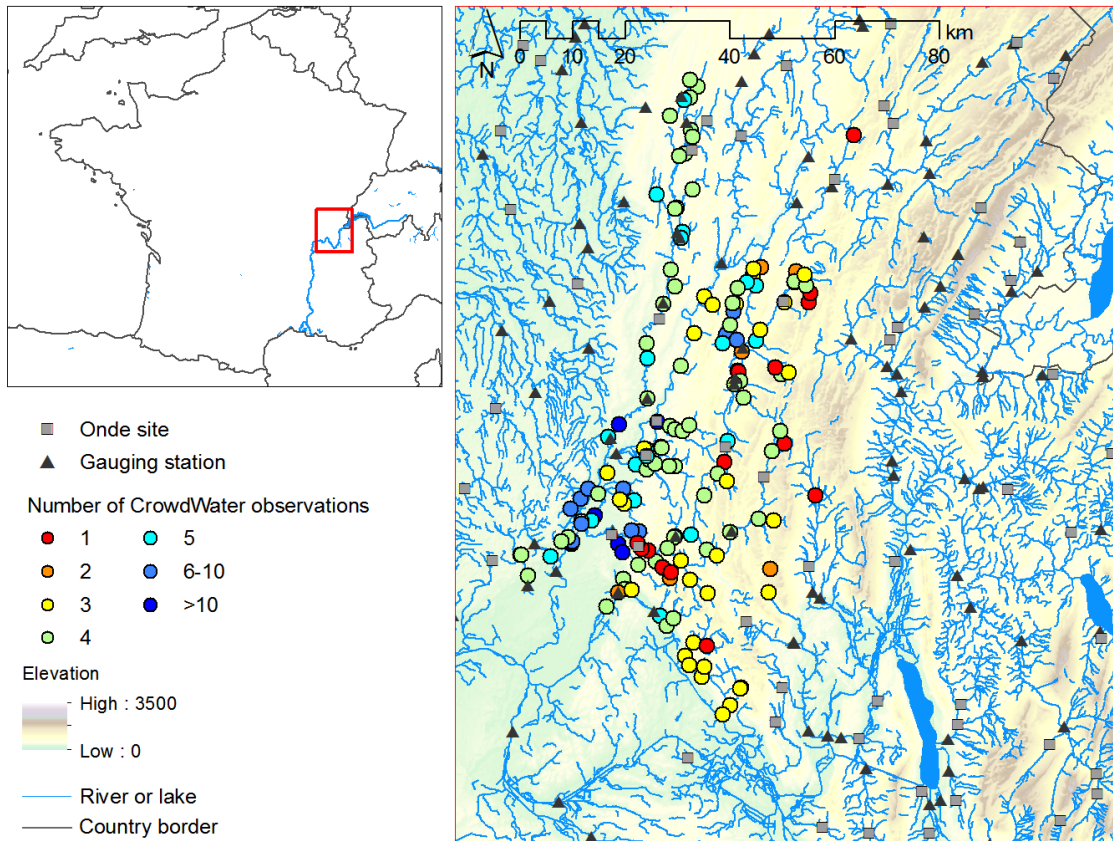
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Figure 2. Examples of eight-month time series of observations of the hydrological state of temporary streams made with the CrowdWater app for a site in Portugal (a) and a site in Switzerland (b). Note that the two Figures show a different period. Source: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



179

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

185

186 Hydrological models (Williamson *et al.*, 2015; Ward *et al.*, 2018; Yu *et al.*, 2018; Gutiérrez-Jurado *et*
 187 *al.*, 2019), topographic data (Prancevic and Kirchner, 2019) and statistical approaches (Snelder *et al.*,
 188 2013; Russell *et al.*, 2015; González-Ferreras and Barquín, 2017; Beaufort *et al.*, 2019; Jaeger *et al.*, 2019;
 189 Konrad and Rumsey, 2019; Durigetto *et al.*, 2020) have been used to predict where streams are
 190 temporary and can be used to determine where additional data on the state of temporary streams
 191 may be most useful. However, to train and validate these models, more observations of the state of
 192 temporary streams and stream network dynamics are needed. Data on the presence or absence of
 193 flowing water in different tributaries or the total flowing stream length can be used to calibrate
 194 hydrological models (Stoll and Weiler, 2010) or to validate the simulations of the stream network
 195 from physically-based coupled surface-subsurface flow models. The comparison of observations and
 196 simulations is less direct for conceptual (i.e., bucket-type) models, but observations can be used
 197 indirectly in model calibration or validation because they provide information on storage dynamics.

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

200 Previous model studies have focused on climate change and other human impacts on flow
201 intermittence, particularly for Mediterranean catchments (Jaeger *et al.*, 2014; Reynolds *et al.*, 2015;
202 Pumo *et al.*, 2016; Querner *et al.*, 2016; Tzoraki *et al.*, 2016; De Girolamo *et al.*, 2017) or globally
203 (e.g., Döll and Schmied, 2012). They predict a shift from perennial to intermittent flow regimes and
204 an increased duration of the dry state, which will impact freshwater ecosystems (e.g., Cipriani *et al.*,
205 2014; Jaeger *et al.*, 2014). Observations of trends in flow persistence in headwater streams can
206 provide important information and an early warning of how the dynamics of larger streams may
207 change due to climate or land-use change because even small changes can cause them to switch
208 from being perennial to temporary.

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

224

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231

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